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BULLETIN 34

REGIONAL ZONATION OF PEGMATITES NEAR ROSS LAKE, DISTRICT OF MACKENZIE, NORTHWEST TERRITORIES

BY

Richard W. Hutchinson

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
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PREFACE

Earlier reports of the Geological Survey have pointed out that the pegmatites in the vicinity of Ross Lake were zoned with respect to a large granite body. In 1952 the author of this report studied the nature and details of this zonation.

In this report physical and mineralogical variations in the pegmatites are described, general conclusions drawn, and the relationship between the occurrence of the rare-element minerals and the zonation pointed out. These details are illustrated by many maps and plates.

Although as yet no commercial deposits have been found, the general principles involved can be applied elsewhere in the search for mineral deposits in pegmatites.

GEORGE HANSON,
Director, Geological Survey of Canada

OTTAWA, March 29, 1955

REGIONAL ZONATION OF PEGMATITES NEAR ROSS LAKE, NORTHWEST TERRITORIES

CHAPTER I

INTRODUCTION

General Statement

In recent years, interest has been renewed in the presence of regional zonation in pegmatite districts. The early work of W. H. Emmons applying the principles of zonation to mineral deposits in general (12, pp. 32-34 and Figure 25; 13, pp. 22-23, 31)[1] probably initiated this interest. In many areas where pegmatites are numerous, systematic and progressive changes in the characteristics of the individual pegmatites may be seen. These changes appear to depend on the distance of the bodies from masses of granite that are thought to be the source from which the pegmatites were derived. Heinrich (25, pp. 68-71, 78-84) has recently discussed the question of regional zonation, and listed a number of areas in which it occurs (25, pp. 70-78). Examples in Asia, Africa, Europe, South America, Canada, and the United States are briefly summarized. Cameron *et al.* (8 pp. 7-8) also discussed the problem and considered some examples in the United States. They concluded that cases of regional zonation offer a fruitful field for investigation.

In addition to the academic problems of origin, regional zonations may have economic significance. The occurrence of rare-element and other valuable minerals is controlled, in at least some cases, by the regional zonation. Furthermore, a systematic variation dependent on distance from a nearby granitic body would offer strong evidence that the pegmatites were derived from that source. This relationship is, however, elusive and difficult to prove in a specific area (8, p. 8; 43, p. 151).

In the region between Upper Ross and Redout Lakes, several hundred individual pegmatite bodies are exposed in continuous outcrops for a distance of almost 3 miles. Previous investigations (28, 42) demonstrated the existence of zonation relative to a body of granite and indicated that this area would offer an excellent opportunity for detailed study.

LOCATION AND HISTORY

The Ross Lake-Redout Lake area is north of Great Slave Lake, Northwest Territories, and 42 miles east-northeast of the town of Yellowknife. The area is of interest because of the occurrence of rare-element-

[1]Numbers in parentheses are those of references listed in the Bibliography, page 3.

bearing pegmatite dykes. Their presence has led to field work on the part of the Geological Survey of Canada, and to the attempted exploitation of some of the pegmatite deposits by a mining company. At Ross Lake, extraction of columbite-tantalite from the pegmatites was begun late in 1946, but operations ceased in 1947. C. S. Lord (32, p. 231) described the property and installations.

PREVIOUS WORK

Pegmatites in the Ross Lake area were first examined for the Geological Survey by Jolliffe (28, p. 10) in 1944 and again in 1946 and 1947 by Fortier (17) during the course of regular geological mapping programs. Both of these officers noted the presence of rare-element minerals and recognized regional zoning of the pegmatites near Ross Lake. In 1951 Rowe (42) investigated the economic possibilities of the Yellowknife-Beaulieu River area and made a preliminary study of the zoning noted by the earlier geologists. As a result of this preliminary study it was recommended that a detailed investigation of the regional zonation be made.

PURPOSE OF THE INVESTIGATION

During the summer of 1952, a detailed study of the area was undertaken by the writer for the Geological Survey of Canada. The purpose of the investigation was to describe in detail the nature of the regional zonation of the pegmatite bodies in the area, and the nature of the bodies themselves, and thus to establish more firmly a genetic relationship between the pegmatites and the granite mass to the east. The investigation was more generally designed to enhance the scientific knowledge of pegmatites and thereby facilitate future work on deposits of a similar nature.

ACKNOWLEDGMENTS

This investigation was undertaken at the suggestion of Dr. R. B. Rowe of the Geological Survey of Canada who drew the author's attention to the possibilities of the region for the study of pegmatites.

Sincere thanks are due to the officials of Peg Tantalum Mines for their courtesy in allowing the author to use their camp and facilities east of Upper Ross Lake. Mr. R. W. Hodder rendered capable assistance in the field.

Thanks are also due to Dr. E. N. Cameron and other members of the staff of the Geology Department of the University of Wisconsin for much helpful advice and criticism.

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CHAPTER II

GENERAL GEOLOGY AND NATURE OF THE INVESTIGATION

GENERAL GEOLOGY

Fortier (17, pp. 1-3) has described the geology of the area in some detail, but the following summary, taken from his work, is necessary to enable the reader to follow the discussion of the pegmatite problem.

All the rocks of the area are Precambrian in age (*see* Figure 1). The oldest of these is a narrow belt of Yellowknife group rocks, including bands of rhyolite breccia, chert, slate, sericite schist, and altered limestone. This belt occurs along the northeast shore of Upper Ross Lake and is in contact along its northeastern edge with a biotite granodiorite that contains numerous bands of biotite schist. The granodiorite has been intruded by numerous basic dykes that are now altered to amphibolite. The basic dykes trend northwesterly, parallel with each other and with the foliation in the granodiorite. The interbanded complex of granodiorite, amphibolite, and biotite schist continues eastward as far as Redout Lake. There it is in contact with a pink, pegmatitic, muscovite granite hereafter referred to as the Redout Lake granite. The granodiorite, amphibolite, and biotite schist complex is also intruded across the entire region between Upper Ross Lake and Redout Lake by hundreds of pegmatite bodies. It is in this area that the regional zonation of the pegmatites occurs. Two sets of brown weathering diabase dykes intrude all the other rocks and are the youngest in the area.

Rock exposures are excellent, and this greatly facilitated the investigation. Much of the area has been burned over so that bedrock is exposed in almost 70 per cent of the map-area, the rest being covered by muskeg and glacial debris. Relief is locally rugged, but does not exceed 200 feet. Successive ridges and valleys trend northwest and the topography is governed largely by the lithology and structural trend of the bedrock units. The Yellowknife group rocks form a high ridge along the northeast shore of Upper Ross Lake. The contact between these rocks and the interbanded complex to the east is marked by topographic lows and a chain of small lakes and muskeg. Within the complex, many granodiorite bands form sparsely covered ridges. Amphibolites and biotite schists generally underlie low ground and are covered with underbrush. Pegmatites resist weathering, and vegetation is sparse on them; they are, therefore, clearly visible in aerial photographs. The diabase dykes weather readily and are expressed by narrow linear depressions cutting across all the other rocks.

FIELD WORK

Three hundred and fifty pegmatite bodies, including all those of mappable dimensions, were carefully examined with respect to the following features: size, shape, attitude, structural control, mode of emplacement, mineralogy, internal structure, relationship of rare-element minerals to internal structure, wall-rock alteration, relationship of the composition of pegmatite to that of wall-rock, secondary wall-rock structures, and radioactivity. Six of the most typical of these were mapped in detail by plane-table methods at scales of 1 inch to 10 feet (*see* Figures 2-5, 7, 8) or 1 inch to 20 feet (*see* Figure 2). A detailed base map of the area on a scale of 1 inch to 400 feet was also made by means of pace and compass traverses and aerial photographs (*see* Figure 1). It shows the exact location, size, and general shape of all three hundred and fifty pegmatites and the occurrences of beryl, columbite-tantalite, tapiolite, lithiophyllite, and spodumene. Every pegmatite body examined in detail was given a number that is recorded on the map and will be referred to in the descriptions that follow.

LABORATORY STUDIES

Thin section examination has yielded much information concerning the mineralogy of the pegmatites, their mode of emplacement, and the changes that accompanied their introduction. Considerable X-ray diffraction work has been done to identify certain oxides of columbium and tantalum. Polished surfaces of these oxides have also been studied in order to substantiate the identifications. Many grain mounts of plagioclase feldspar were prepared, and their compositions were determined using the coloured Becke line method (14, p. 617). The purpose of this was to determine whether a systematic variation in plagioclase composition occurs across the area similar to that reported by Maurice (34, pp. 173-179) in the Spruce Pine district of North Carolina.

A limited number of spectrographic analyses of wall-rock and pegmatite minerals were obtained to study the distribution and derivation of beryllium, columbium, tantalum, and lithium. These rare elements are found in the pegmatites in megascopically visible, independent minerals. All future references to rare elements or their minerals in this paper refer to these elements or compounds containing them. It was hoped that spectrographic determination of Rb:K ratios in various specimens of potash feldspar collected from many pegmatites across the area might show a systematic variation in this ratio as suggested by Mason (33, p. 115). The writer was able to obtain only semi-quantitative determitions of the Rb:K ratio, and these were not sufficiently accurate to offer a solution to the problem.

It was originally intended to determine temperatures of formation of various pegmatites from fluid inclusions in beryl and spodumene. It seemed possible that a sufficient number of temperature determinations might indicate a regional zonation in temperature of formation. The necessary specimens were collected but the initial investigations along these lines indicated that such a study would not yield worthwhile results.

A number of heavy mineral separations were completed in order to study the nature of zircons from both pegmatites and wall-rocks. It was hoped that the physical characteristics of any zircon present might aid in determining the genesis and mode of emplacement of the pegmatites.

CHAPTER III

DESCRIPTION OF THE REGIONAL ZONATION

In order to describe the regional zonation of the pegmatites, their variable features will first be discussed in detail. In this way the systematic changes that occur in the nature of the pegmatites across the area will be revealed. These systematic changes constitute the basic proof of the regional zonation.

VARIATION IN SIZE OF PEGMATITE BODIES

The size of the pegmatites varies widely, but systematically. The largest, 15[1], which lies near the northeast corner of the area (*see* Figure 1), is an irregular body almost 2,000 feet long and 600 feet wide at its broadest point. Large bodies of this type will be referred to hereafter as 'giant pegmatites'. These giant pegmatites constitute the bulk of the pegmatitic material in the eastern part of the area adjacent to the Redout Lake granite and are of prime importance from a genetic standpoint. They decrease in both number and size westward toward Ross Lake.

A complete gradation occurs from the giant pegmatites westward through progressively smaller bodies, down to tiny veinlets and stringers of pegmatite only an inch wide and a foot or two long. The smaller bodies are dyke- or vein-like in character and predominate in the western parts of the area near Ross Lake. In general, they vary in width from 1 foot to 5 feet and are 50 to 300 feet in length. At the scale on which the mapping was done it was impossible accurately to portray dykes or veins less than 10 feet long, and no attempt has been made to show their location although many were examined in the field. Quantitatively these dyke- and vein-like pegmatites represent a minor amount of the pegmatitic material occurring in the area, but they are important in determining the zonal distribution of the rare-element minerals.

Figure 1 illustrates clearly the decrease in both size and number of bodies from east to west across the area. The relationship is a simple one but highly diagnostic of the regional zonation. It points strongly to the Redout Lake granite as the source of the pegmatitic material.

VARIATION IN SHAPE OF PEGMATITE BODIES

Pegmatite bodies of every conceivable shape occur in the area. Eastward, near the Redout Lake granite, extremely irregular shapes are commonplace. Most of the giant pegmatites of this region are irregular, with tongues, lobes, bulbous offshoots, branches, and other complex apophyses. This irregularity may be seen in pegmatites 101 and 172. In general, complexity of shape is most pronounced in the eastern parts of the area near Redout Lake.

Westward, farther from the Redout Lake granite, most of the pegmatite bodies are simple, sheet-like masses that have the form of dykes or

[1]Numbers refer to those used to designate pegmatite bodies on the maps accompanying this report.

veins. The simplest of these are linear, but others are sinuous with gently curving contacts as in dykes 180 and 300 (*see* Figures 3 and 5). Most are lenticular and pinch at both ends, but some are wedge-shaped and pinch in only one direction. Various other shapes also occur but are much less common. Groups of simple dykes are sometimes arranged *en échelon*, as for example dykes 145 and 136 (*see* Figure 1). A paired arrangement of two similar bodies also occurs, for example in dyke 113. Dyke 110 is elliptical in shape, and dykes 192 and 270 are teardrop shaped. Arcuate bodies are seen in pegmatites 297, 309, and 313. Dyke 96 is hook-shaped, and Plate IA shows part of a pegmatite body that consisted of a series of lenticles superficially resembling boudinage structure.

In spite of this wide range of shapes, it is generally true that pegmatites in the western half of the area are of rather simple dyke- or vein-like form. The over-all change in shapes from the extreme complexity of the giant pegmatites near Redout Lake, to the simpler forms in the western parts of the area is another feature that illustrates the regional zonation.

VARIATION IN STRIKE OF PEGMATITE BODIES

The strike of individual pegmatite bodies also varies through a wide range, and again the variation is a systematic one. Many of the pegmatites are so irregular in shape that it was impossible to determine a definite strike, and in cases of this kind the trend of the longest dimension was recorded. This has also been done in the case of sinuous and curved bodies. In general, two over-all directions of strike predominate and may be seen on Figure 1.

In the east and southeast, near Redout Lake, the giant pegmatites strike persistently to the northwest at angles varying between north 20 degrees west and north 40 degrees west. These bodies are, in general, concordant with the banded wall-rock complex of granodiorite, amphibolite, and mica schists (*see* Figure 2).

In the western and northwestern parts of the area, a strong northeasterly trend predominates. There the pegmatite bodies strike at various angles from north 30 degrees east to north 70 degrees east. They are strongly discordant and cut across the layering of the wall-rock complex. Most of the smaller, regular, dyke-like pegmatites are of this type.

Many pegmatites near the centre of the map-area appear to combine both trends. Many of these bodies are elbow-shaped because they follow the northwesterly trend for a part of their length and then turn abruptly and pursue the northeasterly trend. Some send off branches that follow one or both of these directions. They are a transitional type, intermediate between the two groups described above. Dykes 214 and 172 are examples.

Thus there is a definite systematic variation in strike of the pegmatite bodies from predominantly northwesterly near Redout Lake, through transitional types with both northwesterly and northeasterly trends, to a predominantly northeasterly trend near Ross Lake. This is another variable feature of the regional zonation.

The approximate boundaries of these three zones are shown on Figure 6.

The same three zones can be recognized on the basis of structural control and mode of emplacement.

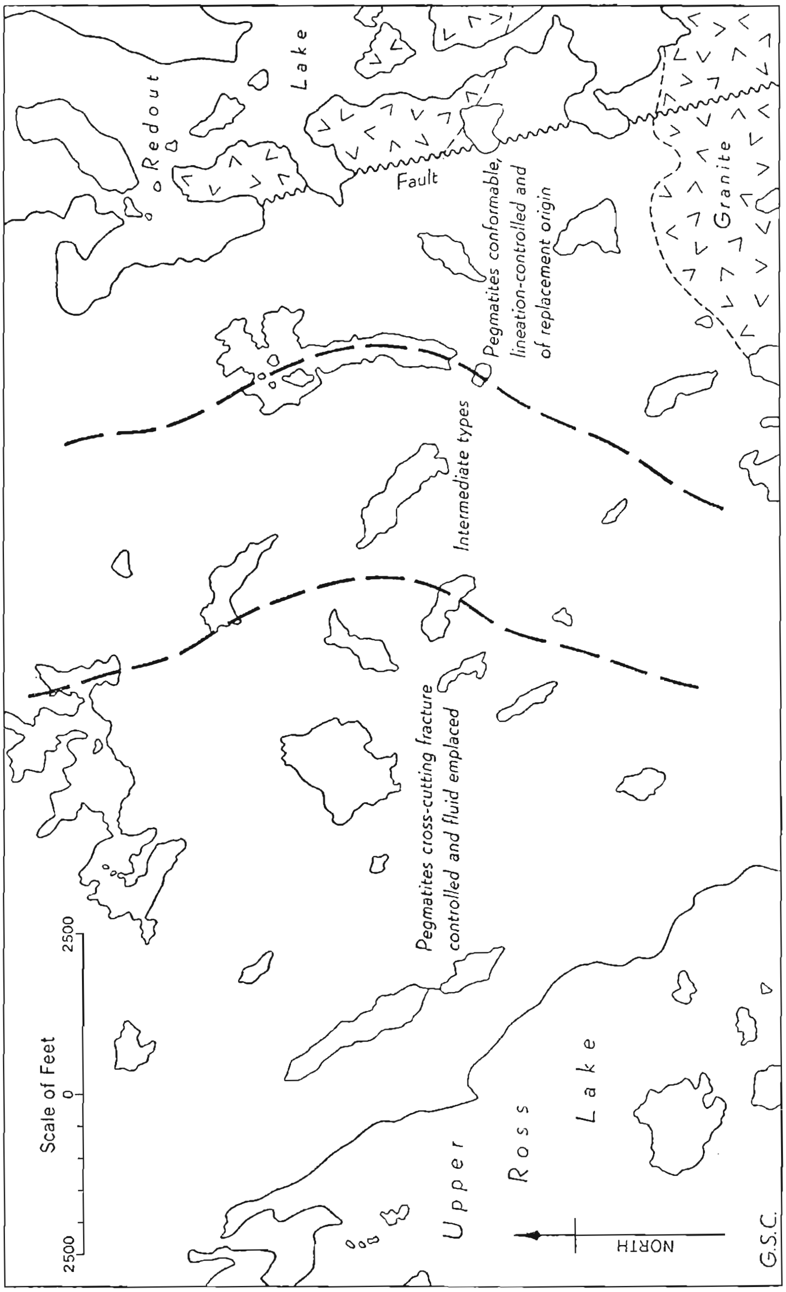


FIGURE 6. Sketch map showing approximate boundaries of eastern, central and western zones.

The pegmatites of the area are remarkably uniform in direction of dip, if not in degree. With few exceptions they dip to the northeast, east, or southeast, depending on their strike, toward the Redout Lake granite. Angles of dip vary from 55 degrees to almost vertical. Where plunging bodies occur the direction of plunge is invariably easterly at angles of 85 to 55 degrees.

VARIATION IN STRUCTURAL CONTROL

Two important structural controls are readily recognized, related to the two predominant trends described above.

The first of these controls predominates in the eastern half of the area (*see* Figure 6), where it has governed emplacement of the giant pegmatites near Redout Lake, and was exerted by the interbanded country rock. The alternate layers of granodiorite-gneiss and amphibolite confined the giant pegmatites, so that they occur within single layers of granodiorite between two adjacent layers of amphibolite. The resulting concordance of invading pegmatites with the layered host rocks is manifest in the northwesterly trend of all formations.

In the west (*see* Figure 6) a different structural control influenced pegmatite emplacement. There northeasterly trending fractures apparently controlled pegmatite formation. These fractures seem to have transected the trend of the interlayered wall-rocks at various angles and dipped to the southeast. Where the fractures cut across the contacts between banded granodiorite and amphibolite rocks they commonly changed direction, probably due to the different competency of the transected bands. Pegmatites emplaced in these fractures now show the same directional changes at, or near, wall-rock contacts. Dyke 180 (*see* Figure 3) illustrates this feature. Pegmatite emplaced in these fractures form the small, linear and dyke-like bodies near Ross Lake.

Near the centre of the area (*see* Figure 6), pegmatite emplacement was guided by a combination of both cross-fractures and layering of the wall-rocks, and composite pegmatites, with both northeasterly and northwesterly trends, resulted.

Thus there is a systematic regional variation with regard to the structural control that influenced pegmatite emplacement. In the east, the banding of the country rocks controlled emplacement, whereas westward this influence gradually gave way to control by crosscutting fractures, until the latter control predominated in the western parts of the area.

VARIATION IN MODE OF EMPLACEMENT

Two entirely different modes of emplacement, in conjunction with the two different structural controls, have resulted in the development of the pegmatite bodies.

All the field and laboratory evidence indicates that the giant pegmatites near Redout Lake (*see* Figure 6) were formed by replacement. These bodies grade into granodiorite both along and across strike within a single layer, and many are restricted on both sides by bands of amphibolite (*see* Figure 2). The following relationships indicate a replacement origin for these bodies.

(1) The bands of amphibolite and granodiorite adjacent to the giant pegmatites are undistorted, the normal, regional trend of the wall-rock layers beside these large, irregular bodies being undisturbed. Neither the contacts between amphibolite and granodiorite bands in the nearby wall-rocks nor the gneissosity within granodiorite bands are in the least distorted. Dykes 65 and 78 (*see* Figure 1) and dyke 161 (*see* Figures 1 and 2) are excellent examples. These pegmatites lie within granodiorite bands that are in contact with amphibolite layers on both sides. In each case the band has the same width regardless of whether it contains pegmatite or not; that is, there has been no expansion where the pegmatites were emplaced. Furthermore, the adjacent amphibolites are undistorted and follow the normal regional trend. The retention of this degree of regional structure strongly indicates a replacement origin.

(2) The problem of space requirement that was applied by Read (40, pp. 7-8) to the origin of granite also applies here. In the eastern parts of the area, the giant pegmatites constitute almost 20 per cent of the bedrock. This volume of pegmatite could hardly have been intruded as a space-occupying fluid without extreme distortion or destruction of the regional structure. No such distortion is present.

(3) Most contacts between giant pegmatites and the granodiorite bands containing them are gradational. This feature makes it extremely difficult to recognize and draw definite boundaries for these bodies in the field. Actually the contact consists of a zone across which gradational changes occur. Pegmatitic microcline, graphic granite, quartz, and muscovite become increasingly abundant at the expense of the plagioclase, biotite, and hornblende of the granodiorite host rock. Suites of hand specimens were collected at regular sample intervals across the gradational contacts. In these samples the increasing abundance of pink pegmatitic microcline, which is absent in the unaltered granodiorite but abundant in the pegmatite proper, offers a striking and readily seen testimony to the gradational nature of the contacts. Microscopic investigation of thin sections cut from these suites of specimens also supports the hypothesis of a replacement origin. The thin sections reveal the gradational nature of the contacts and the mineral changes that transformed granodiorite gneiss into pegmatite. The nature of these changes will be discussed in the section on wall-rock alteration.

These features clearly show that there was extensive marginal replacement along the edges of these bodies consistent with a replacement origin for the giant pegmatites.

(4) Inclusions of granodiorite are common in the giant pegmatites, and several features of these inclusions bear directly on the problem of mode of emplacement.

(a) Commonly the inclusions show rounded and gradational contacts with the pegmatites (*see* Plate IB and Figure 2) and they appear to be partly replaced, or unreplaced remnants.

(b) In dyke 161 (*see* Figure 2) the gneissosity within one inclusion is still visible, and is oriented parallel to the gneissosity in the granodiorite wall-rock beyond the pegmatite.

(c) Also in dyke 161 an inclusion of granodiorite occurs within the pegmatite at a place where the pegmatite lies between walls of amphibolite. It is difficult to see how this inclusion could have reached its present position unless the pegmatite replaced an entire granodiorite band that originally occupied the space between the amphibolite layers. The inclusion then may be interpreted as an unreplaced remnant.

(d) Granodiorite inclusions are common but amphibolite inclusions were never found within the giant pegmatites, although amphibolite is commonly in contact with the pegmatites. This also is difficult to understand if the pegmatites were emplaced as fluid intrusions, but it is simply explained by an hypothesis of selective replacement of granodiorite layers.

It is recognized that there is much controversy over the validity of these features in proving or disproving replacement. It is felt, however, that the nature of the inclusions in the giant pegmatites as described above differs from that of the inclusions in pegmatites farther west, to be described below, and this difference supports the hypothesis of a replacement origin for the former.

(5) The extreme irregularity in the shape of the giant pegmatites is most easily explained by a replacement origin. It is difficult to visualize fractures or other openings of such complexity, into which these bodies could have been introduced as fluids.

The first argument (1) constitutes good proof of pegmatite formation by a replacement process. None of the other arguments is conclusive in itself, but, when they are viewed collectively, they, also, are strongly indicative of a passive, replacement origin. This replacement was highly selective, and occurred preferentially within granodiorite layers of the wall-rock. The amphibolite was apparently impermeable to the pegmatite-forming emanations and was not replaceable by them, but rather served to guide and restrict them along single granodiorite layers.

The linear dykes and veins in the western part of the area (*see* Figure 6) present a striking contrast to the features described above for the giant pegmatites. All the field evidence indicates that these bodies were emplaced by the injection of a fluid, pegmatite 'magma' into dilatant cross fractures, faults, or, less commonly, shear zones. The following features of these dykes support the hypothesis of fluid emplacement.

(1) Where the pegmatites intrude layers of biotite schist in the wall-rock, extreme distortion of the schistosity is commonplace. Dyke 300 (*see* Figure 5) meets such a schistose layer, which is bent, or bulged, around the end of the invading pegmatite. At this place the schist folia are highly crinkled and contorted. Such distortion of schistosity is considered by Noble (35, p. 36) to indicate fluid injection.

(2) Drag of the gneissic bands in the granodiorite wall-rocks occurs at some pegmatite contacts (*see* Plate II A).

(3) Where wall-rock inclusions are found in these pegmatites, the following features were repeatedly observed.

(a) Inclusions invariably have angular, unrounded corners, sharp unreplaced contacts, and match pegmatite-filled re-entrants in the dyke walls (*see* Plate II B).

(b) The direction of the gneissosity in granodiorite inclusions commonly differs from that in the wall-rock proper.

(c) Inclusions of both granodiorite and amphibolite are common (*see* Plates II B and III B), whereas in the giant pegmatite, inclusions were of granodiorite only.

(4) Pegmatite veins or dykes intersect one another with sharp corners and unenlarged vein junctions (*see* Plate III A and B).

(5) Small, dyke-like bodies commonly show matching walls (*see* Figure 5 and Plate III A).

(6) Extremely sharp contacts between pegmatite and wall-rocks are common in these bodies, many contacts being marked by an open fracture where the pegmatite has broken clear of the wall-rock (*see* Plates IV A, B, and V A). These pegmatites appear to have been chilled against the country rocks.

(7) Where these pegmatites cut across bands of layered wall-rocks at oblique angles, the bands are commonly offset in a manner similar to that described by Goodspeed (22, p. 189) and King (30) for dilation dykes. In dyke 180 (*see* Figure 3) repeated offset, all in the same direction, of several bands of amphibolite can be observed.

Dykes near the centre of the map-area (*see* Figure 6) have been described as composite, both in regard to trend and structural control. It appears that these pegmatites have also been emplaced by a combination of the processes of replacement and fluid injection. Dyke 205 (*see* Figure 4) is an excellent example. There the offset of a narrow cherty layer and the presence of inclusions of granodiorite that match declivities in the walls offer evidence of fluid injection. It is, however, also certain that extensive replacement has occurred and has formed the border zone of the pegmatite, for some of the wall-rock inclusions match declivities in the dyke walls only if the border zone pegmatite that occurs along the foot-wall side of the inclusion is considered to be part of the inclusion. Thus, there is little doubt that the body was emplaced by fluid injection accompanied by extensive marginal replacement that caused pegmatitic alteration of parts of the wall-rock.

Again, it is noteworthy that the mode of pegmatite emplacement varies systematically across the area. Both field and laboratory evidence clearly indicate that replacement was the predominant mode of pegmatite formation near Redout Lake. Westward, replacement gives way progressively to pegmatite emplacement by fluid injection into open fractures or shears, and this process predominates in the western parts of the area. In many places in the centre of the area, both processes have operated simultaneously.

VARIATION IN DEVELOPMENT OF INTERNAL STRUCTURE

The recent work by Cameron *et al.* (8) provides the basis for the studies of internal structure made in this investigation, and the terms used here with respect to zoned pegmatites are as defined in their work. Table I (in pocket), lists and describes, as they occur from the walls inward, the mineral assemblages present in pegmatites of the Ross Lake-Redout Lake area. It is significant that the order of occurrence of the mineral assemblages agrees with that described by Cameron *et al.* (8, pp. 62-70) in pegmatite districts of the United States. The table shows that zones are the most important units of internal structure. Minor replacement bodies occur, but no fracture fillings were encountered.

Pegmatites with every degree of development of internal structure are present in the area. For purposes of comparison and description in the field, they were classified as unzoned, poorly zoned, partly zoned, and well zoned. Bodies that showed no visible evidence of contrasted mineral assemblages are called unzoned. Dyke 161 (*see* Figure 2) is a typical example. These pegmatites make up the bulk of pegmatitic material present. Poorly zoned bodies are those in which incipient development of internal structure was observed. Such pegmatites have cores that consist of small, isolated, widely spaced pods of quartz or quartz-perthite, and dyke 180 (*see* Figure 3) is an example. Pegmatites in which contrasted mineral assemblages were present more or less continuously along the entire exposed length were designated as partly zoned. Dyke 300 (*see* Figure 5) is representative of this kind. Well-zoned pegmatites are those in which the units of internal structure were continuous along the exposed length of the body, and dyke 97 (*see* Figure 8, plate VII A) is an excellent example. The zoned bodies are much less common and invariably smaller than the unzoned pegmatites.

The giant pegmatites near Redout Lake are unzoned with an essentially homogeneous composition from wall to wall. They fall into the plagioclase-perthite-quartz-muscovite unit of Table I. In these masses there may be a coarsening of texture from the walls inward, but this is gradational and does not constitute zoning. One of these pegmatites, dyke 161 (*see* Figure 2), was mapped in detail and careful scrutiny failed to reveal the slightest trace of internal structure. As all these bodies were formed by replacement, it appears that replacement does not result in zonal structure in the pegmatites of the Ross Lake area. Furthermore, no zoned pegmatite examined was found to have been formed by replacement.

Zonal structures are developed in most of the smaller, fluid-emplaced pegmatites in the western parts of the area. Poorly and partly zoned pegmatites are common, and dykes 180, 205, and 300 are examples (*see* Figures 3, 4, and 5). Well-zoned pegmatites are rare, but dyke 97 (*see* Figure 8) is a good example. It is significant that the zoned bodies were fluid-emplaced in contrast with the giant unzoned pegmatites already described.

It is evident that a progressive change in the degree of development of internal structure is present across the area. Giant pegmatites near Redout Lake are unzoned and homogeneous, but westward there is an increasing trend toward the development of contrasting mineral assemblages.

ZONATION OF RARE-ELEMENT MINERALS

One of the most striking features of the regional zonation is the zonal arrangement of the rare-element minerals with respect to the main granite body. Rowe (42, p. 28, Figure 1B) has already described this feature in some detail and published a sketch-map illustrating the relationship. One of the aims of this study was to investigate further the distribution of the rare-element minerals, and all occurrences of beryl, columbite-tantalite, tapiolite, and spodumene are plotted on Figure 1. The position of these occurrences substantiates and defines more exactly the regional zonation of the rare-element minerals described by Rowe.

Rowe (42) has divided the area between the Redout Lake granite and Ross Lake into five zones based on the presence of certain minerals in the pegmatites. Each zone is in the form of a belt peripheral to the granite, Zone I being next to it and Zone V farthest removed, near Ross Lake. These zones have been more accurately defined in this study and their approximate boundaries are shown on the accompanying sketch-map (*see* Figure 9).

In Zone I graphic granite in the giant pegmatites is the characteristic mineral, rare-element minerals being absent. Zone II is a narrow belt containing graphic granite but also containing beryl. The pegmatites of Zone III also contain beryl but in these graphic granite is absent. In Zone IV the pegmatites contain beryl and minerals containing columbium and tantalum. Small amounts of lithiophyllite were also found in a few dykes on the western edge of this zone. In Zone V the pegmatites contain spodumene and rare, tiny plates of columbite, but both beryl and tapiolite are absent.

It is thus clear that the rare-element minerals in the pegmatites are arranged zonally with respect to the Redout Lake granite.

RELATIONSHIP OF RARE-ELEMENT MINERALS TO INTERNAL STRUCTURE OF PEGMATITES

The relationship of beryl, columbite-tantalite, muscovite, lithiophyllite, spodumene, and tapiolite to internal structure was one of the most consistent and interesting aspects of this study. Although it is not part of the problem of regional zonation, the main subject of this report, it deserves mention here because of its bearing on the occurrence of rare-element minerals.

Throughout the area, the best concentrations of these minerals lie in pegmatites that have well-developed internal structure. Unzoned pegmatites are invariably barren of them.

In the zoned pegmatites the following relationships have been noted in all pegmatites studied.

(1) The best concentrations and largest crystals of beryl occur in well-zoned pegmatites that contain a core of quartz-perthite composition. The beryl is most abundant at the outer margins of this zone (*see* Figure 8) close to its contact with the next zone, generally the perthite-plagioclase-quartz-muscovite wall zone, but may also be scattered through the quartz-perthite core.

(2) The richest concentrations and largest crystals of columbite are also found in well-zoned pegmatites. They occur at and near the margins of quartz-perthite cores in the perthite-plagioclase-quartz-muscovite wall zone, but tiny plates of columbite may be found all through this zone.

(3) Books of muscovite 3 and 4 inches long lie in zoned dykes along the contact of the same two units, whereas only tiny plates of scrap mica, rarely more than 1 inch long, are found in the border and wall zones.

(4) Lithiophyllite is present in small amounts in some of the pegmatites and the best concentrations and largest crystals were also seen in well-zoned dykes along the margins of quartz-perthite cores.

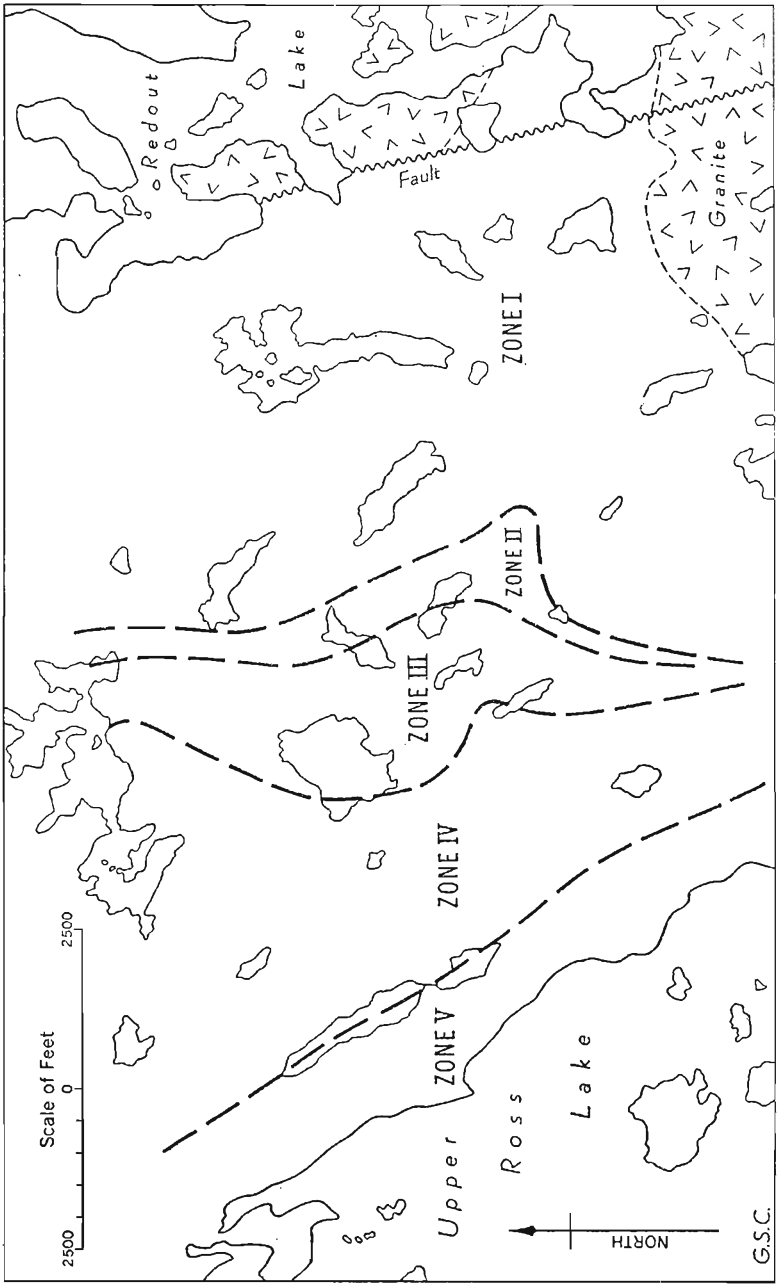


FIGURE 9. Sketch map showing regional zones based on the distribution of rare-element minerals in pegmatites.

(5) Spodumene occurs only in the pegmatites of the extreme western part of the area. In these pegmatites, three zones are present (*see* Figure 7 and Table I). Spodumene is found only in the core where it occurs as coarse, elongated crystals up to 6 inches long and may constitute up to 20 per cent of the rock.

(6) Contrary to previous reports, the most abundant mineral of columbium and tantalum in the area is not columbite-tantalite but tapiolite, the tetragonal polymorph of tantalite. This mineral is present in large aggregates and concentrations, and is found only in pegmatites containing the small mica replacement bodies where it occurs in one of two ways. In some cases, tiny crystals or blocky aggregates of tapiolite up to $\frac{1}{8}$ inch in size are disseminated throughout the mica replacement body itself. More commonly coarse, blocky crystals or aggregates up to 4 inches in size replace primary pegmatite near the margins of the replacement bodies. The farthest distance separating tapiolite crystals from a replacement body was about 2 feet, observed in dyke 84.

The fact that tapiolite was not previously reported in the area is undoubtedly due to the difficulty in distinguishing in the field between orthorhombic columbite-tantalite and tetragonal tapiolite. It was only by laboratory study of both polished surfaces and X-ray diffraction photographs that its recognition was achieved.

WALL-ROCK ALTERATION

The degree of wall-rock alteration present decreases progressively from west to east, and depends upon mode of emplacement of the various pegmatite bodies.

Emplacement of the giant pegmatites near Redout Lake was accompanied by extensive alteration in the adjacent granodiorite wall-rocks. Megascopic evidence of this alteration is the increased amount of pink microcline near the pegmatite bodies. This microcline is abundant in the pegmatites and has been introduced into plagioclase-rich granodiorite wall-rock for distances up to 50 feet.

A suite of specimens was collected across the zone of alteration. Study of thin sections made from these showed that the alteration was progressive and that the end product was a pegmatite formed partly by reorganization of the constituents of the original rock and partly through replacement by introduced material.

The first step in the transformation of fresh granodiorite gneiss to pegmatite was studied in specimens from the margins of the alteration zones. This stage appears to involve hydrothermal alteration of biotite and, where present, hornblende to a magnesium-iron chlorite. Hornblende first passed through a biotite stage and was almost completely reconstituted. Biotite was less altered.

Potassium released in the breakdown of biotite migrated inward toward the pegmatitic centre of the alteration zone where it became involved in the second stage of the pegmatization process.

The second, more intense, stage in the alteration was observed in specimens from within the pegmatites. This stage was apparently typified by the introduction of potassium (and volatiles) and by the metasomatism of magnesium, iron, and calcium minerals.

Iron was leached from remaining biotite which became muscovite. Titanium was also released in the breakdown of biotite and was used in the formation of sphene. Chlorite, which had formed in the first stage of alteration, was largely transformed into muscovite, presumably by potassium additions and through loss of iron and magnesium. Even in the central parts of these pegmatites where the process of pegmatization reached completion small remnant flakes of this chlorite persist.

Plagioclase was extensively sericitized and recrystallization of this sericite took place to form muscovite porphyroblasts within the altered plagioclase. Plagioclase was also replaced by potash feldspar, or was actually dissolved, whereas potash feldspar was re-precipitated in its place. This solution of plagioclase is shown by an abundance of rounded, resorbed inclusions of wall-rock plagioclase (labradorite) within potash feldspar grains. Similar poikilitic inclusions of quartz are also found in potash feldspar.

Extensive recrystallization of quartz occurred and is indicated by the presence of mosaic textures. These mosaic textures involve quartz, potash feldspar, and epidote, and are mostly interstitial to larger mineral grains of the altering wall-rock.

In these complex reactions of the second stage of alteration, iron, magnesium, and calcium were displaced. Iron was precipitated as an oxide, taken up as an impurity in the pegmatite feldspars (to which it imparts the deep pink colour typical of all pegmatite feldspars in the area) or may have migrated into adjacent amphibolite layers. Magnesium apparently migrated outward toward the margins of the alteration zones. There it was incorporated in the abundant chlorite that formed in the initial stage of alteration. In a few localities it combined with other materials to form tremolite. The displaced calcium was re-precipitated in abundance as epidote apatite and less commonly as sphene or tremolite.

The presence of remnant chlorite flakes in the central parts of the pegmatites is one piece of evidence that supports an origin by replacement through reorganization, because this chlorite was originally derived from the alteration of ferromagnesian minerals of the granodiorite. The interstitial mosaic textures of quartz, potash feldspar, and epidote suggest that a fluid phase may have been present along grain boundaries where it facilitated the processes of recrystallization and pegmatization.

Thus alteration in the granodiorite gneiss can be traced from fresh granodiorite across zones of increasing intensity into the pegmatitic end product, the alteration being in part accomplished by additions of volatile constituents and potassium.

In the amphibolites, alteration was confined to a narrow reaction rim at the pegmatite contact. Pegmatization proceeded laterally, and along strike, in the granodiorite layer until exhausted or until it reached amphibolite contacts. Here it was apparently arrested by the impermeability and inactivity of the amphibolite.

The inactivity of the amphibolite is difficult to understand in view of the fact that hornblende was one of the first and most extensively altered constituents of the granodiorite. It is possible that the amphibolite was impermeable to the pegmatitic emanations which, therefore, could not attack and react with this rock. It is more probable, however, that the different bulk chemical and mineralogical composition of the amphibolite from that of the granodiorite and the pegmatitic emanations, was also an important feature. Perhaps hornblende was unstable in alkali-rich granodiorite, but was stable in the amphibolite which was rich in calcium, magnesium, and iron.

Additions to the amphibolite may actually have been made by a metamorphic differentiation effect during metasomatic pegmatite emplacement. In the granodiorite, mobilization of the alkalis occurred, and hornblende was unstable in this environment. The alkalis migrated inward toward the pegmatitic centre of the alteration horizons. The displaced iron, magnesium, and calcium followed the opposite course, and were precipitated locally, or migrated outward. Thus mafic constituents may actually have been added to the amphibolite horizons, and there formed additional hornblende in the calcium-magnesium-iron-rich environment. Thin sections of the amphibolites show that much of the hornblende is impure and full of irregular quartz inclusions. Such hornblende may well be of secondary metamorphic origin. In her discussion of the granite problem, Reynolds suggested (41, pp. 210-211) that a similar process, which she called development of a basic front, may occur during the ionic transfers that accompany metasomatic granite formation.

In a few places at the pegmatite contact, however, extensive sericitization of plagioclase and chloritization of hornblende did take place in the amphibolite. The displaced calcium went to form epidote and apatite.

Wall-rock alterations in the small, fluid-emplaced pegmatites are much less pronounced. In most cases, these bodies have chilled margins and alteration is restricted to local effects resulting from additions of alkali to the wall-rock at the immediate contact. In a few intermediate cases fine-grained border zone pegmatite has originated by replacement of the granodiorite wall-rock. This occurred in dyke 205 (*see* Figure 4), and has already been described (p. 13). The alteration involved the breakdown of hornblende to biotite, biotite to chlorite, and later alteration of the chlorite to muscovite as described for the giant pegmatites. Some plagioclase was sericitized, and this sericite has in places recrystallized to form muscovite. Plagioclase was replaced by microcline, and quartz was recrystallized. Accessory minerals include chlorite, sphene, epidote, apatite, and garnet, and these minerals as a group probably contain the calcium, iron, and magnesium displaced in the alteration.

Where pegmatite 300 (*see* Figure 5) is in contact with a narrow biotite schist layer, a local but intense alteration of biotite to tremolite occurred. The schistosity of the rock was preserved after alteration by alignment of the tremolite plates. The tremolite replaced biotite in such a way that the cleavage in the tremolite is parallel with the original biotite cleavage. Alterations of this kind are rare, always local, and of minor importance.

Thus wall-rock alterations, although similar in nature throughout the area, are most intensive near Redout Lake and decrease in importance westward.

EFFECT OF WALL-ROCK ON COMPOSITION OF PEGMATITES

Almost all pegmatites in the area, except some near Ross Lake, occur in the layered complex of amphibolite, granodiorite, and minor biotite schist. Near Ross Lake the spodumene-bearing pegmatites intrude the complex where it consists essentially of granodiorite, and amphibolite layers are absent. Other pegmatites near Ross Lake intrude volcanic or sedimentary rocks of the Yellowknife group.

The giant pegmatites near Redout Lake in contact with granodiorite, show no visible difference in composition or texture, either in hand specimen or thin section, from those in contact with amphibolite layers. Apparently the nature of the wall-rocks had no visible effect on the composition of these replacement pegmatites, except that they replaced granodiorite only. The smaller fluid-emplaced pegmatites to the west show essentially the same relationships. There a single pegmatite may traverse successive bands of granodiorite and amphibolite without showing any visible differences in composition, megascopic or microscopic. Noteworthy exceptions are those pegmatites that intrude or cut across biotite schist layers in the wall-rock. Dyke 300 is an excellent example (*see* Figure 5). Where a pegmatite intrudes the schistose layer, the schistosity is contorted and a concentration of iron oxide imparts a reddish colour to the feldspars of the pegmatite, both perthite and plagioclase. Farther from the contact with the schistose band, the reddish colour of the feldspars is less pronounced until the normal cream, or flesh-coloured variety is encountered. Apparently iron was rendered mobile in the biotite schist layers by pegmatite intrusion and drained into fractures that were also the loci of pegmatite injection. There it was precipitated in the feldspars as iron oxide dust and as a constituent of tantalite, tapiolite, and lithiophyllite (*see* Table II in pocket). In rare instances, this iron seems to have been incorporated in biotite formed in the outer zones of these pegmatites, but normally biotite is exceedingly rare.

Conditions are less favourable to study the relationship between the spodumene-bearing pegmatites near Ross Lake and the composition of the wall-rock. The wall-rocks are not only different, being altered sedimentary and volcanic rocks of the Yellowknife group, but tend to be homogeneous. Furthermore, fewer pegmatites are present for comparison. It is, therefore, impossible to decide to what extent, if at all, the composition of the pegmatites has been influenced by that of the wall-rocks.

It is possible that the spodumene content of some of these dykes is due to the different character of the wall-rocks, but nothing was observed to bear out this hypothesis. On the contrary, both the lithium content of these bodies and the composition of the plagioclase fits into the over-all zonation and sequence of the rare elements across the area. It, therefore, seems probable that the difference in composition of these pegmatites is due to their position in the sequence rather than to differences in wall-rock composition.

In general, it is, therefore, fair to conclude that wall-rock composition has had little effect upon pegmatite composition or texture. It is true that field evidence clearly indicates that minor amounts of iron were drained from the wall-rocks and incorporated into the pegmatites, and wall-rock constituents were reorganized during the emplacement of pegmatites in the eastern parts of the area. There is no evidence to suggest any other relationship between wall-rock and pegmatite composition.

Spectrographic analyses of both granodiorite and amphibolite wall-rocks indicate that the rare elements in pegmatites were not derived locally from the surrounding wall-rocks. They were apparently introduced with the fluid-emplaced pegmatites.

VARIATION IN PLAGIOCLASE COMPOSITION

Variation in Individual Pegmatites

Several pegmatites were sampled systematically from the walls inward and the plagioclase composition in the various samples was determined, using the coloured Becke line method outlined by Emmons and Gates (14, p. 617). No difference was noted between the composition of the plagioclase near the margins of the pegmatite bodies and that near the centre except in the fluid-emplaced pegmatites near Ross Lake. In these the plagioclase near the borders is slightly more calcic than that near the centre. The greatest difference found was in dyke 205 where the plagioclase near the wall was An_{10} and that near the centre An_5.

Regional Variation

A systematic regional variation in plagioclase composition, similar to that described by Maurice (34, pp. 173-179), occurs in pegmatites across the area. As the plagioclase composition varies within individual pegmatites, all samples were taken from the border zones of dykes. Samples from thirty-five dykes were selected for study of the regional variation. The anorthite content of these samples was determined and plotted in their correct position on the sketch map (*see* Figure 10). Specimens of plagioclase from the walls of pegmatites near Redout Lake are all relatively high in anorthite, whereas those from the walls of dykes near Ross Lake are albite-rich. There is a systematic variation from a maximum of An_{17} near Redout Lake, (dykes 64 and 162) to a minimum of An_4 near Ross Lake (dyke 3).

It was suggested to the writer that differences in the degree of ordering of aluminium and silicon in the various specimens of plagioclase might influence the refractive indices of the samples on which the variation in albite-anorthite content is postulated. Investigations of the optic angles of the plagioclases indicate, however, that all are low temperature varieties and, therefore, probably have the same degree of ordering. The optic angle determinations also verify the determinations of the anorthite content shown in Table III, that were first determined by the coloured Becke line method. This gives an independent check on the compositional variation.

RADIOACTIVITY

The degree of radioactivity of pegmatites is rather constant in the area. Variations were encountered in some dykes, but these were not systematic in nature. Apparently radioactivity is not related to the regional zonation.

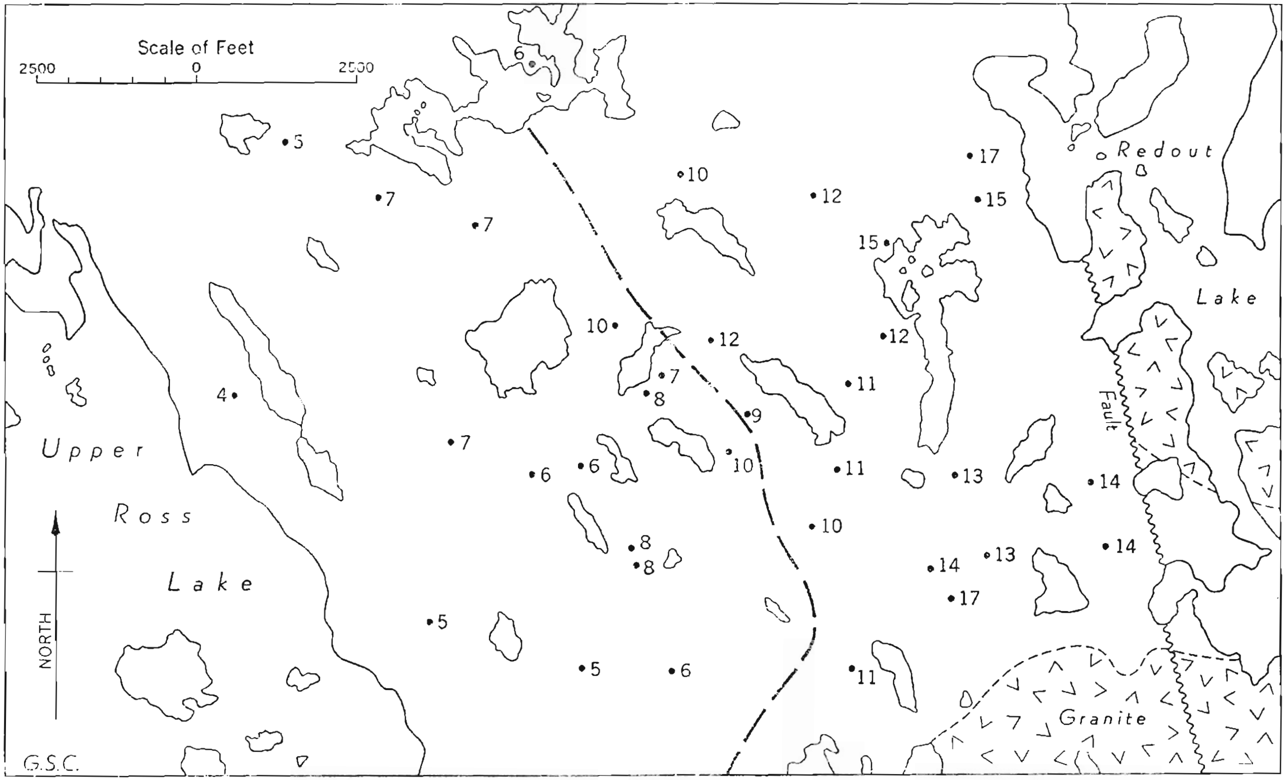


FIGURE 10. Sketch map showing anorthite content of plagioclase from permatite walls. East of line plagioclsse is obligoclase, west of it is albite.

Potassium: Rubidium Ratio

Mason (33, p. 115) points out that, as Rb^+ is considerably larger than K^+ and is admitted into potassium minerals, the Rb:K ratio increases with increasing differentiation The concept seems ideally suited to the system under consideration, in which progressive and continuous differentiation seems to have occurred. Accordingly, twenty-four samples of potash feldspar from dykes throughout the area were submitted for spectrographic analyses. Quantitative determinations of their K and Rb contents could not be obtained, and the semi-quantitative results are not sufficiently precise to be applicable to the problem of regional zoning. One interesting feature of the analyses may, however, be noted. Two samples of perthite were submitted from the same pegmatite, one collected from the wall zone and the other from the core. The spectrographic data indicate that perthite from the wall zone has a much lower Rb:K ratio than that from the core. If this relationship were found to persist in other zoned pegmatites, it would be in complete accordance with the concept of crystallization and differentiation in a restricted system as the mode of origin for these bodies (Mason, op. cit.).

ZIRCON STUDIES

A few heavy mineral separations were completed in the hope of obtaining zircons from the wall-rock and pegmatites. It was believed that a comparison of the zircons would aid in determining the genesis of the pegmatites. Unfortunately no zircons were recovered in the separations from samples of pegmatite. As the giant pegmatites formed by replacement of zircon-bearing wall-rocks, the absence of zircon in these bodies is a puzzling feature. It can only be concluded that zirconium was mobilized in the pegmatitic alteration, joined the migrating constituents, and moved on. It should then be found in the later fluid-emplaced pegmatites. No zircon was recovered from specimens of this type of pegmatite either, but Table II shows that the columbium-tantalum minerals in these dykes contain zirconium, and this may be how the mobilized zirconium was utilized.

CHAPTER IV

DISCUSSION OF REGIONAL ZONATION

GENERAL STATEMENT

A hypothesis to explain satisfactorily the regional zonation of the pegmatites in the vicinity of Ross Lake must account for the origin of all features seen in the field and noted in the laboratory. These are: zonal differences in size, shape, attitude, structural control, mode of emplacement, and internal structures of the pegmatites; zonal occurrence of the rare elements and their minerals; progressive changes in wall-rock alteration; and zonal variations in plagioclase composition.

HYPOTHESIS OF ORIGIN

Many workers have discussed the relation of pegmatites to batholiths and have suggested explanations for the presence of zoning in pegmatite districts. It is unnecessary to enumerate here all the publications to which reference could be made, but the recent paper by Heinrich (25) summarized many of the pertinent articles that deal with systematic regional variations. In general four basic hypotheses have been, or may be, advanced. These hypotheses, briefly stated, suggest that regional variations in the nature of pegmatites are related to:

(1) Differences, either in metamorphic rank or in composition, of the invaded rocks.

(2) Differences in physical characteristics, such as shape, size, or external structure, of the pegmatites themselves.

(3) Progressive stages of differentiation in the batholithic source combined with withdrawal of the differentiate at two, or more, distinct times.

(4) Differences in distance from the batholithic hearth that supplied the differentiates and initiated pegmatite emplacement.

Any one, or any combination, of these hypotheses may offer the true explanation in a given pegmatite district. Each was applied and tested in the Ross Lake area, and was critically evaluated in the light of the known field and laboratory evidence. The following discussion is a summary of this evaluation.

The first hypothesis, that zoning is due to differences in the wall-rock, is definitely untenable in the area under consideration. It has been clearly shown that there is no relationship between wall-rock and pegmatite composition, except for the transfer of minor amounts of iron from the country rock to the pegmatites. Furthermore, the granodiorite and amphibolite wall-rocks of uniform metamorphic grade and composition are present across the entire district, except in the extreme west where a narrow band of Yellowknife group rocks is found.

External structure, which included size and shape, of pegmatite bodies was proposed by Vlassov (Heinrich 25, p. 79) as an explanation for variations in internal structure, and in rare-element mineralogy. However, in the Ross Lake area, size and shape of pegmatites are, themselves, two of the systematic variables of the regional zonation. Furthermore, it is not possible to explain the zoning of the rare-element minerals, the progressive change in structural control, or the variation in mode of emplacement on the basis of external structure. It is also difficult to explain in this way the variation in plagioclase composition. It is, therefore, clear that the second hypothesis fails to explain satisfactorily the regional zonation in this area. Heinrich moreover pointed out (25, p. 79) that a relationship between external structure and systematic variations in nature of pegmatites is untenable in many regions, and to these may be added Ross Lake.

The third hypothesis, that zoning is due to progressive differentiation at the source and withdrawal of material at two or more times, is the explanation favoured by many workers in the field of economic geology, including Bateman (1, p. 53), Gevers (18, pp. 352-353), and Heinrich (25, p. 84). Critical examination, however, suggests several facts that indicate that it is not the explanation of the zoning in the Ross Lake area.

In his recent paper, Heinrich (25, p. 68) suggested that two separate withdrawals of pegmatitic differentiates tapped the batholithic hearth. The earlier of these would give rise to the barren pegmatites close to the source, of Gever's transitional zone (18, p. 339). The later withdrawal on the other hand would be richer in volatile constituents and mineralizers, due to advanced differentiation in the source. It would, therefore, penetrate the country rocks to a greater distance, yielding pegmatites carrying rare-element minerals. Thus he explained the regional zonation in the occurrence of the rare-element minerals. This process might produce some of the zoning noted in the Ross Lake area, including the variations in rare-element mineralogy, plagioclase composition, and internal structure. Differences in structural control and mode of emplacement might also result from the proposed hypothesis. The following arguments have, however, led the writer to reject this hypothesis for the Ross Lake area.

The bulk composition of pegmatites formed from material withdrawn at different times should be recognizably different (1, p. 53; 25, p. 83). That is, it should be possible to assign an individual pegmatite to one suite or other by determining its mineral content. In the Ross Lake area this cannot be done. On the contrary, there is a complete and progressive variation from large, homogeneous pegmatites in which rare-element minerals are absent, through smaller, partly zoned pegmatites, to small, well-zoned pegmatites in which rare-element minerals are common. This progressive variation is not in accord with the hypothesis of a process essentially discontinuous.

The hypothesis implies that all pegmatites, whether early or late, were formed by the injection of fluid differentiates from the parent body. It has been shown that in the Ross Lake area most of the pegmatites were formed by recrystallization and replacement and only those most remote from the parent granite were fluid emplaced.

The hypothesis also implies that the material from which the younger, rare-element bearing pegmatites were formed must have crossed the area already occupied by older, barren pegmatites. If this were true it is surprising that, in an area where exposures are so complete, nowhere is there a single case of the one cutting the other. On the contrary, in many places rare-element pegmatites of the outer or intermediate zones are contemporaneous offshoots of larger barren bodies (*see* Figure 5, dyke 300).

For these reasons, the third hypothesis cannot be accepted as a valid explanation of the regional zonation of pegmatites at Ross Lake.

The fourth hypothesis, that zoning is due to different distances from the source of the pegmatitic materials, seems to the writer to offer the most satisfactory explanation for the regional zoning in Ross Lake area. The systematic variations of all the characters considered are clearly related to the distance from the batholithic hearth. Details of this hypothesis will be discussed in the following sections.

SOURCE AND COMPOSITION OF PEGMATITIC FLUIDS

Progressive changes in the character of pegmatites with increasing distance from the granite show that the pegmatite bodies are zoned spatially around the Redout Lake granite. Truly the pegmatites are satellites of the granite. This Redout Lake batholith was apparently the motivating agent by which pegmatite formation was induced, and it appears to have been the source from which the initial pegmatitic differentiates were derived. Whether these differentiates were generated from the batholithic hearth as a consequence of progressive crystallization (3, pp. 21-24, and 4), or whether they were mobilized in the wall-rocks close to the batholith, is not known. It is possible that both processes contributed to the pegmatitic fluids.

The composition of the pegmatitic differentiate as it left the batholith can only be deduced from the composition of the pegmatites and that of the invaded rocks.

The only potash mineral in the unaltered granodiorite is biotite, and, as it is present in minor amounts only, the rock as a whole is potassium poor. The pegmatites, on the other hand, that were formed by replacement of this rock contain abundant muscovite and potash feldspar. Thus it is evident that much potash was introduced and could have come only from pegmatitic fluids derived from the Redout Lake granite by differentiation during crystallization. It is noteworthy that this rock is an alkali granite and contains abundant potash minerals and may be expected to have produced a differentiate high in potassium (2, pp. 86-87).

There is extensive chloritization and sericitization around the centres of pegmatitic development. This alteration is hydrothermal and, as it must have been caused by the same differentiates that produced the pegmatites, it shows that they were hot and largely composed of water.

The occurrences of tourmaline, apatite, and lithiophyllite in some of the pegmatites indicate that other volatiles, including fluorine, boron, and phosphorus, were also present in the fluids. Further evidence for this is the presence of coarse crystals in pegmatites near Ross Lake.[1]

The pegmatites in the western part of the area contain minerals of beryllium, columbium, tantalum, and lithium. These rare elements

[1]Buerger (7) explained the influence of these mineralizers, with special reference to fluorine, in facilitating crystal growth to yield the typical coarse crystals in fluid-emplaced pegmatites.

must also have been present in, and transported by, the migrating pegmatitic fluids, but the matter will be discussed fully in the next chapter.

All pegmatites in the area contain sodium, aluminium, and silicon, but these components may in part or wholly have been added to the pegmatitic fluids by solution from the rocks through which the fluids passed to reach their final resting place.

Thus it appears that the original differentiate, upon leaving its source, may have been an alkali-bearing aqueous solution rich only in potassium, the volatiles, and the rare elements. This solution affected the wholesale reorganization of the country rocks to form the giant pegmatites by replacement near the batholith. Sodium, displaced from the plagioclase in the original rock by potassium, as well as silicon and aluminium were added to the migrating pegmatitic emanations. These emanations continued to move outward and eventually formed the fluid-emplaced pegmatites, farthest from the batholith.

MIGRATION OF DIFFERENTIATES

Whatever the exact state and composition of the differentiates may have been, they were genetically related to the Redout Lake granite, which was at elevated temperature and pressure. The differentiates migrated outward from it to lower energy levels.

Because of the complete lack of fractures in the wall-rocks close to the granite, this migration must have been an ionic transfer of all the components of the differentiate. The extensive, but selective, penetration of the wall-rock by pegmatitic material is difficult to understand if solid diffusion is proposed as the mechanism by which the transfer was effected. It is more probable that the migration took place in a 'pore fluid' that occupied the interstices of the wall-rocks. The differentiates were rich in water and other volatile materials and, upon leaving the batholithic source, these constituents could form such a pore fluid because of the progressive decrease in temperature and pressure. Mosaic textures along grain boundaries in partly pegmatized wall-rocks probably resulted from solution of the original minerals and the precipitation of new ones by means of this pore fluid.

As the replacement pegmatites are found only in the granodiorite bands, there is little doubt that the migration was easiest through these rocks. Differentiates released from the batholith were under great pressure. As few open fractures or other spaces existed at the margins of this parent granite, diffusion through permeable layers of the wall-rock was thus the only means of escape open to the differentiate. The granodiorite apparently offered these permeable layers. In some places the granodiorite has apparently been sheared near the margins of the giant pegmatites and it is possible that tight, concordant, shear zones in this rock may have served as channels for the migration of the pegmatitic fluids.

Much has been written regarding the ionic migrations and transfers that occur in granitization (37, 40, 41). It seems generally accepted that potash, soda, silica, alumina, and the volatile materials are mobile under granitizing conditions. Ramberg (37, p. 178), for example, stated that granitization is characterized by the mobility of sodium and potassium, by magnesium and iron metasomatism, and by transfer of aluminium. Hence, it appears that in granitization the alkalis and alumina, as well as the volatiles and mineralizers, are capable of migration by diffusion. It is probable that silicon, too, would be mobilized and transported in such migrating fluids. Ramberg (37, p. 201) concluded that the hypothesis of a flowing pore fluid as the carrier of these constituents is not convincing, and that the migration must be of an ionic nature. Hence, regardless of whether the pore fluid moved or whether it served only as the medium in which diffusion took place, an ionic diffusion of the pegmatitic differentiate, such as has been proposed here, is plausible under high rank metamorphic conditions.

Ramberg (37, p. 242) also pointed out that "it is likely now that granitization selectively attacks some layers and thereby creates conformable structures", and that (37, pp. 241, 242) "the metasomatic growth of a quartz-feldspathic body may create conformable as well as crosscutting relations to the adjacent host rocks depending upon the structural situation in which the fixation takes place". This concept is directly applicable in the Ross Lake area, where granodiorite provided the favourable horizons for migration and was selectively attacked. The migrating emanations were not in equilibrium with the granodiorite host rocks, and wholesale alterations resulted, culminating in conformable, metasomatic pegmatite emplacement near Redout Lake. Farther from the batholith, crosscutting pegmatites resulted as the remaining emanations were localized in fractures.

EMPLACEMENT AND CRYSTALLIZATION OF PEGMATITES

If emanations from the parent batholith occurred during an appreciable length of time, the system must have been an open one, due to continued renewal from the source. At any locus of pegmatite formation within the inner zone, new supplies of the migrating constituents must have been continually supplied, while earlier emanations, now impoverished in the already crystallized constituents, moved on. For this reason, the new formed minerals, stable near the source, were the same throughout the period of emplacement, and the resulting pegmatites are mineralogically homogeneous. The composition of the plagioclase in these pegmatites would thus also be homogeneous, a result not inconsistent with the concept of formation in an open system.

In the giant pegmatites, replacement began with the breakdown of the mafic minerals (hornblende and biotite) of the host rock. When these had reached the chlorite stage, additions of the alkalis, and especially of potash, began the actual transformation to pegmatite. The most striking feature of the dyke contacts is the gradual increase both in grain size and amount of potash feldspar from the walls inward. As replacement proceeded outward from the initial path of migration, crystals of potash feldspar began to grow in the host rock. As the alteration zone expanded, already formed crystals behind the 'front' increased in size, and small, new ones began to form in the wall-rock beyond them. This growth of crystals would readily take place if a fluid existed, even as a thin film around crystals, in the central parts of the growing body. That is, the same pore fluid in which the ionic transfer took place could have served to dissolve old minerals and precipitate new, coarse, pegmatitic crystals. Thus, it seems reasonable that a simple gradation in grain size may result in replacement pegmatites. Coarse crystals would be expected in the original migration channels and smaller crystals to either side.

As the emanations proceeded outward along the granodiorite layers, they entered areas of successively lower temperature and pressure more remote from the batholithic hearth. In these areas, they encountered cross fractures that offered new channels for migration. Where the fractures were tight, relatively close to the source, pegmatite formation probably occurred by replacement outward from the fracture walls. Dykes 170, 214, and 18 (*see* Figure 1), for example, are large, unzoned, homogeneous pegmatites that cut across gneissosity in the granodiorite. They resemble the giant replacement pegmatites in mineralogic homogeneity, but, like the fluid-emplaced bodies, are discordant to the layered country rock. They appear to be fracture controlled, replacement pegmatites.

Farther from the Redout Lake granite, in the intermediate zone, the remnants of the emanations drained into open fractures, and there the first fluid-emplaced pegmatites were formed. Marginal replacement may still, however, have been an important process. The mechanics of these emplacements were described by Ramberg (37, p. 252) as follows: "We have seen how a pegmatite can start to grow on a joint and expand as a replacement body from that joint. It is also possible that the pegmatite grows in a joint which either opens up freely or is pushed apart by the growing pegmatite because of its force of crystallization". Although the role of crystallization force in pushing apart fracture walls is open to controversy, the draining of constituents into dilatant fractures is widely accepted. In reference to the nature of the constituents entering the fractures, Ramberg said (37, p. 219) that "the minerals that concentrate in the cracks in the brittle rocks consist of Si, Na, K, and Al". He further implied (37, pp. 218, 219) that the draining into dilatant fractures need not be local but may be areal. These principals apply to the mode of emplacement of the pegmatites in the central parts of the Ross Lake area. They would follow naturally after the first step that caused the emplacement of the giant pegmatites by selective replacement.

Once the remnants of the pegmatitic emanations entered the fracture system, their westward migration continued. These fluids moved through the fracture system down the temperature-pressure gradient, and were finally emplaced as a pegmatitic magma in the western parts of the area.

Once the pegmatitic fluids had been trapped in fractures, crystallization and differentiation began. This process, operating in the manner described by Cameron *et al.* (8, pp. 104-105), yielded the zoned pegmatites that occur in the western half of the area. Plagioclase composition in samples of dykes studied in this region varies from An_{10} in early formed plagioclase at the walls to An_5 in late-formed plagioclase near the centre. This feature, in sharp contrast with that of the giant pegmatites, is in accordance with the concept of fluid crystallization in a restricted system as the origin of the body. The rare elements, whose concentrations were too low in the original emanations to form independent minerals in the early stages of the system, were also trapped in these fluids. As crystallization proceeded the rest-fluids were progressively enriched in these elements in a manner analogous to that classically described by Bowen

(4, pp. 118, 123, 109-111) and Daly (10, pp. 221-246) for igneous rocks. Finally, with increasing concentration and falling temperature the point was reached where crystallization of rare-element minerals occurred. It is significant that this took place at approximately the same stage of crystallization in all the pegmatites in which these minerals occur. This is shown by the remarkable persistence in the relationship of the rare-element minerals to internal structure. This feature strongly indicates a uniform composition in the final, pegmatite-forming fluids over the entire area. This, in turn, suggests that all the pegmatites were finally derived and emplaced at the same late stage in the development of the system.

At this point, it is pertinent to contrast the views presented above with those of Schaller (43; 44, p. 145). He maintained that simple homogeneous pegmatites resulted from crystallization of an early pegmatitic differentiate in an essentially closed system. He proposed that "complex" pegmatites, containing contrasting mineral assemblages, resulted from successive waves of replacement, acting in a later open system on the original, simple pegmatites. These views received wide acceptance, and were applied by many workers, including Derry (11), Gevers (18; 19), and Landes (31), to the problem of pegmatite origin.

Abundant evidence has come to light in recent years that indicates that such an origin for the complex, zoned pegmatites is true only to a very minor degree (8, pp. 98-106). The field evidence presented here further substantiates the recent view that zones in the complex pegmatites originate by fractional crystallization of a pegmatitic fluid in a semi-restricted system. Furthermore, the field relationships in the Ross-Redout Lakes area clearly indicate a replacement origin for the simple, homogeneous, unzoned pegmatites; and these bodies apparently formed at an early stage in an open system. Hence the origin of simple and complex pegmatites in the Ross Lake area is the exact opposite of that proposed for comparable types by Schaller.

REGIONAL VARIATION IN PLAGIOCLASE COMPOSITION

The regional variation in plagioclase composition could have resulted either from progressive crystallization and differentiation in the pegmatite-forming system or from metamorphic differentiation. Magmatists point out that plagioclase in dykes near the batholithic hearth formed early in the system at high temperature and pressure and was, therefore, relatively rich in anorthite. Fluid-emplaced pegmatites were, however, formed later and at lower temperatures and are, therefore, richer in albite. This sequence is in accord with Bowen's reaction series for crystallization of a silicate melt under falling temperature conditions.

It is felt, however, that metamorphic differentiation offers a more satisfying explanation, especially as many pegmatites in the area did not crystallize from a pegmatitic fluid. The giant pegmatites near Redout Lake as already described were formed by replacement through reorganization of the constituents of the wall-rocks. The additions of potash and volatiles caused mineral changes that displaced sodium, calcium, iron, and magnesium. Calcium was re-precipitated locally as a constituent of epidote, apatite, sphene. or tremolite, but the sodium was mobilized, entered the pegmatite forming fluids, and migrated westward. The fluids were thus enriched in sodium, but not in calcium, and later-formed plagioclase in the pegmatites was increasingly soda-rich.

RELATIONSHIP BETWEEN TYPES OF ZONATION

The hypothesis proposed here appears to account satisfactorily for all the features of the regional zonation. As Heinrich pointed out (25, p. 68), these features are not all independent variables. The progressive decrease in size westward was a simple result of progressive exhaustion of the emanations with outward migration. The zonal distribution of the rare-element minerals was also a function of distance from source. Their distance was determined by progressive changes in temperature and concentration and, as will be pointed out in the next chapter, the solubility and geochemical characteristics of the rare elements themselves. The regional variation in plagioclase composition likewise depended on distance from the source.

Structural control varied with the regional pressure across the area, from high in the east to low in the west. The structural control, in turn, governed the mode of emplacement. It resulted in replacement pegmatites in granodiorite in the east and fluid-emplaced pegmatites occupying open fractures in the west. The variation in attitude also depended on structural control. The shape of the pegmatite bodies was controlled jointly by existing structures and mode of emplacement, as both factors influenced the shape. Internal structure, however, was a complex, dependent variable governed indirectly by mode of emplacement and size, and will be considered in detail in the following chapter.

CHAPTER V

GENERAL DISCUSSION

RELATIONSHIPS BETWEEN COMPOSITION OF PEGMATITE AND WALL-ROCK

This investigation provides information that may be valuable when applied to certain long-standing problems of pegmatite origin. Among these is the ever recurrent hypothesis that pegmatites may be derived from the adjacent country rock by selective solution and redeposition of pegmatitic constituents in existing openings.

In the Ross Lake area, the well-documented regional zonation clearly shows that the Redout Lake granite was the source of the pegmatitic fluids. Thus it seems highly improbable that the pegmatites could have been derived entirely from local constituents. It is more likely that the pegmatites were derived on a regional scale from materials supplied by the Redout Lake granite or secured from the wall-rocks near the batholithic source. Pegmatite formation then occurred during and as a result of the migration of these materials. There is no compositional difference between pegmatite that is in contact with granodiorite and pegmatite that is in contact with amphibolite except in the rare instance cited where iron is derived from biotite-schist bands.

ORIGIN OF THE RARE ELEMENTS

The application of the proposed hypothesis to the rare elements deserves careful consideration. It is possible that pegmatite emplacement set up a thermo-chemical gradient that might have induced migration of rare elements from the wall-rocks into the pegmatite. The present investigation clearly shows that this has happened in the case of iron. It was suggested to the writer that the high migration energies of ions such as Cb^{+5} and Ta^{+5} and to a lesser degree of Be^{+2} and Li^{+} as well as the general refractory nature of their compounds, would not permit their migration for long distances. If so, the distance of these rare elements from the Redout Lake granite source, and their zonal distribution are difficult to explain. On the other hand, only restricted and localized mobilization and migration would be required if they were derived from the wall-rocks.

It is difficult to see why mobilization should have been easier under local conditions in the area being considered. The Redout Lake batholith, whether igneous or metamorphic, was a definite centre of thermal energy. It seems more difficult to propose that a smaller, late-differentiated satellite of that body could induce mobilization of the rare elements, than to accept the Redout Lake granite itself as the mobilizing agent. Moreover, the giant pegmatites in the eastern parts of the area are barren, whereas the smaller bodies to the west are rare-element-bearing. Yet surely the former, being larger, closer to the granitic source, and, therefore, at higher temperatures and pressures, would have set up a higher thermo-chemical gradient. Hence, we would expect greater rare-element concentration in these pegmatites than in the smaller, more remote bodies. Actually the reverse relationship was encountered. This brings us back to the original hypothesis proposed here, namely, that the rare elements were mobilized near or in the Redout Lake granite and were distributed by migration through the system, crystallizing only in the late-formed pegmatites.

In an attempt to determine whether the rare elements migrated locally from the wall-rocks into pegmatites, samples were collected at regular intervals along both granodiorite and amphibolite layers approaching dyke 113, a beryl-bearing pegmatite, from both sides. These samples were analysed spectrographically for Be, Cb, and Ta. The wall-rocks generally did not contain sufficient amounts of the rare elements to be detected by analytical methods that are sensitive to amounts of beryllium, columbium, and tantalum in excess of 0·001 per cent, 0·01 per cent, and 0·1 per cent respectively. Detectable concentrations were found in some samples close to, or at, the pegmatite contacts, or in wall-rock inclusions in the pegmatite. The investigations by Boyle (6), Chapman (9, pp. 701, 702), and Emmons *et al.* (15, pp. 91, 93) indicate that where constituents are mobilized in the wall-rock and drained into a vein the wall-rock is most impoverished in the mobilized constituents close to that vein. Hence, as the opposite relationship is true, it appears that the rare elements in dyke 113, which is in the western part of the area, were introduced with the pegmatite, and migrated outward from it into the wall-rocks.

There are abundant descriptions in the literature of how and why the rare elements, including beryllium, columbium, tantalum, and lithium, are concentrated in pegmatitic differentiates during crystallization of the granite source (38, pp. 172, 179, 424, 609; 39, p. 58; 47, p. 388).

Turner and Verhoogen (46, p. 330) concluded that concentration is due to differences in ionic radius, ionic charge, or some kinetic property, between the rare-element ions and ions of the common rock-forming elements.

Thus there seems to be no real reason why the rare elements could have been mobilized only on a local scale from the wall-rocks. The Redout Lake granite was the motivating force that caused pegmatite emplacement and surely it was capable of mobilizing and supplying the rare elements to the system. Once mobilized by this agent, their migration, distribution, and precipitation were governed only by the physical chemistry of the emanations.

GEOCHEMICAL ASPECTS OF THE ZONATION OF THE RARE-ELEMENT MINERALS

It is now interesting to consider the relationship between the zonal distribution of the rare elements and their minerals and the geochemistry of the rare elements. In order of their appearance outward from the batholithic hearth the following elements are encountered: beryllium, columbium and tantalum, and lithium. Columbium and tantalum appear together, as may be expected from the similarity between the two elements.

TABLE III

Some Ionic Properties of the Rare Elements

Ion	Charge	Ionic radius in kx units	Usual co-ordination
Be	2	0·34	4
Cb	5	0·69	6
Ta	5	0·68	6
Li	1	0·78	6 or 8

Table III summarizes the important properties of the ions of the rare elements. It is significant that the order of occurrence of these elements across the area agrees both with their co-ordination numbers and ionic sizes. According to Rankama (38, p. 170), who quoted Wickman (47, pp. 384-388), these two factors, co-ordination and size, are the most important in determining the migration energies of ions. It is known from crystal chemistry that ions of low co-ordination tend to crystallize early whereas those of high co-ordination are later. Likewise, Goldschmidt described (20, p. 660) how ions of larger size tend to be concentrated as crystallization differentiation proceeds, and hence are incorporated in late-formed minerals. Both these principles are in agreement with the order of occurrence of the rare elements in the Ross Lake area.

Shaw recently pointed out (45, p. 151) that ionic size alone does not govern the distribution of trace elements. He stressed the importance of the melting point of minerals involved. The discussion above does not take this factor into account nor does it consider the concentration of the rare elements in the emanations, which also would operate in determining their final distribution. Nevertheless, the agreement between order of occurrence, ionic size, and co-ordination of the elements and ions involved, illustrates that the zonal distribution of the rare-element minerals is in agreement with basic geochemical considerations.

Table II (in pocket), shows the results of spectrographic analyses of some of the common pegmatite minerals. These determinations reveal the distribution of trace amounts of the rare elements in the silicate minerals. Albite (cleavelandite) from both border and wall zones contains appreciable amounts of beryllium, which probably substitutes for silicon in the albite structure. Lithium was trapped in the structure of later potash feldspars in both wall zone and core. Columbium and tantalum were detected only in lithiophyllite and spodumene, both relatively late lithium minerals. Quartz from the pegmatite cores is apparently barren of these rare elements, although it contains a number of others in trace amounts. Replacement muscovite (*see* Plate VIII), which formed after all the above minerals, contains concentrations of tantalum but no detectable columbium.

It was pointed out that no separation of columbium and tantalum took place on a regional scale, yet within single pegmatites a definite segregation did occur. Columbium-rich columbite developed early and crystallized with the initial zones, whereas tantalum-rich tapiolite formed afterwards and crystallized with the later replacement bodies[1]. Evidence of this feature may be found in Table II, which shows that tantalum was more abundant than columbium in the late lithium minerals and, to an even greater degree, in still later replacement mica. The relationship is typical of many pegmatites in other districts where columbite is early and occurs in outer zones, whereas tantalite is late and is related to inner zones or replacement bodies (8, pp. 69, 99). The chemistry of this separation of columbium and tantalum is not known, although Rankama (38, p. 604) mentioned the feature. It is possible that relative concentrations of the two elements are the controlling factors. Columbium is generally more abundant than tantalum (38, p. 607), and, as the geochemistry of the two elements is so similar, columbium compounds would be first to exceed their solubility products. Columbite would, therefore, crystallize early whereas tantalum-rich members would be later. If true, this argument would be in accordance with the hypothesis of crystallization in a restricted system for the origin of zoned pegmatites.

Another interesting feature of the columbium-tantalum minerals in these pegmatites is the change from orthorhombic columbite to tetragonal tapiolite that occurred during crystallization. It may be that with increasing tantalum content in the orthorhombic columbite-tantalite series, a change to tetragonal symmetry takes place. If so, only a single series exists, and this is not isomorphous in the strict sense of the term. The extreme scarcity of mossite (36, pp. 776, 777), which was originally named by Brogger (5), lends support to this supposition. The cause of the dimorphic relationship in the tantalum-rich range is unknown. These features are described in more detail in a paper now in press that will appear in the American Mineralogist (27).

THE DEVELOPMENT OF INTERNAL STRUCTURE

Many aspects of the origin of internal structure in pegmatites are, as yet, imperfectly understood. One of the most puzzling is the problem of what factor or factors lead to the development of contrasting mineral assemblages. The basic mechanism of progressive crystallization and differentiation is widely accepted, but, as Heinrich (25, p. 81) pointed out, it is not known why, in a single district, some pegmatites develop zones whereas others of the same general shape and bulk composition do not. Certain features encountered in this investigation suggest a solution to the problem, at least for the area studied.

Even in the western parts of the Ross Lake area, small pegmatites tend to be better zoned than large ones. Narrow offshoots and branches of large bodies are more perfectly zoned than the main masses themselves, and dykes 300 and 180 (*see* Figures 5 and 3) illustrate this feature. Dyke 97 (*see* Figure 8) is the best zoned pegmatite in the area, but dyke 96, a larger dyke only 40 feet from it, is unzoned. In these cases, it is diffi-

[1]Thin, platy crystals of columbite-tantalite from the outer zones have not been analysed, but, judging from their extreme platy habit, they are probably columbium-rich. One sample No. 28 of tapiolite was analysed and proved to be tantalum-rich with a Ta:Cb ratio of 8.1:1.

cult to attribute differences in internal structure to variations in original pegmatite composition, in depth of erosion, in metamorphic rank or composition of wall-rock, or even to mode of emplacement. The development of internal structure in the Ross Lake area would, therefore, appear to be directly related to size. It has, however, been well established in other districts that size is not a controlling, or even important, factor in governing the development of internal structure (25, pp. 79, 82) and some other explanation must be sought.

It is suggested that an important factor is the degree of restriction of the pegmatite-forming system. In the Ross Lake area, small, well-zoned pegmatites were emplaced in blind or disconnected openings where quiescent conditions prevailed during crystallization. Additions to, and subtractions from, the system were limited, and the course of crystallization differentiation was uninterrupted. This led to well-developed internal structure. On the other hand, the giant pegmatites and also the larger fluid-emplaced bodies were main channels for the migration of the pegmatitic fluids. They were parts of a semi-continuous, open system to which continued renewals of the original emanations were supplied. This upset the course of crystallization differentiation because the differentiates were continually pushed on. Even where the necessary chambers occupied by liquid were present, the development of internal structure was thereby inhibited.

Fersman (16, p. 200) also stressed the importance of a closed system in developing mineralogically complex pegmatites. It is felt that the degree of restriction of the system offers a good explanation for local variations in internal structure. It operates in conjunction with the basic mechanism of crystallization differentiation to control internal structure. In the Ross Lake area, it happens that the smaller pegmatites formed in highly restricted systems and are, therefore, well zoned. This need not be, and is not the case in many other areas, because large pegmatites also may be sealed up after their injection into schistose wall-rocks and then would crystallize in restricted systems. This may explain the common occurrence of large, zoned pegmatites in schistose rocks of rather high metamorphic rank (19, p. 138; 8, pp. 41, 47, 50, 53, 55).

ORIGIN OF BORDER ZONES

Still another problem relating to internal structure is the origin of border zones in pegmatites. The border zone was defined by Cameron *et al.* (8, pp. 20-30) simply as the outermost zone of a pegmatite, and a discussion of typical examples was presented (8, pp. 24-30). There is no doubt that in the Ross Lake area border zones of essentially the same composition and texture have originated in two ways. The simplest are true, chilled margins only a few inches wide, and are present persistently along the pegmatite contacts. They have a sharp and distinct contact with the wall-rocks and on many weathered outcrops this opens up to form a narrow fissure. The second type of border zone apparently originated by reaction between wall-rock and emplaced pegmatitic fluid at the contacts. For example, the granodiorite wall-rock may be replaced to form the border zone of some pegmatites. It develops only in granodiorite wall-rock for where the pegmatite is in contact with amphibolite the chilled type of border zone is found. The replacement border zones are generally more irregular and broader than the chilled type, and they have gradational contacts with granodiorite. In many dykes they are most extensive along the foot-wall contacts with wall-rock or around wall-rock inclusions (*see* Figure 4, dyke 205). The broad border zones are commonly banded (*see* Table I, in pocket; Plates V B, VI A, and Figure 5) parallel with their walls and show coarse pegmatitic and fine aplitic layers. These coarse and fine layers are muscovite-rich and muscovite-poor respectively, and their origin is a problem. Derry (11, pp. 455, 469) described compound, banded aplite and pegmatite bodies and attributed the banding to a process of "squeezing" during emplacement. This mechanism does not seem applicable in the Ross Lake area where the banded border zones apparently originated by replacement of country rock at the contacts of fluid-emplaced pegmatites. The fact that the coarse layers are muscovite-rich and the fine layers muscovite-poor suggests a difference in water content and this would also explain the coarse- and fine-grained textures. Whether progressing crystallization accompanied by successive renewals of pegmatitic fluids could cause such a cyclical variation in water content and result in the banded border zones by marginal replacement is not known. In places the banded border zones have the appearance of diffusion banding, and this may be another possible explanation. No other satisfactory means of origin can be advanced by the writer.

ORIGIN OF LATE REPLACEMENT BODIES

Another problem is the origin of the late pegmatites that replace primary pegmatite. In the Ross Lake area, replacement bodies of this type represent only a small fraction of the pegmatitic material present. As Cameron *et al.* (8, p. 106) pointed out, "it seems reasonable to regard the bodies as the work of the final residua of consolidation of the pegmatites in which they are found". Landes (31, p. 55) also favoured this viewpoint. At Ross Lake the replacement bodies are composed predominantly of muscovite and albite with minor tapiolite, and the mica is apparently soda-rich (*see* Table II.) It is probable that the components of these minerals were contained in the final residua of crystallization. The sodium may be derived in part from the unmixing of earlier-formed perthite. Microscopic examination of some perthites indicates that as unmixing took place sodium was, at least locally, mobilized and moved out of the host perthite crystal to form albite. This mechanism may also account for the general abundance of albite (cleavelandite) in replacement bodies in other pegmatite districts (8, pp. 86-87).

ORIGIN OF THE SPODUMENE-BEARING PEGMATITES

Figure 1 shows that there is an area in which pegmatites do not occur, between the beryl-columbite-tapiolite pegmatites and the spodumene pegmatites near Ross Lake. The presence of this barren area, which interrupts the otherwise complete gradation westward, raises some doubt as to whether the spodumene-bearing dykes are part of the regional zonation or are related to a different, unexposed intrusive mass. There is no field evidence to support the latter hypothesis, but it remains a possibility. However, the spodumene-bearing pegmatites fit the zonal sequence well in all other respects, including the distribution of rare elements and the regional variation in plagioclase composition. Hanley (24) reported a similar relationship in the Poland quadrangle in Maine, where pegmatites with lithium minerals are farther from the granite contact than the potash feldspar-beryl pegmatites. In view of these features, the spodumene pegmatites are considered to be a part of the regional zonation and, therefore, to be genetically related to the Redout Lake granite.

INTERIOR PEGMATITES

On Figure 1 it can be seen that along the margins of the Redout Lake granite pegmatites are generally smaller than the giant pegmatites slightly farther west. Because of their gradational nature the contacts of the Redout Lake granite were extremely difficult to locate exactly, and many of these smaller marginal pegmatites lie in the gradational contact zone. They may, therefore, be equivalent to the 'interior pegmatites' of Gevers (18, p. 339; 19, p. 138), which are typically small and lie within the source granite itself. In the Ross Lake area these smaller pegmatites are few, and do not seem to be a part of the regional zonation. Their origin is imperfectly understood and this study has little to offer in solving the problem. It is suggested, however, that they may be the result of a separate process operating within the source granite. Perhaps they are local differentiated pockets that were not tapped and formed pegmatite bodies in situ. Gevers suggested a similar late internal origin for his interior zone pegmatites.

CHAPTER VI

SUMMARY AND CONCLUSIONS

In the Ross Lake area, a systematic variation in the nature of pegmatite bodies occurs with increasing distance from the Redout Lake granite mass. The resulting regional zonation of the pegmatites is illustrated by systematic changes in size, shape, attitude, structural control, mode of emplacement, development of internal structure, distribution of rare-element minerals, wall-rock alteration, and plagioclase composition. It is postulated that all the pegmatites in the area were derived directly or indirectly from the Redout Lake granite, which supplied the original pegmatitic differentiates. These were withdrawn from the source and migrated outward down a temperature-pressure gradient. That gradient was responsible, directly or indirectly, for the progressive changes in the nature of the resulting pegmatite bodies.

A hypothesis is advanced to explain the changes in the physical features of the pegmatites in the light of the system outlined above. The variables are not independent, nor are they simply related to distance from the batholithic hearth. Rather they are inter-related and integrated factors and must be considered as such in understanding the regional zonation. The following conclusions are pertinent, and may be of value in the future study of pegmatites in this and other areas.

(1) The pegmatites are spatially zoned around, and genetically related to, the Redout Lake granite.

(2) Lithium-bearing pegmatites are found farther from the batholithic hearth than columbium-tantalum bearing bodies, and these are, in turn, farther from the batholith than beryllium-rich pegmatites.

(3) Pegmatites have originated in the area both by replacement of country rock and by crystallization of pegmatitic fluid. The origin of each pegmatite body must be determined from close examination of all its field relationships. Generalizations taken from one pegmatite and applied to others will be misleading and commonly erroneous.

(4) In the Ross Lake area replacement pegmatites are simple and homogeneous, whereas fluid-crystallized pegmatites are complex with contrasting mineral assemblages. The former are barren of rare-element minerals; the latter may contain them.

(5) Development of internal structure appears to depend on the degree of restriction of the system in which the pegmatites formed.

(6) Pegmatite border zones originate in at least two ways in the area. Both chilled margin and replacement types have been recognized.

(7) Late replacement bodies are believed to originate within the pegmatite itself as final differentiates. Soda-rich contributions to these final fluids may be made through the unmixing of perthite.

(8) It is extremely unlikely that concentrations of the rare-element minerals will be found in pegmatites lying within 1 mile of the Redout Lake granite.

(9) Pegmatites with well-developed internal structure are most likely to contain concentrations.

(10) Concentrations of beryl and columbite will most probably be found in pegmatites containing well-developed zones of quartz-perthite.

(11) Tapiolite is the most abundant mineral of columbium-tantalum present in the area and more abundant than columbite. It occurs in pegmatites contajning the late muscovite-albite replacement bodies.

PLATE I

A. Boudinage structure in pegmatite, dyke 48.

PLATE I

B. Partly rounded and replaced inclusion of granodiorite in pegmatite, dyke 214.

A. Drag of gneissosity against pegmatite contact, dyke 16.

B. Angular amphibolite inclusions matching re-entrants in wall, dyke 177.

A. Matching vein walls and unenlarged intersections, north end of dyke 180.

B. Angular, unenlarged vein intersection, with granodiorite inclusion in pegmatite, dyke 322.

PLATE IV

A. Sharp contact between pegmatite and granodiorite, dyke 60.

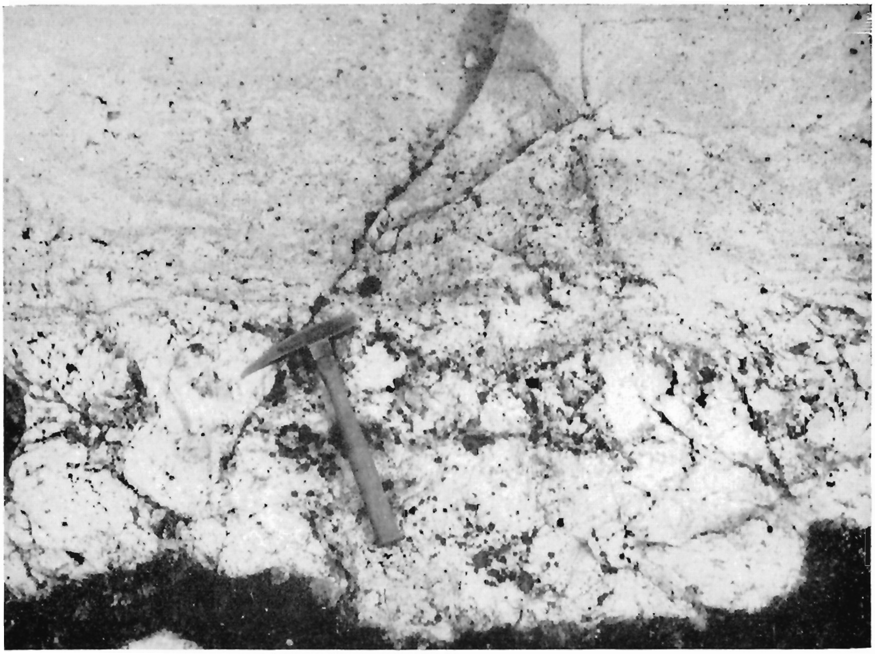
PLATE IV

B. Quarry face showing dip of pegmatite body and sharp, matching walls, dyke 84.

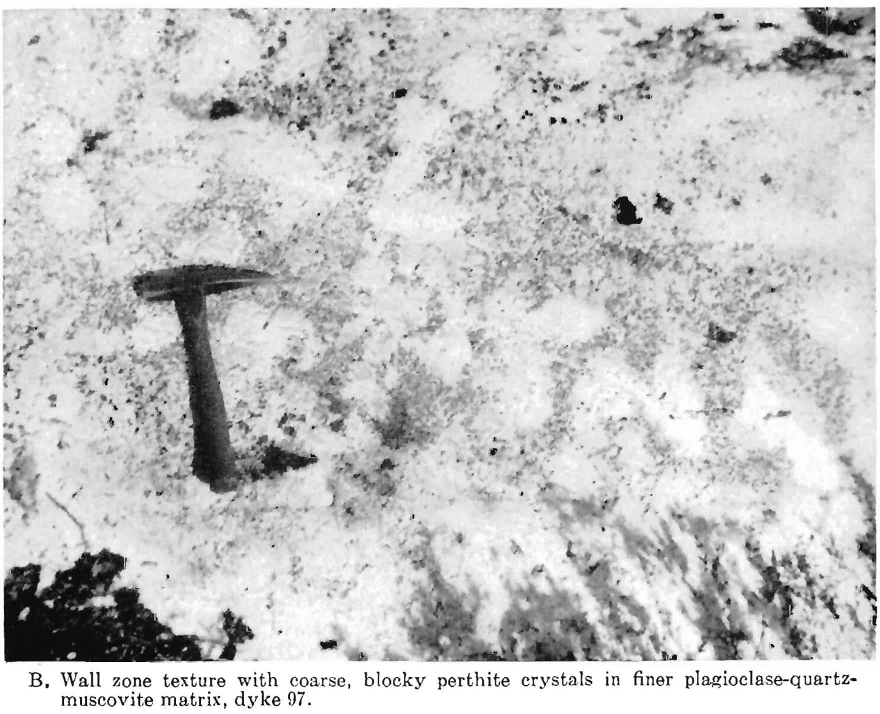
A. Sharp contact between sheared amphibolite and pegmatite, dyke 304.

B. Long, sinuous pegmatite dyke with fine, banded border zone, dyke 179.

PLATE VI

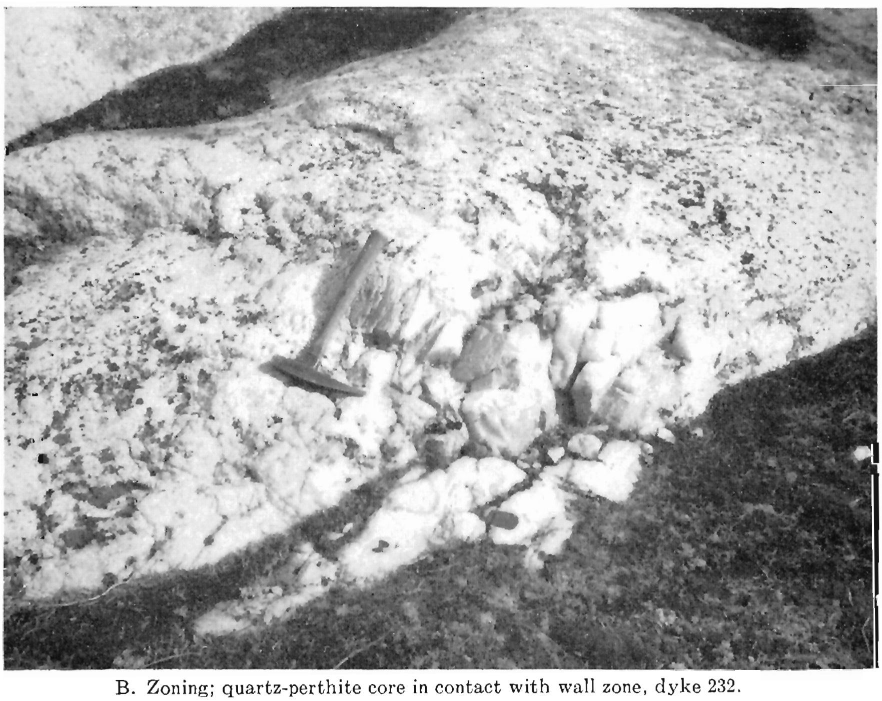


A. Banded border zone with alternate aplitic and pegmatitic layers (above hammer head), dyke 178.



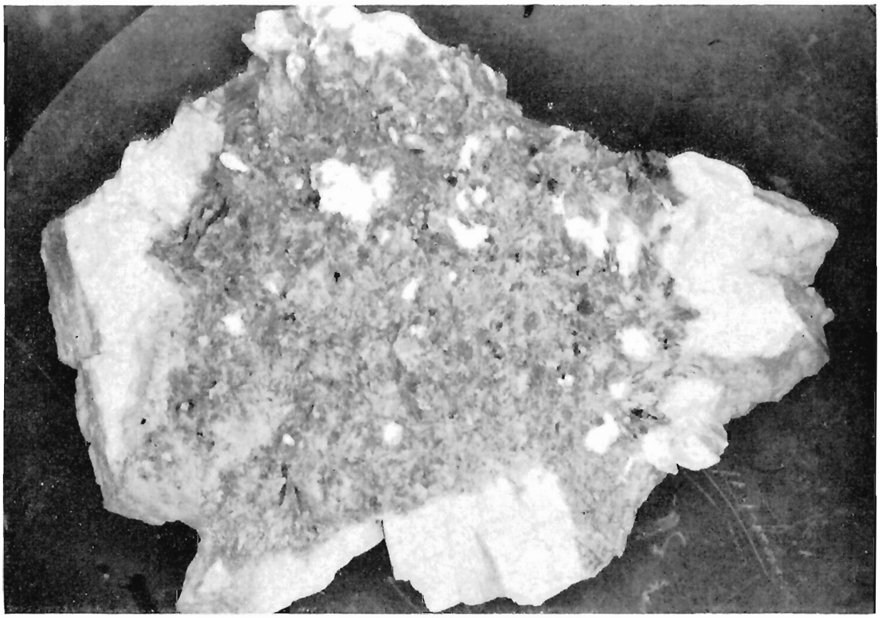
B. Wall zone texture with coarse, blocky perthite crystals in finer plagioclase-quartz-muscovite matrix, dyke 97.

A. Zoning; quartz-perthite core under hammer, wall zone around core, narrow muscovite and beryl-rich layer at core margin, dyke 97.



B. Zoning; quartz-perthite core in contact with wall zone, dyke 232.

PLATE VIII



Late muscovite replacing quartz (extreme top and top left) and perthite along zone contact; hand specimen from dyke 84.