ACID ROCKS ASSOCIATED WITH AN INTRUSIVE COMPLEX COPPERMINE RIVER AREA, NORTHWEST TERRITORIES

BY

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ABSTRACT

An intrusive complex in the Coppermine River Area, Northwest Territories appears to be a greatly elongated lopolith approximately 5 miles wide and 60 miles long. Multiple intrusion and magmatic differentiation have combined to produce layers of rocks which range in composition from dunite to granophyre within the lopolith.

The acid rocks of the complex were emplaced as a number of separate injections of magma after the crystallization and cooling of the basic and ultrabasic rocks. The structural relations of the acid and basic rocks indicate that the acid intrusions were accompanied by faulting and subsidence of a part of the northern end of the lopolith.

A prominent textural feature of the granophyre, an oscillatory mantling of nuclei of graphic quartz and potash feldspar by quartz-free potash feldspar and plagioclase, is believed to be the result of fluctuations in water vapour pressure during crystallization of the magma.

The fragments in a breccia cemented by granophyre were probably, in part, formed by fault movements which accompanied the intrusion of the acid magma.

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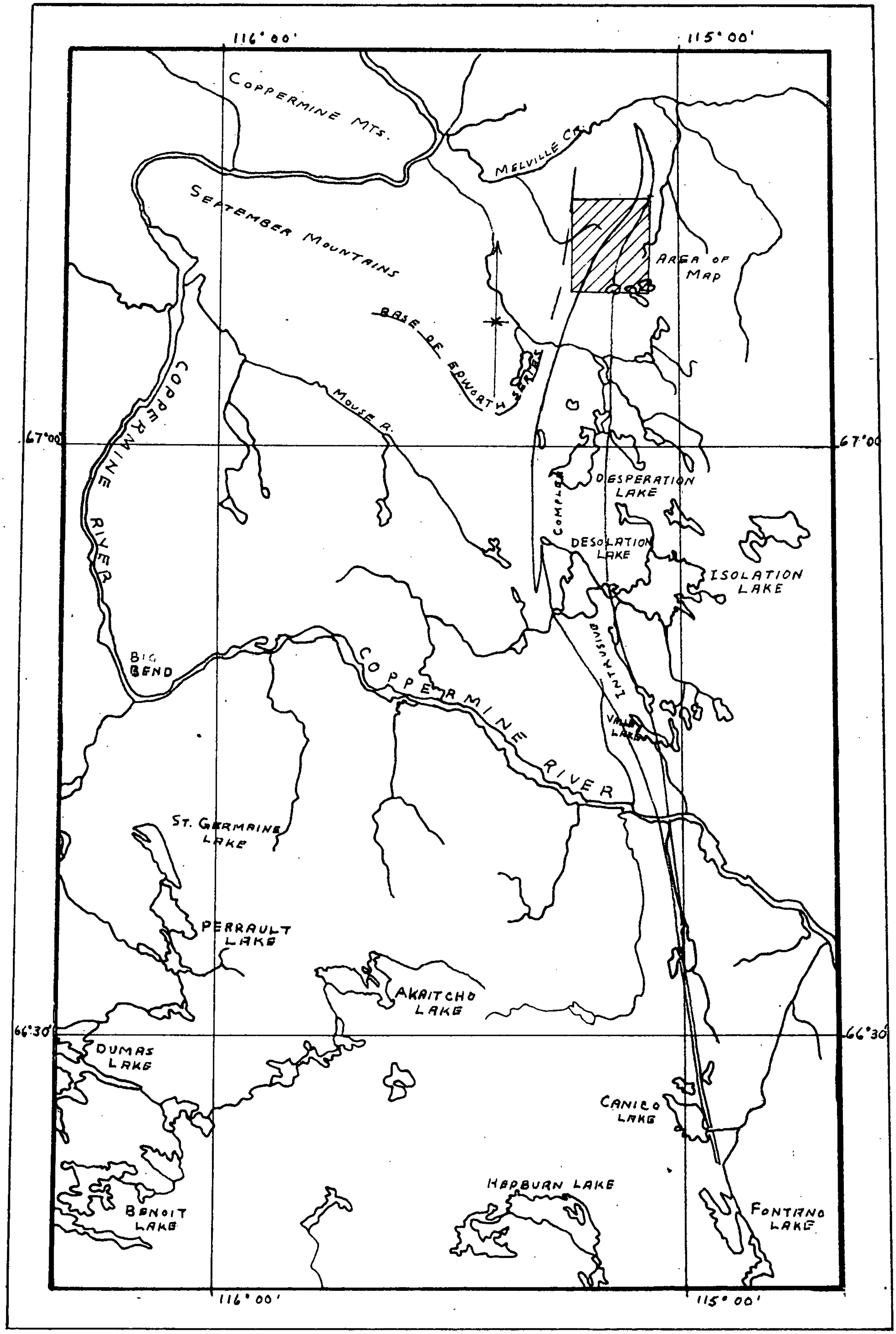
ACKNOWLEDGMENTS

The writer wishes to thank Dr. K.C.McTaggart and Dr. J.V. Ross for their direction of laboratory studies, their helpful suggestions, and discussions of the results obtained. The writer is also indebted to Dr. C.H. Smith of the Geological Survey of Canada for permission to use this problem as the subject of a thesis.

FIGURE I LOCATION MAP OF AREA



INTRODUCTION

Location of the Area

The rocks to be described are located approximately 45 miles south of the settlement of Coppermine in the District of Mackenzie, Northwest Territories. The names Desolation Lake, Desperation Lake, Isolation Lake, Valley Lake, and Canico Lake which will appear on the enclosed maps or in the text are not officially recognized, but are used locally.

Previous Work

The first white man to visit the area was Samuel Hearne, who descended the Coppermine River in 1745 in search of the deposits of native copper which were reported to exist in this area. From that time until after World War II the only persons to visit the area were a few trappers and hunters.

After the discovery of nickel deposits in northern Manitoba, the International Nickel Company began a comprehensive exploration program throughout the western part of the Canadian Shield. A differentiated intrusion was discovered as a result of this exploration program and investigation of sulphide deposits associated with it begun. The intrusion was mapped by geologists employed by the International Nickel Company, but none of the results of these investigations has been published.

Mapping of the intrusion on a scale of 1 inch to 1000 feet by C.H. Smith of the Geological Survey of Canada was begun in 1959. Mapping during the field season of 1959 was completed on the southern portion of the intrusion as far north as Desolation Lake. The material for this thesis was collected while the writer was engaged in mapping the northern limit of the intrusion. At this time, the intrusion was mapped about 4 miles further north of the limit of the mapping done by the International Nickel Company geologists.

The following problems arose as a result of the mapping done by the author in the northern part of the intrusion.

1. The structure of the intrusion at its northern end, and in particular the structural relation of the granophyre to the other rocks in the intrusion.
2. The origin of the granophyre.
3. The origin of a breccia associated with the granophyre.

These problems will be discussed in the forthcoming text along with the petrology of the granophyres.

Methods of Investigation

The majority of the specimens used in this study were collected during the field mapping of the intrusion. These were supplemented by specimens of the basic and ultrabasic rocks collected by Dr. J.V. Ross. Representative specimens of the acid rocks were collected at 50 foot intervals on two traverses across the intrusion. Specimens from other localities were collected primarily to study special features of the rocks at these points.

The laboratory work consisted of examination of thin sections and the estimation of the proportion of constituent minerals. The compositions of feldspars were determined by means of the universal stage.

For the alkali feldspars, the determination of 2V and the optic orientation were found to fix the compositions. In order to determine the compositions, the measurements were applied to curves published by Tuttle[1] (1952). Errors in 2V due to differences in the indices of refraction of the feldspar crystals and hemisphere did not amount to more than 2 degrees.

Plagioclase composition determinations were made with the universal stage using the method described by Turner[2] (1947). Checks of the composition by the Carlsbad-Albite twin method gave results which were reasonably consistent with those obtained by Turner's method. Curves published by Trogger[3] (1952) gave inconsistent results.

No detailed study was made of the basic and ultrabasic parts of the intrusion.

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1 Tuttle, O.F.: Optical Studies on Alkali Feldspars, Am. Jour. Sc., Bowen Volume, 1952, p. 553-567.

2 Turner, F.J.: Determination of Plagioclase with a 4-axis Universal Stage. Am. Min. Vol. 32, 1947, p. 389-410.

3 Trogger, W.E.: Tabellen zur optischen Bestimmung der gesteinbildenden Minerale. E. Schweizerbursche, Verlagsbuchhandlung, Stuttgart, 1952.

General Character of the Area

The area lies north of the limit of trees. The land surface is gently rolling with rock outcrops rising abruptly as much as 200 feet above grassy tundra. The only major topographic feature of the area is the valley of the Coppermine River, the bottom of which lies 800 to 1000 feet below the level of the surrounding country. Most of the lakes and streams are small and shallow.

GENERAL GEOLOGY

Principal Rock Types[4]

The oldest rocks in the area are Archean or early Proterozoic sedimentary rocks which have been folded and regionally metamorphosed. In the vicinity of Fontano Lake these rocks consist principally of quartz-muscovite schists with minor interbedded metaquartzites. The grade of metamorphism increases northward. This progressive metamorphism is characterized by the successive appearance of biotite, garnet and plagioclase porphyroblasts, and pegmatitic veins. The progressive metamorphism reaches its maximum intensity in the vicinity of the Coppermine River where the schists have been converted into paragneisses. North of Valley Lake the intensity of metamorphism decreases until the quartzites and slates at the northern limit show only slight evidence of metamorphism.

The oldest intrusive rocks in the area are granodiorites and quartz diorites with minor granites. In zones of low-grade metamorphism the contacts of these intrusives with the country rocks are sharp and discordant with little evidence of thermal metamorphism of the country rock. In zones of high-grade metamorphism the granitic rocks are more abundant and the contacts between the intrusives and the country rocks are gradational. These contacts are character-

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4 Dr. J.V.Ross: Personal Communication.

ized by assimilation, lit-par-lit injection, and replacement of country rock by pegmatitic veins.

This basement complex is overlain unconformably by the Epworth series which is believed to be late Proterozoic in age. The basal unit of the Epworth series is an orthoquartzite with conglomeratic facies. The orthoquartzite is overlain by conglomerate which in turn is overlain by dolomite. The total thickness of this sequence ranges from 8500 to 9000 feet.

The Epworth series is overlain with possible disconformity by the Coppermine series which is composed of lavas and sedimentary rocks. The thickness of the Coppermine series ranges between 18,000 and 28,000 feet.

A swarm of basic dikes which are probably equivalent in age to the Coppermine lavas cuts the older rocks and some units of the Coppermine series. The dikes are for the most part gabbroic in composition. The general trend of the swarm is northerly.

The differentiated intrusion is associated with the dike swarm and is of the same age to the dike swarm. Some dikes are cut by the intrusion but it is cut in turn by younger dikes.

Regional Structural Geology

The general structural trend in the basement complex is northward. The schistosity which is developed along the axial plane cleavage of the folds strikes consistently toward the north. The strike of bedding generally is parallel to that of the schistosity. Lineations also have a northerly trend. Dips of schistosity and bedding commonly exceed 60 degrees.

The Epworth and Coppermine series have been folded into a broad regional anticline whose axis trends east-west. The limbs of this regional structure dip less than 10 degrees. A few small cross-folds are present on the north limb of this fold.

The Differentiated Intrusion

The general shape of the differentiated intrusion resembles that of a much elongated lopolith, but is more like the hull of a ship, as illustrated in the accompanying block diagram. South of the Coppermine River, erosion has removed all of the intrusion except the dike-like feeder or "keel". The width of the feeder varies from 800 to 1,500 feet south of the Coppermine River. North of the river the width of the lopolith increases and reaches approximately 5 miles at Desolation Lake. North of Desperation Lake the width decreases and it pinches out south of Melville Creek.

Basic and ultrabasic rocks in the intrusion show well-developed layering. The chilled margin is composed of fine-grained norite. The central portion of the feeder and a small portion of the lower part of the lopolith itself are composed of picrite. This is overlain by layers of peridotite, dunite, pyroxenite, and gabbro in that order. The overall aspect of the successive layers is that of a series of troughs stacked one inside another, the whole sequence plunging 2 to 3 degrees north. In plan, the layering results in a symmetry of distribution of rock types about the longitudinal axis of the intrusion, slightly distorted by the effects of relief of the land surface.

Metamorphism of the rocks of the basement complex by the intrusion is limited to the conversion of schists to hornfelses for a few tens of feet out from the contacts of the intrusion. Pockets of sulphides, mainly pyrrhotite and chalcopyrite, occur in brecciated zones along the contacts of the lopolith with the country rock.

The only obvious structural control of the emplacement of the lopolith is the regional schistosity, which apparently acted as a surface of weakness along which the dike swarm and the lopolith intruded. In the vicinity of Canico Lake there is a definite correlation between the development of schistosity and the feeder of the lopolith. Near the contacts of the feeder the axial plane cleavage on the country rock becomes so intensely developed that bedding in the country rock is obliterated. The origin of stresses which presumably opened the fractures along which the basic rocks were intruded is unknown. The wide part of the lopolith occupies the north limb of the anticline. In this portion of the intrusion successively higher layers of rock are exposed to the north, which strongly suggests that the lopolith has been folded along with the Epworth and Coppermine series.

Structures associated with the acid rocks in the northern part of the lopolith are more complex than those in the southern part of the intrusion and will be discussed in detail below, but the distribution of rock types may be summarized at this point. In the area to be described, the eastern margin of the lopolith is formed by a band of peridotite up to 600 feet wide. This is bounded on the west by a band of gabbroic rocks approximately 400 feet wide. At the southern edge of the area, a small band of peridotite about 1000 feet long and 20 to 50 feet wide occurs to the west of the gabbro band. This peridotite band will be referred to subsequently as the small band of peridotite. A sequence of rocks which will be referred to as the quartz gabbro group occurs in the southern part of the map area to the west of the small band of peridotite. The quartz gabbro group is overlain to the north by granophyre which is chilled against the gabbro to the east. The granophyre in turn is overlain by a breccia composed of fragments of quartzite from the basement complex in a granophyric matrix.

The relation of the intrusion to the Epworth series can be established. The walls of the lopolith are formed by rocks of the basement complex, but a large block or raft of Epworth quartzite occurs within the lopolith north of Desperation Lake.

BASIC AND ULTRABASIC ROCKS

Basic and ultrabasic rocks in the lopolith are exposed south of Desolation Lake and along the eastern side of the intrusion over its full length. Many rock types are present, but the information and specimens available are not sufficient to allow any detailed study to be made.

At least three types of layering are present in these rocks, which along with the attitudes of the contacts of the lopolith define the shape of the intrusion. The largest scale layering is formed by the distribution of the different rock types. These layers lie roughly parallel to the walls of the lopolith, forming canoe-shaped masses stacked one inside the other. Within each layer two small-scale types of layering occur. One type which may be termed igneous lamination, is formed by the parallel orientation of tabular crystals. This type of layering frequently occurs within the gabbroic rocks. The second type of small-scale layering is formed by variations in the mineralogical composition within any one rock type. This layering is best developed in a troctolite band at Desolation Lake where anorthositic and olivine-rich bands occur within the troctolite.

The chilled margin of the lopolith is composed of norite. The layer above it is composed of picrite and peridotite. The peridotite is overlain by dunite which is overlain by pyroxenite which in turn is overlain by gabbroic rocks. Quartz gabbro and its associated rocks, and the granophyre will be discussed in detail at a later point.

The occurrence of plagioclase and its changes in composition suggest that one, and possibly at least two separate injections of magma occurred in this part of the lopolith. Plagioclase of composition An_{73} is present in the chilled norite. It occurs in the picrite in the "keel" or feeder as a subordinate constituent, and as an accessory mineral in the peridotite. The plagioclase disappears in the dunite and pyroxenite, and reappears in the gabbro. The composition of the plagioclase ranges from An_{73} in the chilled norite to An_{64} in the gabbro, then the anorthite content increases to An_{73} in the uppermost layer of the gabbro.

Extensive alteration has occurred throughout the basic and ultrabasic rocks. The alteration is characterized by the serpentinization of olivine and pyroxene, and the alteration of plagioclase to sericite and clay minerals. A red-brown biotite occurs throughout the basic and ultrabasic rocks associated with the pyroxene. The biotite has also been affected by the alteration of the basic and ultrabasic rocks, and is partially altered to chlorite.

The alteration appears to be a secondary effect rather than the result of deuteric alteration. The red-brown biotite itself is probably the result of deurteric alteration of pyroxene.

The alteration of the gabbro adjacent to its contact with the chilled granophyre is distinct from the general alteration of the basic rocks. The plagioclase has been partially sericitized, and the mafic minerals completely altered to uralite or chlorite. The introduction of small quantities of carbonate accompanies the alteration at this contact. The contact between the gabbro and chilled granophyre is illustrated in Figure 2.

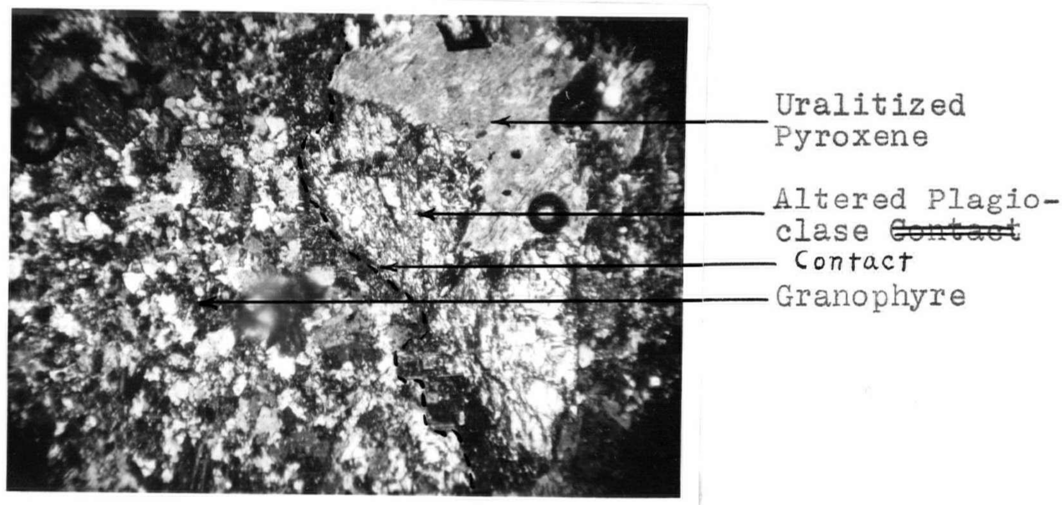

Figure 2. Contact between chilled granophyre and gabbro. Chilled granophyre shows mosaic texture of fine-grained quartz and feldspar, gabbro composed of partially sericitized plagioclase and uralitized pyroxene.

QUARTZ GABBRO AND ASSOCIATED ROCKS

This unit includes a variety of rock types, but for convenience in mapping it has been subdivided into two main types, the quartz gabbros and the granogabbros. This group lies above a zone of layered gabbro, with the greater proportion lying west of the small band of peridotite. The lowest layer of the quartz gabbro group is a fine-grained black diabasic gabbro which does not extend across the full east-west width of the group.

The black fine-grained diabasic unit weathers brown. The texture ranges from hypautomorphic to sub-ophitic. The rock is composed of approximately 40 per cent plagioclase, An_{57}, 35 per cent of a clinopyroxene, probably augite, 8 per cent biotite, 10 per cent sericite and clay minerals, and 4 per cent chlorite. The plagioclase occurs as euhedral lath-shaped crystals which show slight normal zoning at their rims. The pyroxene occurs chiefly as anhedral grains interstitial to the plagioclase, but a few large lath-shaped twinned crystals are also present. A red-brown and a greenish variety of biotite occur in the rock. The red-brown variety is found as shreds and flakes associated with the pyroxene. The greenish variety is associated with the chlorite formed by the alteration of the pyroxene.

The quartz gabbros show a wide variation in composition and texture. They weather brownish. The fresh surface is mottled. The grain size ranges from medium to fine. The texture is also variable. Granitic and sub-ophitic textures are the most common. Some of the rocks of this unit show a well-developed igneous lamination formed by the parallel orientation of tabular feldspar crystals. The principal minerals in the quartz gabbros are a greenish-black pyroxene, green plagioclase, and pink potash feldspar which is intergrown with quartz.

The general trend throughout the quartz gabbro group is toward an increase in both the grain size and the quartz-potash feldspar content from the base to the top of the unit. With the increase in the content of potash feldspar and quartz, the quartz gabbro grades into granogabbro.

The granogabbros also exhibit a wide range of composition. They all weather brown. The fresh surface is mottled. The grain size ranges from medium to coarse. The principal mafic mineral is greenish-black pyroxene which has been altered to uralite and chlorite. The plagioclase, of composition An_{44}, which has been largely altered to sericite and clay minerals, occurs as greenish subhedral crystals. The third major constituent is pink potash feldspar which is intergrown with quartz. Some specimens contain plates of titaniferous hematite up to 3/4 of an inch in diameter. The variations in composition in the granogabbro appear to resemble those described by Phemister[5] (1937) in the transition zone of the Sudbury Nickel Irruptive.

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5 Phemister, T.C.: A Review of the Problems of the Sudbury Irruptive. Jour. Geol. Vol. 54, No. 1, 1937, p. 1-47.

The quartz and potash feldspar in the upper part of the quartz gabbro group may have been introduced from the overlying granophyre, or they may have been concentrated in the last fraction of the differentiated gabbro magma.

A metasomatic origin for the quartz and potash feldspar appears to be unlikely since the alteration of the gabbro adjacent to its contact with the granophyre is not accompanied by the introduction of quartz and potash feldspar.

The upward gradation in composition and texture from a fine-grained diabasic gabbro to a coarse granogabbro suggests that the granogabbro is probably the result of magmatic differentiation and crystal settling as discussed by Bowen[6] (1928). The texture, which is characterized in part by interstitial micropegmatite, is typical of the texture Goodspeed[7] (1959) attributes to deuteric action rather than metasomatism.

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6 Bowen, N.L.: Evolution of the Igneous Rocks. Princeton University Press, 1928.

7 Goodspeed, G.E.: Some Textural Features of Magmatic and Metasomatic Rocks, Am. Min. Vol. 44, 1959, p.211-250.

ACID ROCKS

The acid rocks associated with the intrusion include at least two types, a gray granophyre and an intrusive breccia. Since mapping of the lopolith was not completed north of Desolation Lake, the exact total extent of the acid rocks is unknown.

Granophyre

The granophyre weathers reddish or purplish-pink. The fresh surface is medium light gray with a slight pink or brownish tinge. The depth of weathering averages 3 to 4 inches, but may reach 6 inches. Grain size ranges from medium to fine, the latter being more common. The texture appears to be hypautomorphic. Irregular patches of quartz and potash feldspar in graphic intergrowth are scattered throughout the granophyre near its contacts with the intrusive breccia.

Up to 35 per cent of the rock is composed of inclusions of gray fine-grained quartzite. The maximum size of these inclusions is about 1/2 inch in diameter. They are well-rounded, corroded, and embayed. Narrow black rims surround the inclusions. A typical inclusion with its dark rim is illustrated in Figure 19. Scattered inclusions of slaty material are also present in the granophyre.

In thin section the gray granophyre was found to be composed of 20% to 35% quartz, 35% to 50% potash feldspar, and up to 7% red-brown biotite. Other primary minerals include plagioclase, sphene, rutile, and pyrite.

The texture is typically granophyric, as described and illustrated by Johannsen[8] (1931). It is characterized by subhedral or euhedral crystals of potash feldspar with interstitial graphic intergrowths of quartz and potash feldspar. The general textural relations are illustrated in Figures 3 and 4.

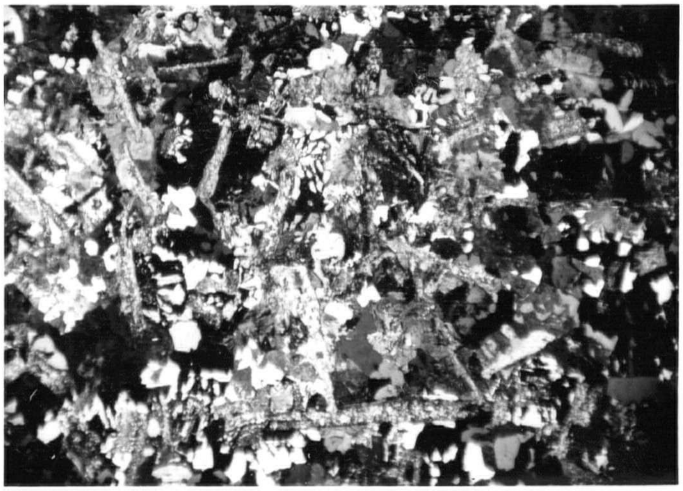

Figure 3. General Textural Relations. Partially altered lath-shaped potash feldspar crystals, a few subhedral quartz and potash feldspar crystals with quartz and feldspar in graphic intergrowth. X16.

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8 Johannsen, A.: A Descriptive Petrology of the Igneous Rocks, Vol. 1, University of Chicago Press, 1931.

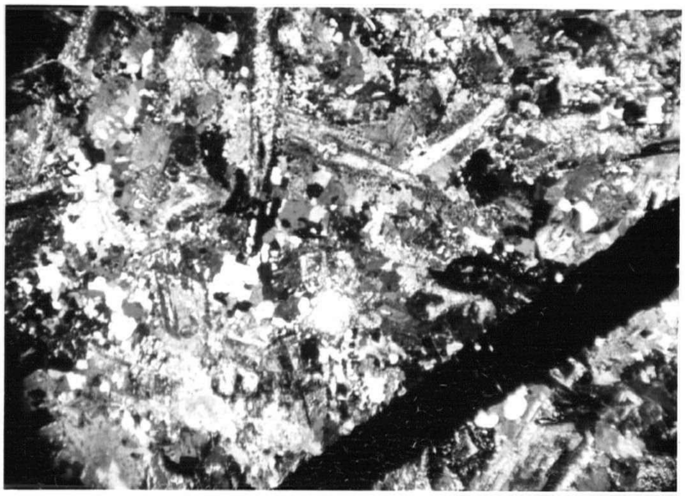

Figure 4. General Textural Relations. Similar to Figure 4, but with lath-shaped crystals of altered plagioclase surrounded by quartz and potash feldspar in graphic intergrowth. X16.

The feldspar and quartz-feldspar intergrowths commonly show a relationship that may be described as oscillatory mantling. A typical mantle relationship consists of a core of quartz and potash feldspar surrounded by a shell of feldspar containing no quartz, which is in turn surrounded by quartz and feldspar in graphic intergrowth. The feldspar shells show crystal outlines, but may be penetrated by intergrowth material which is continuous with that in the core of the crystal. In some mantled crystals, the intergrowth core is not present. The relation is then one of a euhedral feldspar crystal surrounded by an intergrowth of quartz and feldspar. In all types of mantling, the potash feldspar is optically continuous from the core to the outer intergrowth.

Some of the feldspar crystals show a slight patchiness under crossed nicols, but perthitic intergrowths and well-defined zoning as shown by optical properties are not apparent unless more detailed investigations are made of the feldspars, such as determination of 2V in the core and mantle. Intergrowth relations are illustrated in Figures 5 and 6.

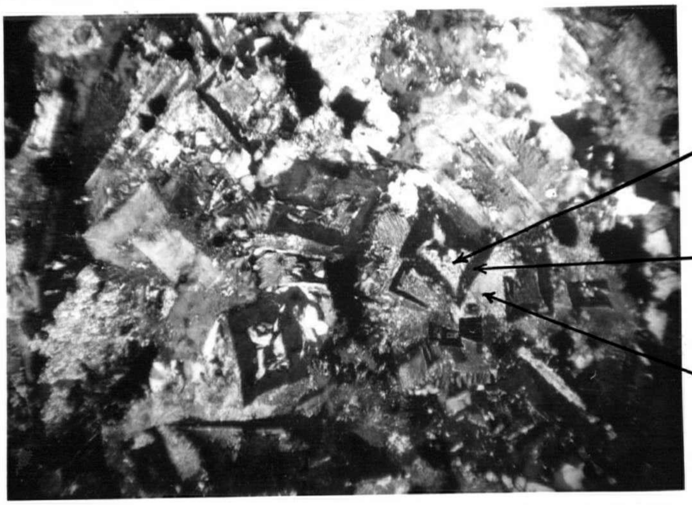

Figure 5. Zoned Quartz-Feldspar Intergrowths. Intergrowth cores, feldspar shell, interstitial quartz-feldspar intergrowth, as described above. Note optical continuity of feldspar. X47.

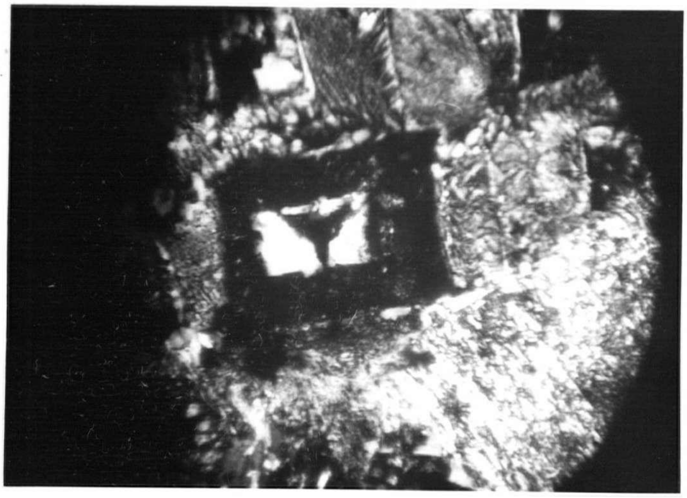

Figure 6. Zoned Quartz-Feldspar Intergrowth. Core of quartz and feldspar, and feldspar shell surrounded by quartz and feldspar in graphic intergrowth. X150.

The compositions of the alkali feldspars were determined from the value of 2V as measured with the universal stage. Determination of indices of refraction could not be made due to the small size of the crystals. The use of 2V alone may yield an ambiguous composition, but good results were obtained by staining the feldspars with sodium cobaltinitrite, hence they are probably potassium-rich varieties.

The compositions are tabulated in Figure 16 where the feldspar compositions are shown in relation to the positions of the specimens across the section of granophyre. The majority of the feldspars are orthoclase cryptoperthites with a range in composition from $Or_{65}Ab_{35}$ to $Or_{100}Ab_0$.

Plagioclase occurs in the granophyre which lies between the two chilled zones. The crystals are either lath-shaped or occur as shells around intergrown quartz and potash feldspar. Because of the extensive alteration, the composition of the plagioclase could not be determined with any degree of accuracy, but the anorthite content is probably not more than 15 per cent. Plagioclase appears to precede potash feldspar and quartz in the paragenesis, and appears to be partially replaced by quartz. The textural relations of plagioclase are illustrated in Figures 7 and 8.

Quartz and Potash Feldspar core

Sericitized Plagioclase

Figure 7. Shell of Seriticized Plagioclase enclosing Quartz and Potash Feldspar. X47

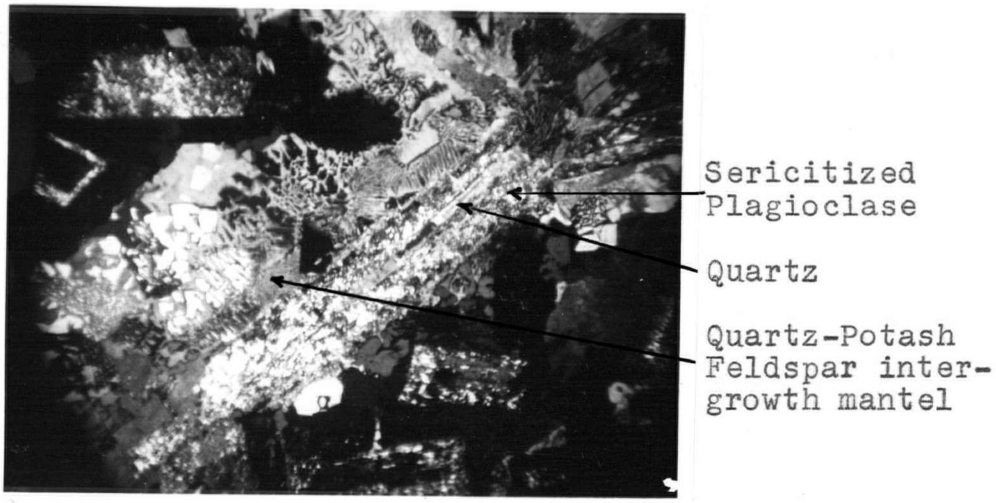

Figure 8. Seriticized plagioclase which appears to be partially replaced by quartz, and surrounded by quartz and potash feldspar in graphic intergrowth. X47

The biotite is the common red-brown variety, with pleochroic haloes. These haloes persist as gray patches in chlorite where the biotite has been altered to chlorite.

Alteration of the primary minerals has occurred throughout the granophyre. Feldspars have been partially altered to sericite and clay minerals, biotite to a chlorite, probably penninite, and titanium-bearing minerals to leucoxene. The alteration of the feldspars occurs in irregular patches whose boundaries show no relation to individual crystal outlines. Instead one area of a thin section may show more intensive alteration than another. The sericitization of potash feldspar is accompanied by the replacement of the feldspar by tourmaline. The tourmaline is visible in hand specimen as rosettes of black acicular crystals on joint planes. In thin section, the tourmaline occurs as radiating aggregates of acicular crystals. The crystals are pleochroic from very pale yellow to pale greenish-blue. The pleochroism and low birefringence of the tourmaline suggest that it is an alkali variety.

The black rims around the quartzite inclusions were found to be composed of chlorite with minor amounts of biotite. The inclusions are penetrated and partially replaced by quartz-feldspar intergrowths. However, this replacement is not particularly common, nor is the amount of replacement extensive. A chlorite-biotite rim around an inclusion is illustrated in Figure 9. Figure 10 shows replacement of an inclusion by quartz and intergrown potash feldspar.

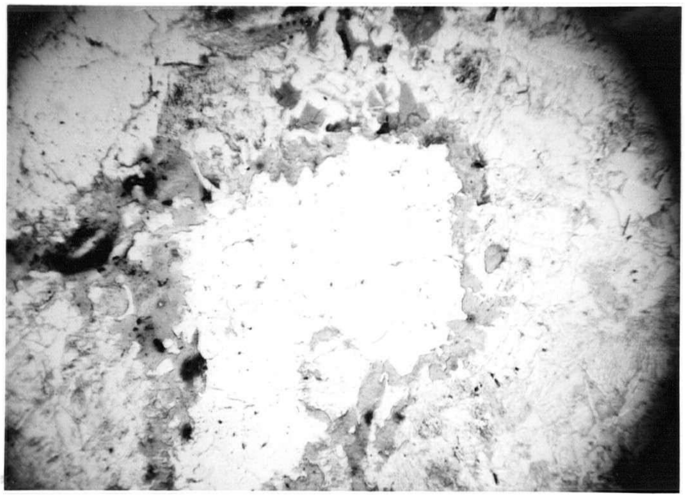

Figure 9. Rim of chlorite and biotite around an inclusion of quartzite in granophyre. X47.

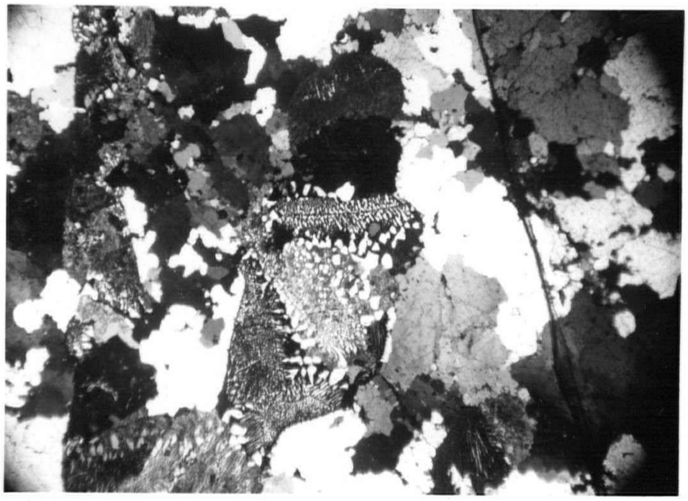

Figure 10. Replacement of a quartzite inclusion in granophyre by quartz and potash feldspar in graphic intergrowth. X47.

The chilled zone in the granophyre resembles in hand specimen, a fine-grained acid lava or a hornfels. In outcrop, it weathers to a medium brown. The fresh surface is dark brownish-gray with a subconchoidal fracture. The quartzite inclusions present in the chilled zone are identical in appearance to those in the coarser granophyre. In thin section the chilled granophyre was found to be composed of a fine-grained mosaic of anhedral quartz and potash feldspar with traces of biotite and chlorite. A few partially altered phenocrysts of potash feldspar are present. Alteration in the chilled zone is not as extensive as in the coarser granophyre, but the intensity of alteration increases near the contact of the chilled zone with the breccia. The texture of the chilled zone is illustrated in Figure 11.

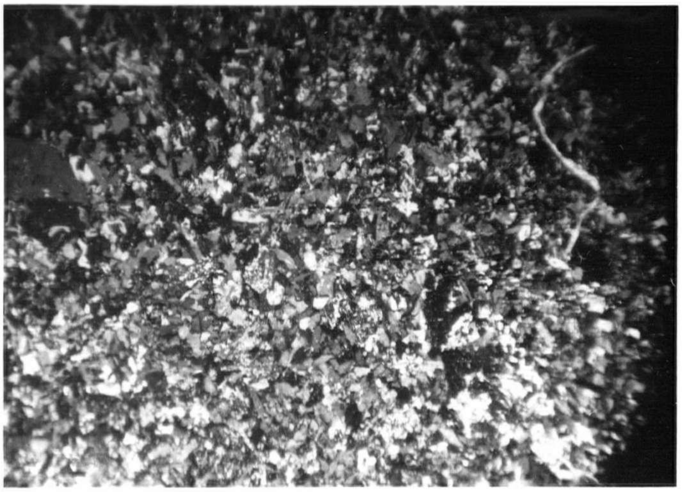

Figure 11. Texture of chilled granophyre. Fine-grained mosaic of quartz and potash feldspar. X47.

The feldspar in the chilled zone was found to be sanidine-anorthoclase, with a composition of Or_{93} Ab_7 as determined from $2V=20^{o}$.

Intrusive Breccia

The intrusive breccia for the most part overlies the gray granophyre. The breccia is composed of fragments of quartzite and gneiss derived from the basement complex in a quartzofeldspathic matrix.

The weathered and fresh surfaces of the matrix are pink. The breccia fragments, which make up from 40 per cent to 60 per cent of the rock, are mainly angular to subangular blocks of quartzite with minor amounts of gneiss, both derived from the basement complex. The maximum size of the fragments varies up to 2 feet in the greatest dimension. The size and shape of the fragments in the breccia contrast markedly with the small rounded fragments in the granophyre. Dark rims are present around the breccia fragments, as in the granophyre. The fragments in the breccia do not show the rounding, corrosion, and embayments which are characteristic of the fragments in the granophyre. Scattered vugs occur throughout the breccia and contain chlorite and specular hematite. One small quartz vein in the breccia was found to contain abundant graphite.

In thin-section, the breccia matrix is composed of a fine-grained mass of quartz and potash feldspar in graphic intergrowth. Some crystals of potash feldspar occur as radiating aggregates of lath-shaped crystals. The feldspar is extensively sericitized and partially replaced by greenish-blue tourmaline. The feldspar is orthoclase cryptoperthite of composition Or_{75}.

The textural relations of the breccia matrix are illustrated in Figures 12 and 13.

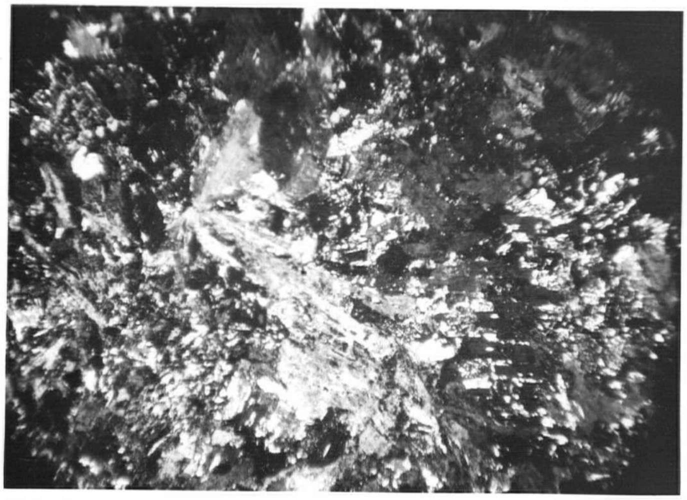

Figure 12. Breccia. Fine-grained mass of quartz and feldspar, quartzite inclusion, and a few sheaf-like aggregates of lath-shaped feldspar crystals. X16.

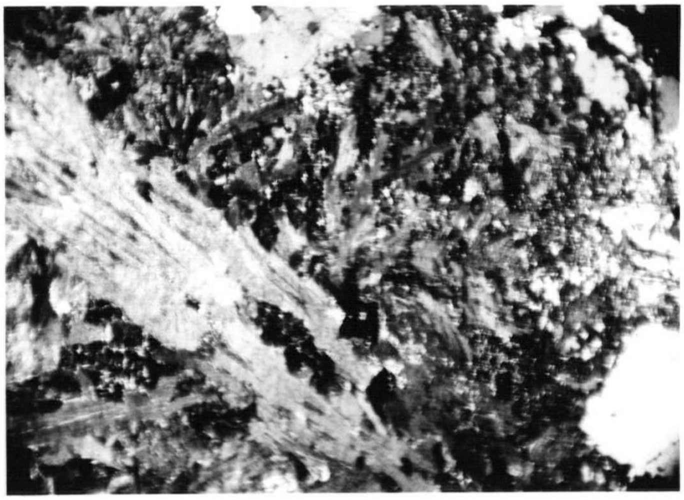

Figure 13. Aggregate of lath-shaped feldspar crystals in breccia matrix. X47.

Petrogenesis of the Acid Rocks

Intrusion of the granophyre magmas probably occurred at depths of from 6,000 feet to 20,000 feet, depending on the thickness of the Epworth rocks and the amount of Coppermine rocks which had been deposited up to that time. Since the granophyre is chilled against the gabbro, it appears that sufficient time passed after the intrusion of the gabbro for it to cool to a temperature no higher than that due to a normal geothermal gradient, hence the temperature at the depth at which the granophyre magma was emplaced was probably no higher than the temperature that would be due to a normal geothermal gradient.

Tuttle[9] (1952) discusses the alkali feldspars in extrusive, hypabyssal, and plutonic rocks. The feldspars in the granophyres are of the type regarded as hypabyssal by Tuttle. The term hypabyssal appears to be used only in a relative sense in literature to denote an environment intermediate between the plutonic and extrusive environments.

Laves[10] (1952) states that inversion of orthoclase to microcline occurs around 700°C. With microcline present, and assuming a geothermal gradient of 50°C per mile, emplacement of the acid magmas should then occur at a depth of 14 miles or less. The maximum possible depth of intrusion, assuming a maximum thickness of Epworth and Coppermine rocks, would be about 8 miles.

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9 Tuttle, O.F.: Extrusive and Plutonic Sialic Rocks, Jour. Geol., Vol. 60, 1952, p. 107-124.

10 Laves, F.: Phase Relations of the Alkali Feldspars Jour. Geol., Vol. 60, 1952, p. 436-450, 549-574.

The composition of the feldspars in the granophyre differs from the composition of the feldspars in the acid rocks discussed by Tuttle[11] (1952) in that the feldspars in the granophyre in question are more potassic. However such differences are to be expected as rocks in different petrographic provinces may show distinctive differences in their chemical and mineralogical character as described by Bowen[12] (1926).

A plot of the average normative quartz, orthoclase, and plagioclase in the granophyre is shown in Figure 14, along with the normative proportions of the same minerals in other acid igneous rocks. The norm for the granophyre is computed from estimated compositions, hence the error is probably large, but the norm is still indicative of an abundance of potassium in the granophyre.

In view of the hypabyssal environment into which the magma intruded and the chilling of the magma against the walls of the chamber, high temperature feldspars might be and are present in the chilled zone. However, intermediate temperature and low temperature forms of the same feldspar are present in the granophyre which is enclosed by the chilled zone. In the light of the information available, the occurrence of more than one polymorph of the same feldspar in the same rock cannot be satisfactorily explained.

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11 Tuttle, O.F.: Ibid.

12 Bowen, N.L.: Evolution of the Igneous Rocks. Princeton University Press, 1928, p. 3.

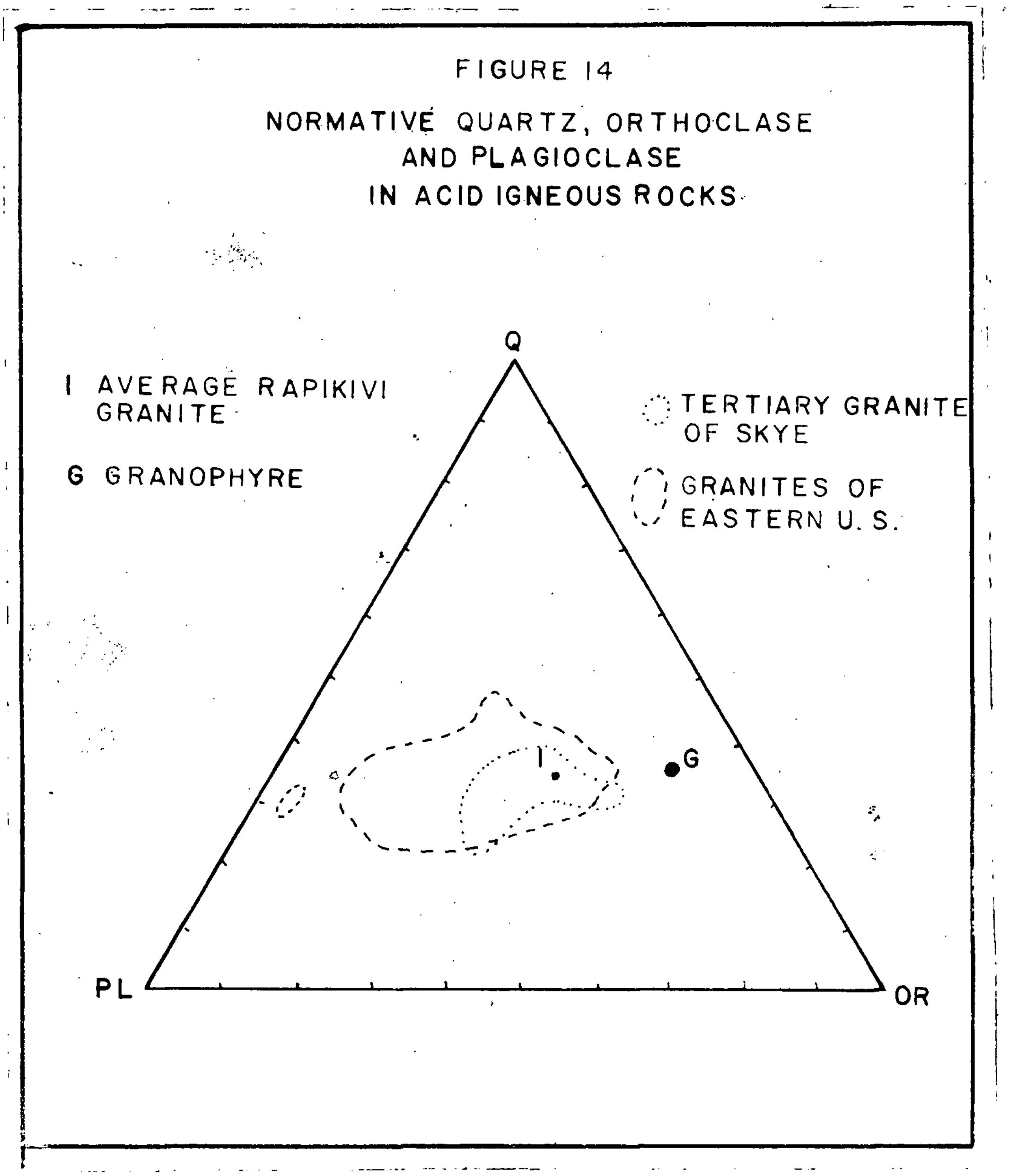

Figure 14

In this respect, Tuttle and Bowen[13] (1958) state that as many as four solid state phases may coexist in the same alkali feldspar crystal. These phases may include high, intermediate, and low temperature feldspars, but up to the

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13 Tuttle, O.F., Bowen, N.L.: <u>Origin of Granite in the Light of Experimental Studies</u>, Geol. Soc. Am. Mem. 74, 1958.

present time, no details are known of the solid state phase relations of the alkali feldspars.

The rate of inversion of a feldspar from the high to the low temperature form may be a factor responsible for the presence of two forms of the same feldspar in the same granophyre. Laves[14] (1952) states that the solid state feldspar phases are of an order-disorder type. The degree of disorder in the crystal lattice appears to be proportional to the temperature to which the feldspar has been heated. This is shown by the progressive variation in optical orientation from microcline through orthoclase to sanidine. It is possible that the feldspar in the chilled zone crystallized at a higher temperature than the feldspar in the main body of the granophyre and thus would require more adjustment in its crystal lattice than the feldspar in the main body of the granophyre. But since the feldspar in the chilled zone crystallized first, it should have more time for the inversion from a high to a low temperature form to occur.

Experimental results quoted by Laves[15] (1952) indicate that the rates of inversion of feldspars vary in specimens which apparently have the same composition, so additional research is still necessary on this subject. If information were available on the rates of inversion of feldspars from high to low temperature forms, it might be possible to determine whether cooling could have taken place before

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14 Laves, F,: Phase Relations of the Alkali Feldspars. Jour. Geol. vol. 60, 1952, p. 436-450.

15 Laves, F,: op. cit.

the inversion of the feldspar in the chilled zone. Data on the temperature of the magma within limits, thickness of the roof of the magma chamber, and thermal conductivity of the roof rocks are available or could be computed and the information used to determine the rate of cooling of the magma.

The mantled intergrowth relations of quartz and feldspar may have two possible modes of origin.

One possibility is replacement of feldspar by quartz and/or quartz feldspar intergrowths. The optical continuity of the quartz and feldspar means little as an argument either for or against replacement. However, the boundaries of the feldspar shells which enclose the intergrowths are rectilinear. It seems improbable that replacement would be so selective unless the feldspar possessed well-developed zoning. Zoning is present, but it is so slight that it can only be detected by means of the universal stage. Thus a replacement origin for the zoned quartz-feldspar intergrowths is unlikely.

Some of the textural relations, and in particular the zoned intergrowths in which the cores connect with the intergrowths which fringe the feldspar shell, are suggestive of the corroded partially resorbed, and skeleton phenocrysts which occur in lavas. One mechanism by which resorption could occur is by a rise in temperature of the magma, but the source of heat necessary is not apparent. One possible source of heat may be from exothermic reactions which could result from material low in Bowen's Reaction Series assimilating material high in the reaction series. Both these materials are present in the form of basic and ultrabasic rocks and acid magma, but the solid chilled granophyre would prevent the acid magma from coming in contact with and assimilating gabbro and peridotite.

If the compositional zoning of the feldspar in the intergrowths and the phase relations of the alkali feldspars are examined, resorption of feldspar by the magma appears to be unlikely. Tuttle and Bowen[16] (1958) found that an increase in the pressure of water vapour in the system albite-orthoclase-quartz-water lowered the crystallization temperature of the other three components. If the pressure rose in the magma after crystallization of the feldspar began, it is possible that the feldspar would be partially or wholly resorbed.

However, the slight zoning present in the feldspars indicates that the feldspar in the intergrowths fringing the shells around the intergrowth cores is slightly enriched in plagioclase components, and that this zoning is not oscillatory. According to the phase relations of the alkali feldspars, the albite-rich portion should be the first to be resorbed. This may have occurred in the case of the outer portions of the crystals, but does not apply to the orthoclase-rich cores, which also appear to have been partly resorbed.

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16 Tuttle, O.F., Bowen, N.L.: Origin of Granite in the Light of Experimental Studies. Geol. Soc. Am. Mem. 74, 1958.

Spencer[17] (1945) summarizes the studies made of graphic granite and the conclusions drawn by a number of investigators. The early investigators, (Vogt, Makinen, Eskola, Holmes) concluded that graphic intergrowths were the result of the crystallization of quartz and feldspar in eutectic proportions. Later investigators,(Schaller, Andersen, Alling Hess) attributed graphic intergrowths to replacement. More recent investigators (Switzer, Mitchell, Uspensky) favour the crystallization of a eutectic as the origin of graphic intergrowths. Spencer discusses the arguments pro and con replacement origin and concludes that there is no proof that graphic intergrowths are due to replacement. Investigations of the quartz content of graphic intergrowths show a range of 24 to 32 per cent quartz. The estimated quartz content of the granophyre under consideration ranges from 20 to 35 per cent.

The oscillatory intergrowth-feldspar-intergrowth relations may be explained conveniently by the quartz-feldspar phase relations. Investigations of the system albite-orthoclase-quartz-water by Tuttle and Bowen[18] (1958) disclosed that an increase in water vapour pressure displaced the quartz-feldspar boundary toward the feldspar side of the ternary field.

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17 Spencer, E.: Myrmekite in Graphic Granite and Vein Perthite. Min. Mag. Vol. XXVII, No. 189, 1945, p. 79-98.

18 Tuttle, O.F., Bowen, N.L.: Origin of Granite in the Light of Experimental Studies, Geöl. Soc. Am. Mem. 74, 1958.

If crystallization of the granophyre began under relatively high pressure with quartz and feldspar in eutectic proportions, for that pressure, a graphic intergrowth might form. Release of pressure either by loss of volatiles from the magma chamber or by movement of the magma to a region of lower pressure would cause the boundary between the quartz and feldspar fields to move toward the quartz end of the field leaving the composition of the liquid in the feldspar field. When this occurred, feldspar shells would begin to form around the crystallized quartz-feldspar intergrowths, as well as pure feldspar crystals. As crystallization continued, the composition of the liquid would move toward the quartz-feldspar boundary where quartz and feldspar in graphic intergrowth would again begin to crystallize.

The plagioclase shells which surround the quartz-potash feldspar intergrowths may have originated by direct crystallization under rising pressure, or by resorption of the cores of the plagioclase crystals.

Tuttle and Bowen[19] (1958) proposed an origin for rapikivi texture which involved the lowering of the liquidus surface of the system orthoclase-albite-quartz-water by increasing water vapour pressure. The shells of plagioclase which surround cores of quartz-potash feldspar intergrowths have some similarity to rapikivi texture. Their proposed mechanism may be applied to the mantled intergrowths in the

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19 Tuttle, O.F., Bowen, N.L.: Origin of Granite in the Light of Experimental Studies. Geol. Soc. Am. Mem. 74, 1958.

following way. At the start of crystallization, the liquid probably had the composition of a quartz-feldspar eutectic, the crystallization of which produced graphic intergrowths represented in the granophyre by the cores of the mantled intergrowths. Conditions at this stage are represented by Figure 15A. With the concentration of volatiles and the rise of pressure during crystallization, the liquidus surface of the system was depressed until it intersected the solvus, as illustrated in Figure 15B. At this stage, two feldspars began to crystallize rather than one, resulting in the mantling of the intergrowths, some by potash feldspar and others by plagioclase. Shifts in the position of the quartz-feldspar boundary trough with consequent temporary crystallization of feldspar unaccompanied by quartz may account for the quartz-free feldspar mantles around the intergrowth cores. With continuing crystallization, the outer mantles of quartz and feldspar in graphic intergrowth were then produced.

An alternative origin for the plagioclase mantles which surround the quartz-potash feldspar intergrowths involves resorption and replacement. Studies by Carr[20] (1954) showed that an increase in pressure results in a raising of the temperature of crystallization of plagioclase. The lath-shaped plagioclase crystals appear to precede quartz and potash feldspar in the paragenesis. If these crystals formed early in the crystallization of the magma under relatively

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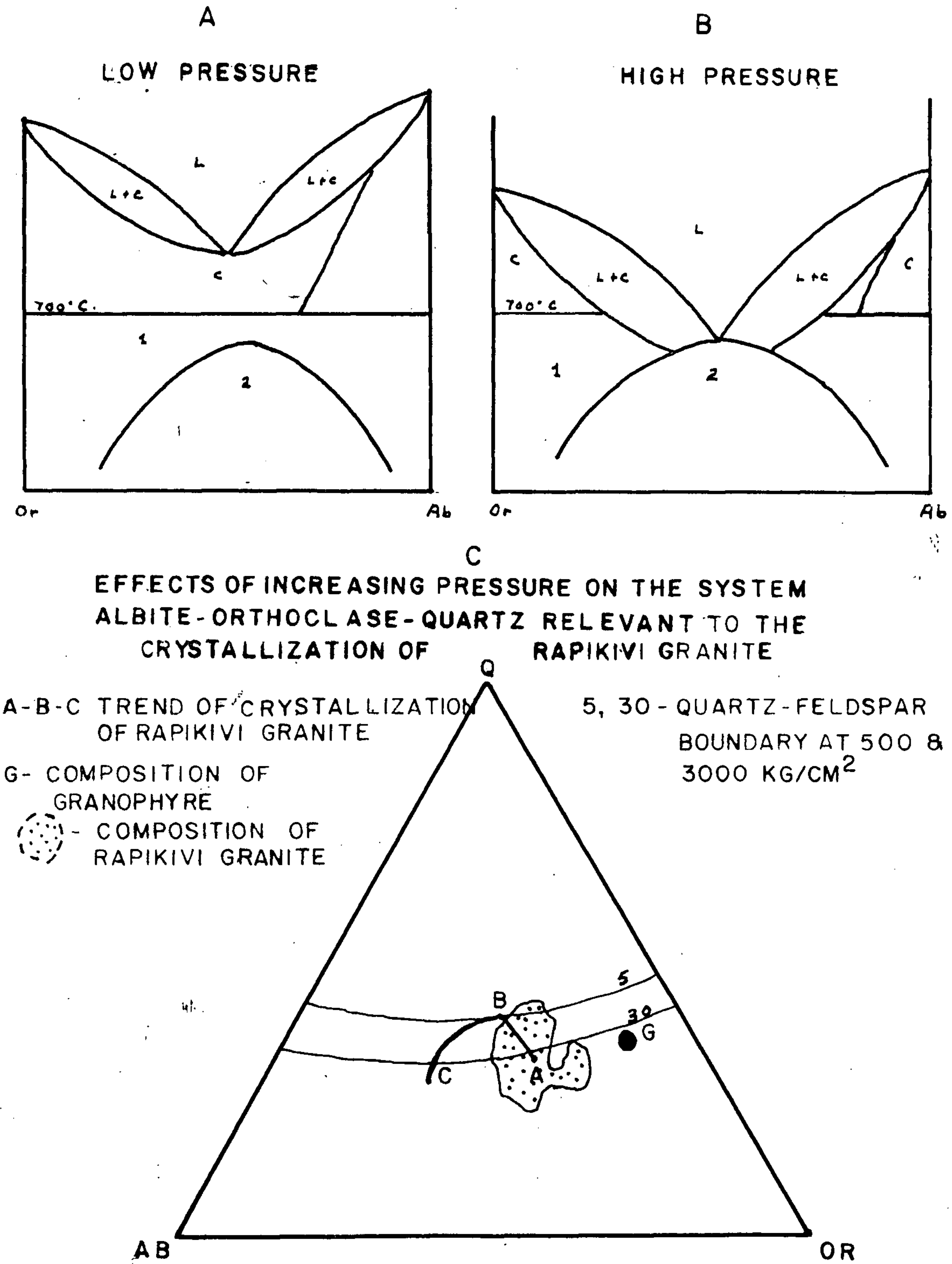
20 Carr, J.M.: Zoned Plagioclase in the Layered Gabbros of the Skaergaard Intrusion, East Greenland. Min.Mag. Vol. XXX, No. 225, 1954, p. 367-375.

FIGURE 15
ALKALI FELDSPAR PHASE RELATIONS AND THE EFFECTS OF CHANGING WATER VAPOUR PRESSURE



high pressure, a drop in pressure would develop reversed zoning. If the crystals were still near the melting point of plagioclase, the more sodic cores might be resorbed leaving hollow shells of more calcic plagioclase which could be filled later by quartz and potash feldspar in graphic intergrowth. In this respect, it should be noted that the interior boundaries of the plagioclase shells are irregular and are penetrated by quartz along cleavage planes as contrasted with the rectilinear boundaries of the potash feldspar shells which also enclose graphic intergrowths.

Two possible patterns of environmental changes during the crystallization of the granophyre magma emerge from the foregoing discussion.

The first pattern involves rising pressure, probably due to expulsion of volatiles from the magma during crystallization. The rise in pressure might account for the origin of the shells of plagioclase which surround quartz-orthoclase intergrowths. This origin is essentially similar to that proposed by Tuttle and Bowen[21] (1958) for rapikivi texture. Resorption of Potash feldspar crystals with rising pressure could also account for the oscillatory mantling of feldspar and graphic intergrowths, but this origin does not take into account the selectivity of the resorption that would be necessary to form the sharp boundaries of the quartz-free

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21 Tuttle, O.F., Bowen, N.L.: Origin of Granite in the Light of Experimental Studies, Geol.Soc. Am. Mem. 74,1958

potash feldspar, and conflicts with the zoning and phase relations of the alkali feldspars.

The second pattern is one of falling pressure during crystallization of the granophyre magma. The origin of the plagioclase shells which surround the cores of quartz and orthoclase may be accounted for in this environment, but the explanation is cumbersome. The oscillatory zoning of potash feldspar and graphic intergrowths and the presence of high and low temperature feldspars in the chilled zone and the coarse granophyre may be accounted for by crystallization of the magma under conditions of falling pressure.

The role of assimilation of country rock by the granophyre magma is difficult to evaluate. Assimilation of country rock has occurred, as is shown by the corroded and embayed inclusions of quartzite in the granophyre. Assimilation of phyllitic rock also appears to have occurred, as frayed inclusions of slatey material are also present in the granophyre. However, it is not known how much country rock has been assimilated or how much the composition of the original magma has been altered by the assimilated material. Graphitic phyllite was noted in one drill core, so assimilation of this phyllite may have supplied the graphite found in a quartz vein in the breccia.

Alteration of the granophyre, which is characterized by the formation of sericite and tourmaline, may be deuteric or it may be a later effect, with the agents responsible coming from an outside source. If crystallization occurred under conditions of decreasing pressure, it is reasonable to suspect that the volatiles in the granophyre magma may have been lost, which could account for the falling pressure, but would make deuteric alteration unlikely. The emanations responsible for the alteration are believed to have come from the breccia. A comparison of the chilled zone material shows that the alteration is more intense in the chilled zone near the contact of the chilled zone with the intrusive breccia.

FIGURE 16 GEOLOGIC MAP OF AREA OF STUDY

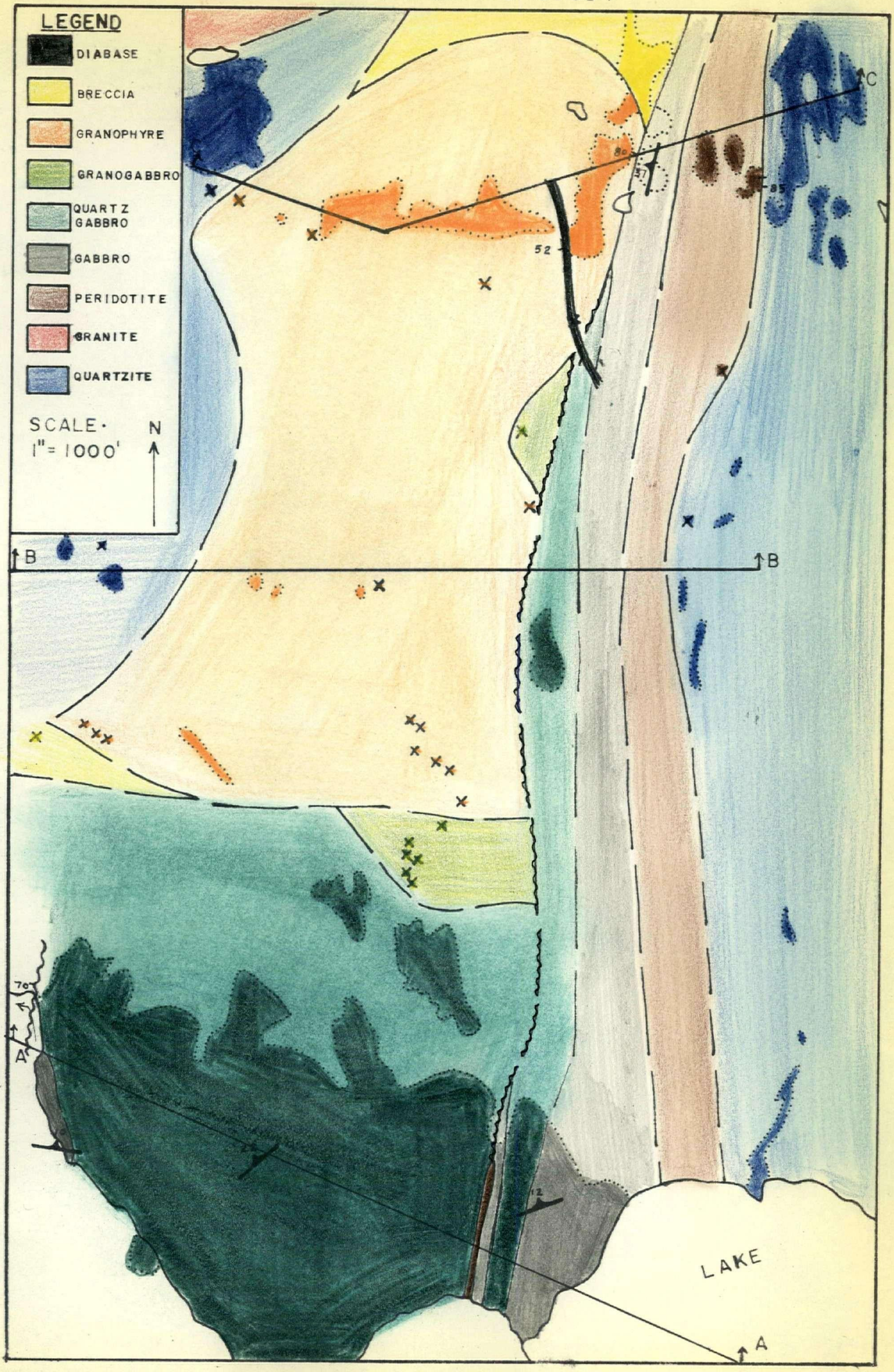
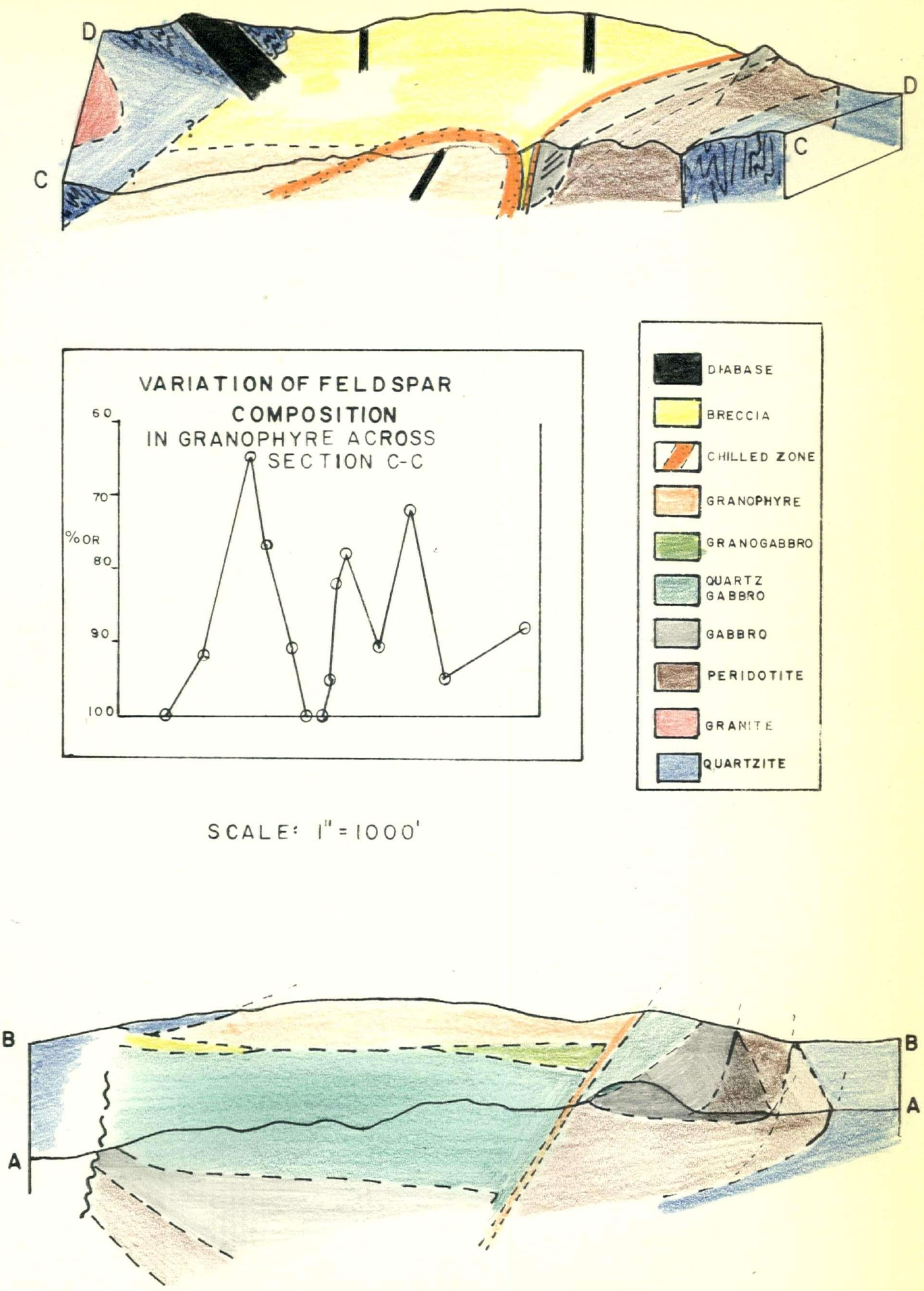


FIGURE 17 COMPOSITE SECTIONS



Structural Relations of Acid and Basic Rocks

Stream valleys in the northern part of the lopolith provide two well-exposed sections across the intrusion. The following observations are significant in the interpretation of the structure in this part of the intrusion.

The contact between the layered gabbro and quartz gabbro is sharp but not chilled. If the gabbro and quartz gabbro were the products of the differentiation of a single magma, the transition from one to the other would probably be gradual. The quartz gabbro on the other hand grades upward into a coarse-grained granogabbro.

The thickness of the quartz gabbro layer shows a marked variation from east to west. East of the narrow band of peridotite, the quartz gabbro layer is thin. West of the narrow band of peridotite, it is thick and the base of the layer is lower than it is to the east.

Granophyre is chilled against, and intrudes gabbro. This relationship was observed at several locations.

The intrusive breccia cuts the chilled zone in the granophyre along the granophyre-gabbro contact, but the breccia matrix is not chilled. The contact between the breccia and granophyre is characterized by irregular penetration of apophyses of breccia matrix into the chilled zone and the development of irregular patches of potash feldspar in the chilled granophyre adjacent to its contact with the breccia.

The contact between the chilled granophyre and gabbro dips west at 80 degrees. At the same location, layering in the gabbro dips west at 35 to 40 degrees.

The contact on the west between granophyre and country rock appears to dip west at a shallow angle. This dip is inferred from the trend of the contact where it crosses a stream valley. No basic or ultrabasic rocks are exposed in the western part of this valley although the elevation here is lower than that to the east where gabbro and peridotite are exposed.

A chilled zone occurs in the middle of the granophyre. (Lack of outcrop has prevented mapping the full extent of this chilled zone). The chilled zone dips about 20 degrees west and grades into granophyre to the east. The western boundary is obscured by rubble.

Shearing occurs in gabbro or peridotite at the western edge of the intrusion. Also, slickensides frequently occur in blocks of gneiss in the breccia.

Of these structural relations, the asymmetric distribution of rock types across the intrusion and in particular the lack of basic and ultrabasic rocks along the western side of the body are believed to be most significant. Drill hole information indicates that ultrabasic rocks extend west across part of the width of the intrusion below the granophyre.

Two assumptions may be made as to the original form of the intrusion at its northern end. The elongated pattern of the basic and ultrabasic rocks in plan suggests that they may have the form of a composite dike. The other possibility is that the intrusion may have been a canoe-shaped body as to the south.

There are several objections to the dike hypothesis. The first concerns the attitude and origin of the layering in the gabbro, which might be flow layering in a dike. Balk[22] (1937) discusses flow layering in dikes, quotes numerous authors, and concludes that flow layering in undeformed dikes commonly lies parallel to the walls of the dikes. The exception to this is layering which has been drag-folded by flow. No such parallelism occurs in the intrusion in question and there is no evidence of deformation or drag-folding during flow.

The second possible origin of the layering is by crystal settling during crystallization. In this type, there is either a gravitative stratification of crystals according to density, or gravitative accumulation so that tabular crystals lie flat on the surface of deposition. This type of layering could occur if the magma chamber had a floor. However, since gravity and the angle of repose are involved, such layering is commonly flat or dips at moderate angles. The layering in the gabbro dips at a fairly steep angle, so presumably it did not originate within a dike-like body.

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22 Balk, R.: Structural Behavior of Igneous Rocks, Geol. Soc. Am. Mem. 5, 1937.

However, if the intrusion originally had a canoe-shaped form at this point as it does to the south, then gabbro and peridotite should appear on the west, provided that the intrusion has not been deformed. This absence of gabbro and peridotite along the western side of the intrusion may be explained by subsidence of the western edge of the lopolith.

Simple tilting of the intrusion does not fully explain all the attitudes of layering and contacts. In the canoe-shaped part of the intrusion, layering in the basic and ultrabasic rocks dips inward along the flanks. If the top of this part of the lopolith were essentially horizontal and if the intrusion were tilted by subsidence along the western edge and granophyre magma filled the space between the top of the mass of basic and ultrabasic rocks and the roof of the lopolith, then the granophyre-gabbro contact would dip at a shallower angle than the layering in the gabbro in the eastern half of the intrusion, but in the same direction. The actual field relations indicate that the granophyre-gabbro contact dips more steeply than the layering in the gabbro adjacent to the contact.

An alternative interpretation of the structure in this part of the intrusion explains all the observed structural relations. The absence of gabbro and peridotite could be explained by subsidence of the western part of the intrusion, but if subsidence of the western side occurred by downfaulting of a block bounded on both sides by faults, then no anomalous structural relations remain to be explained.

The strongest evidence of subsidence of a fault-block is the discordant relations of the quartz gabbro. In the eastern portion of the intrusion the quartz gabbro layer is thin and the base of the layer is at a relatively high elevation. West of the narrow band of peridotite, the quartz gabbro layer is thicker and the base of the layer lies at a lower elevation than to the east.

The structural relations of the granophyre are similar to those of the quartz gabbro, and the same arguments as to the interpretation of the structure apply.

The presence of a fault along the western boundary of the lopolith is shown by the sheared gabbro or peridotite. The other fault is presumably located along the granophyre-gabbro contact, near the axis of the lopolith.

Subsidence and intrusion of the quartz gabbro and acid rocks appear to have occurred in the following sequence. First the two faults formed and the block along the western edge of the lopolith sank. This subsidence was accompanied by the intrusion of the quartz gabbro magma. With further subsidence, the first injection of granophyre magma occurred. This magma was chilled against the walls and roof of the chamber. With more subsidence, this chilled zone was torn loose from the roof of the magma chamber and a second injection of granophyre magma occurred into the space west of the chilled zone. Emplacement of the breccia was the last event, since the breccia intrudes the chilled granophyre.

The feeder along which the quartz gabbro magma intruded was not found, but the granophyre appears to have intruded along the fault near the center of the lopolith. The presence of a feeder at this location is suggested by the occurrence of chilled granophyre below the level of the base of the granophyre sheet and along the strike of the fault. The same fault presumably served as a feeder for the breccia, since chilled granophyre is cut by breccia along this line.

One objection to the subsidence of the mass of basic and ultrabasic rocks is the lack of evidence of the collapse of the roof of the intrusion. Presumably the intrusion of the basic magma stopped at the unconformity between the basement complex and the Epworth series, but there is no conclusive evidence that the overlying Epworth series subsided with the block below. It is possible that the faults terminated at the unconformity between the Epworth series and the older rocks.

While fragments of the Epworth rocks are conspicuous by their absence from the breccia, there is evidence that some parts of the roof did collapse or that blocks were stoped from it, as is shown by the quartzite raft near Desperation Lake.

However, if the entire roof did subside, it would involve a block with a maximum width of about 3000 feet. If a section is considered across the intrusion, with a minimum thickness of 6,300 feet of Epworth rocks, it could be regarded as a beam with both ends fixed and a depth/span ratio of at least 2/1, assuming that none of the Coppermine rocks were present. If any of the Coppermine rocks were present, their effect would be to increase the depth/span ratio of the roof. It is possible that the eruption of the Coppermine lavas would be accompanied by the injection of dikes and sills into the Epworth series. Such a system of dikes and sills might serve to bind the roof together in a manner similar to rock bolts or stitching.

No intrusions with similar structural relations have been described in any of the literature examined. The only ones which have any resemblance to the one at Desolation Lake are the Tertiary ring-dikes of the northern British Isles.

In the ring-dikes, subsidence of a more or less cylindrical block bounded by a fault was accompanied by the intrusion of magma along the fault. Observed field relations indicate that intrusion of magma along faults has occurred. Some of the circular faults reached the surface, in which case the fault enclosed an area of cauldron subsidence. In other instances, the faults did not reach the surface. Structures of this type are referred to as "piston-faults" or subsurface cauldron subsidences. In these structures, the fault terminated at some level below the surface, probably along bedding plane. The block enclosed by the fault subsided then magma intruded along the fault and filled the space between the sunken block and the roof.

Papers by Bailey and Maufe[23] (1916), and Anderson[24] (1937) describe ring-dikes and piston-faulting, but few structural data are provided as to how these investigators arrived at their structural interpretations. The Ben Buie intrusion on the Island of Mull has also been interpreted as the result of subsurface cauldron subsidence. Lobjoit[25] (1959) arrives at a different interpretation of the structure of the intrusion, but this interpretation also involves sub-surface subsidence of a block of country rock accompanied by the intrusion of magma into the space left by the sub-sidence.

If these structural interpretations are correct, the intrusion at Desolation Lake is analogous to the subsurface cauldron subsidences of the British Isles in that the faults terminated at some level below the ground surface while the roofs over the intrusions remained undisturbed. In the case of the intrusion at Desolation Lake, the surface of the un-conformity between the basement complex and the Epworth series appears to be a more favourable level for the termination of faults than bedding planes in the case of the subsurface cauldron subsidences.

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23 Bailey, E.B., Maufe, H.B.: The Geology of Ben Nevis and Glen Coe. Mem. Geol. Surv. of the United Kingdom, 1916.

24 Anderson, J.G.C.: The Etive Granite Complex. Q.J.G.S., Vol. XCIII 1937, p. 487-533.

25 Lobjoit, W.M.: On the Form and Mode of Emplacement of the Ben Buie Intrusion, Island of Mull, Argyllshire, Geol. Mag. Vol. XLVI, No. 5, 1959, p. 393-402.

The absence of fragments of Epworth rocks from the breccia is one of the principal arguments against subsidence of the roof of the intrusion. However, when the amount of subsidence and the amount of material removed by erosion are considered, this argument loses some of its weight. The minimum amount of material removed from the top of the intrusion by erosion is estimated at from 200 to 500 feet. This estimate is arrived at by projecting the dip of the basal member of the Epworth series back to the top of the intrusion and estimating elevations. The total amount of subsidence, as shown by the section of acid rocks, is estimated at 300 to 500 feet. Thus, it is possible that the roof over the intrusion did collapse, but any fragments of the roof were removed by erosion.

Origin of the Breccia Fragments

The breccia fragments are composed mainly of orthoquartzite with a small amount of gneiss derived from the basement complex. No fragments of Epworth rocks, gabbro, or peridotite were found. The fragments may have several possible modes of origin. They may be the result of explosive activity, rockbursting, magmatic stoping, or of tectonic activity.

The extensive deuteric alteration of the breccia matrix, the presence of vugs, and the manner in which apophyses of breccia matrix penetrate the country rocks suggest that the matrix was a highly mobile liquid rich in volatiles. Such conditions might be expected to favour explosive activity. In this respect, Richey[26] (1940) states that subsurface explosive activity may occur at depths down to 6000 feet. This is the minimum estimated depth at which this intrusion was emplaced. However, if explosive activity did occur and the country rock were shattered, fragments of the basal member of the Epworth series should be present in the breccia as well as quartzite from the basal complex. For this reason, the breccia is not believed to be due to an explosive origin.

The depth of the intrusion (over 6000 feet) is in the zone at which rockbursting begins in mines, though this varies according to the rock types present. In general, the brittle siliceous rocks such as form the country rock around the intrusion are more susceptible to rockbursting than basic and ultrabasic igneous rocks. Presumably, if rockbursts did occur, open spaces would be necessary, and there is no evidence that open spaces existed below the ground surface. However, such spaces could be formed by the subsidence of the fault block. If rockbursting did occur, it is difficult to explain why fragments of the basal member of the Epworth series are not present in the breccia. The unit in question is also a siliceous rock like the quartzose rocks of the basement complex, and would presumably be as susceptible to rockbursting as the metaquartzite.

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26 Richey, J.E.: Association of Explosive Brecciation and Plutonic Intrusion in the British Tertiary Igneous Province. Bull. Volcan. Ser.2, vol. 6,1940, p. 157-176.

A third possibility is that the breccia fragments originated during movements along the faults which bound the sunken block. Presumably some shattering of the country rock occurred along the faults during their formation. When movement occurred on the faults, grinding of irregularities on the fault surface occurred which tore loose fragments of the country rock which were incorporated into the breccia. Since the faults are believed to terminate at the surface of the unconformity between the Epworth series and the basal complex, there is no reason to expect that fragments of Epworth rocks should be present, so the absence of Epworth fragments presents no objection to this origin for the fragments.

A fourth possible origin of the breccia fragments is magmatic stoping of country rock from the sides of the magma chamber. In the case of this intrusion, the exact role and mechanism of stoping are difficult to evaluate. Gates[27] (1959) attributes stoping in breccia pipes to a pumping action of the magma accompanied by pressure changes, rock-bursting, and collapse of the top of the magma conduit. In this intrusion, where the breccia is in contact with slaty country rock, the country rock has been spalled off, but anastomosing veins in the country rock which are characteristic of brecciated granite contacts are not present. In addition

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27 Gates, O,: <u>Breccia Pipes in the Shoshone Range, Nevada</u>. Econ. Geol. Vol. 54, No. 5, 1959, p. 790-815.

the feldspars in the breccia matrix show no zoning. This may not be indicative of the absence of pressure changes, but reduces the probability of such pressure changes.

Gneissic fragments are also present in the breccia although no gneiss was found near the contacts between this part of the intrusion and the country rock. The fragments of gneiss may be derived from a gneiss which occurs at depth, and were carried up by the rising magma. The absence of gabbro fragments may be explained by the difference in specific gravity between the gabbro fragments and acid magma. The denser gabbro fragments would presumably sink in the magma. However, some gabbro fragments might be held in the chilled zone of the granophyre, but they are not present.

To sum up, the majority of the breccia fragments appear to have originated by the brecciation of the country rock during fault movements. Explosive activity and rock-bursting probably did not occur. Magmatic stoping may have contributed to the brecciation of the country rock, but was probably a subordinate agent of brecciation.

The quartzite fragments in the granophyre probably originated in the same fashion as the breccia fragments.

SUMMARY AND CONCLUSIONS

Apparent reversals of differentiation trends and the structural relations of basic and ultrabasic rocks in the lopolith suggest that multiple intrusion as well as differentiation contributed to the development of layering in the intrusion.

The chilling of the granophyre against gabbro and the structural relations of the granophyre and the basic and ultrabasic rocks indicate that the acid rocks represent separate intrusions of magma rather than products of the differentiation of a basic magma in situ. The intrusion of the acid magmas was accompanied by the downfaulting of an elongated block in the western part of the lopolith. The faults which bound the block probably terminated at the surface of the unconformity between the basement complex and the Epworth series.

The depth at which the acid magmas intruded (below 6000 feet) is within the hypabyssal environment. The presence of high and intermediate temperature forms of alkali feldspar in the acid rocks is consistent with this environment.

The oscillatory mantling of the alkali feldspars and quartz-feldspar intergrowths is believed to be the result of pressure changes during the crystallization of the acid magmas. Two trends of pressure change are possible. Increasing pressure during crystallization is one possibility but the textural relations of some of the feldspar crystals are not typical of resorption which would occur if the pressure rose. Falling pressure during crystallization is a more satisfactory explanation for the origin of the oscillatory mantling of the feldspar and quartz-feldspar intergrowths as it does not conflict with theories for the origin of other features in the granophyre.

The breccia fragments probably originated as a fault breccia during subsidence of the downfaulted block. However other possible origins should not be discounted completely.

No chemical analyses were available, so variation diagrams could not be constructed and the genetic relation if any of the acid rocks to the main body of the lopolith established. However, the mineralogical composition of the various rock types strongly suggests that the entire sequence is deficient in sodium, which may be indicative of a possible genetic relationship.

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