MICA DEPOSITS OF CANADA

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MICA DEPOSITS OF CANADA

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PREFACE

Mica has been produced in Canada for many years. This country was once the world's leading producer of phlogopite mica, and mining for muscovite mica was particularly important during World War II. At present mica is not being mined extensively in Canada, chiefly because of cheap production in other countries.

A few years ago the author of this report undertook on a part-time basis a comprehensive study of mica deposits of Canada, with particular emphasis on their geology. The principal deposits were examined and other data was compiled from various sources. This report will be particularly useful in the event of increased demand for Canadian mica, and will also assist prospectors and companies who contemplate searching for or developing exceptional deposits that might be competitive under present conditions. Considerable information on foreign deposits is included because it might assist in searching for similar occurrences in Canada. A separate chapter is devoted to vermiculite, an insulation material which is closely related to mica.

J. M. HARRISON,
Director, Geological Survey of Canada.

Ottawa, July, 1958.

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AUTHOR'S PREFACE

In writing a technical report to be read by persons with widely differing technical backgrounds it is difficult to decide where to draw the line regarding the amount of technical information to be included. This is especially true in this report because the commercial value of the minerals under discussion depends, to a great extent, on their physical properties, which, in turn, are directly related to their atomic structure. Thus in order to understand why some of them are valuable while others are not, it is necessary to have an understanding of the basic atomic structure. Therefore, at the risk of being considered too technical, the writer has endeavoured to present this information in condensed form, to relate it to the physical properties, and thus to the commercial value of the minerals under discussion. It is hoped that this will give the reader a much clearer understanding of the mica-group minerals than a purely factual account of their physical properties.

Chapter I

COMMERCIAL SHEET MICA

The outstanding physical characteristic of the minerals of the mica group is their almost perfect basal cleavage. Theoretically a crystal of mica can be split or cleaved into films about one millionth of a millimeter thick (10Å), the thickness being determined by the distance between successive layers of cations (*see* Figure 9, p. 24). In actual practice the thinnest films obtainable are about 1/1000 inch (1 mil) thick. The laminae obtained from crystals containing no imperfections or impurities, are tough, flexible, elastic, and extremely low in electric and heat conductivity. These physical properties are therefore the basis upon which the commercial value is dependent. The actual value of any particular specimen is, however, governed by a very great number of variables, which will be discussed later in this chapter.

Of the several species of true micas, the most important is muscovite or potassium mica, whereas phlogopite, which contains magnesium, and biotite which contains iron and magnesium, are of lesser importance. Lepidolite, and lithium mica and zinnwaldite, a lithium-iron mica, are sometimes of value for their lithium content.

Commercial deposits of muscovite, phlogopite, and biotite are known to be present in Canada. Of these the muscovite deposits are the most important due to the increased demand for strategic quality muscovite. Overall demand for phlogopite is much less, and Canadian producers are unable to compete with Madagascar. Although Canada has at least one deposit capable of producing excellent quality, large-size sheet biotite, the demand is so low that operation is uneconomic. The only known deposit of lepidolite of possible commercial significance is located in Manitoba. However, as yet, it has not been exploited.

Physical Features

Morphology

The minerals of the mica group crystallize in the monoclinic system, but possess pseudohexagonal symmetry (*see* Chapter II, Atomic Structure). Most commercial mica occurs in rough crystals or 'books', some of which are partly or completely bounded by poorly developed faces. However, in some cases the faces are smooth and well developed. Most of the crystals are tabular with the shortest dimension perpendicular to the cleavage, but a few are elongated in this direction, and are usually tapered and often distorted by slippage along cleavage planes. Such books are termed step crystals. Most well-developed crystals are hexagonal or rhombohedral in outline, with six or more faces. The simplest forms comprise basal, prismatic and clinopinacoidal faces, but modifying faces are common. As observed on a cleavage surface or basal face of a crystal, the traces of the prismatic and clinopinacoidal faces meet at angles of almost exactly 120 degrees. Twinning is common chiefly with crystals united along the base or along irregular surfaces nearly perpendicular to the base.

Percussion and Pressure Figures

The symmetry of muscovite crystals, or for that matter of a crystal of any of the true micas is clearly shown by percussion figures. If a cleavage plate of sheet mica is struck sharply by a blunt punch or large needle with a dulled point, a partial six-rayed pattern of cracks is developed. Individual rays of this percussion figure extend outward from the point of impact, and their orientation is constant regardless of where the mica plate is struck (Figure 1). Two of the cracks, generally deeper and longer than the other four intersect the cleavage surface to form a single line parallel to the trace of the clinopinacoidal face. The others form two lines that meet at angles ranging from less than 53 degrees to nearly 65 degrees and are nearly parallel to the trace of the prismatic faces.

A second type of figure can be developed by firmly pressing a dulled point against a piece of mica, especially if the mica rests on a flat, but elastic surface. Like the percussion figure, this pressure figure is six-rayed wherever complete, but only two or three rays are commonly developed. Some pressure figures are formed simultaneously with percussion figures and the two have common centres. One set of cracks is perpendicular to the trace of the pinacoidal face and hence perpendicular to the principal direction of the percussion figure (Figure 1). The others are perpendicular to the prism faces and therefore do not bisect the angles between the rays of the percussion figure. The cracks of the pressure figure coincide with distinct glide or parting planes in the crystal and meet the cleavage plane at an angle of about 67 degrees. Both percussion and pressure figures are very useful in determining the crystallographic orientation of the mica books where no faces are present.

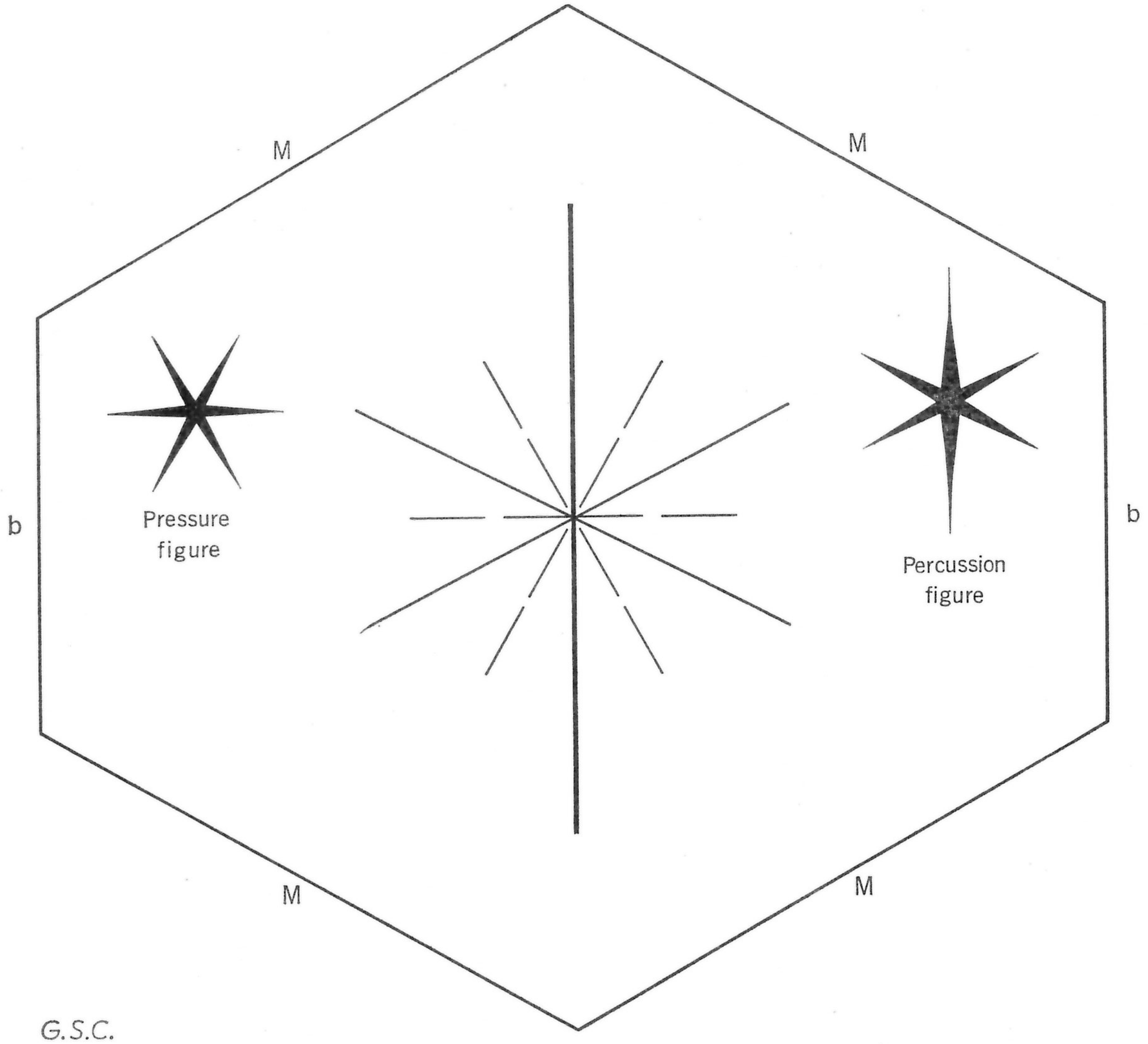

Figure 1. Pressure and percussion figures in muscovite, showing orientation with respect to the prismatic (M) and clinopinacoidal (b) faces. (From Jahns and Lancaster, 1950)

Colour, Lustre, and Hardness

Muscovite is transparent, and nearly colourless in thin sheets, but most thick plates are opaque, and usually distinctly coloured in shades of green, brown, yellow, and pink. Phlogopite is yellow, golden brown, dark brown, or black. Much of it has a coppery to silvery translucent appearance, and in general is less transparent than muscovite. Biotite is commonly black, but sometimes green; thin laminae may be green, blood-red, or pale yellow by transmitted light. Freshly cleaved fragments of mica have a hard, brilliant to pearly lustre in contrast to the rough appearance of most books. Hardness varies considerably within any one species: of the three common types, muscovite is the softest, varying from 2 to 2.5; phlogopite next with 2.78 to 2.85; and biotite hardest, 2.5 to 3.0. In general the hardest books are the least flexible and the most difficult to split.

Intergrowths and Inclusions

In many deposits intergrowths of biotite in muscovite are common. In such cases the biotite is seldom euhedral in outline, but the cleavage planes of the two micas are generally parallel. In some instances well-crystallized inclusions of muscovite occur in books of biotite. Inclusions of magnetite, hematite, and goethite occur in muscovite and phlogopite in some deposits, commonly as lattice-like crystals or crystal aggregates that are distributed in accordance with the crystal directions of the host mineral. Such inclusions are so abundant in some books that thin laminae are opaque or nearly so. Apatite, quartz, garnet, zircon, tourmaline and many other minerals occur as inclusions within or between laminae in muscovite. Apatite and calcite are the most common inclusions in phlogopite.

Properties Affecting Value

Jahns and Lancaster (1950, pp. 7-16) give an excellent detailed description of the various properties of muscovite that affect its value. The value of phlogopite is, to a large extent, governed by the same properties so that what is true for muscovite is likewise true for phlogopite. The following is a brief condensation of the material in this work.

The commercial value of mica (muscovite and phlogopite) is largely dependent upon (1) its perfect basal cleavage, permitting splitting into thin laminae, (2) the hardness, flexibility, and elasticity of the laminae so produced, (3) the very low electric and heat conductivity of the laminae, and (4) to some extent, upon colour. The possession or absence of these desirable properties is affected by many factors. Some are physical whereas others are chemical. They are described in the following sections.

Cleavage

Films or cleavage plates that are uniform in thickness, and have flat or nearly flat surfaces are commercially the most desirable. Their value increases with their size, and the rate of increase is greatest in the large sizes. Book mica that yields such films is said to be free splitting. However, much mica does not split uniformly, but tears into irregular, partial films. Such material may split easily and evenly in some places, but very imperfectly in others. This is known in the trade by a variety of names which vary among different countries. In the United States and Canada it is termed 'locky', 'gummy', 'tangled', 'tangle sheet', or 'tacky'. The designation 'tangle sheet' is also applied to coarse aggregates of irregularly intergrown books of 'bull' mica.

Discontinuity of cleavage and resultant 'lockyness' is generally caused by partial intergrowth of books or of laminae of a single book; by internal distortion of a book, probably during crystallization; by finely divided inclusions; or rarely, by twinning with composition planes nearly normal to the base. Many 'locky' books do not differ in outward appearance from those that split freely and evenly.

The hardest varieties of muscovite are usually more difficult to split than the softer varieties, but numerous exceptions are known. Disseminated flakes, shreds, and very thin plates of biotite and chlorite appear to be the cause of 'lockyness' in some muscovite, especially the hard brown, brownish olive, or buff micas. Prismatic crystals of silicate minerals, such as quartz, apatite, etc. effectively 'tie' or 'nail' the laminae together thus impairing cleavage. Inclusions of smaller, differently oriented crystals of mica in the larger host crystal produce a similar result. In rare cases all the books in one deposit, or in one shoot of a particular deposit may exhibit multiple crystallization. In such cases, the inner and outer crystals usually have parallel cleavage planes and similar crystallographic orientation, but the line of contact forms a crystal imperfection often marked by a concentration of inclusions such as garnet, thus impairing cleavage.

Hardness, Flexibility, and Elasticity

The hardness of mica varies from one deposit to another, less commonly from one book to another, and in some instances within a single book. In general, pink and brown varieties of muscovite are harder than green muscovite. Other factors being equal, the hardest varieties are the least flexible, and consequently are among the most difficult to split. Pieces of very hard mica sound like glass when shaken together. Flexibility and elasticity are important properties of sheet mica since most commercial specifications require that a sheet of mica .005 inch (5 mils) thick must return promptly to its normal planner state after being rolled around an ordinary lead pencil and then released. Flexibility and elasticity are most seriously impaired by physical imperfections, such as holes, cracks, and other structural defects. Most of these are easily detected but some extremely fine cracks known as 'hair cracks' are difficult to detect.

Structural Imperfections

While perfection of cleavage is of fundamental importance in determining the usefulness of sheet mica, the size and flatness of the sheets obtainable from mica books is limited by a number of structural imperfections. Chief among these are 'reeves', 'wedging', 'warping', and 'ruling'.

Reeves—Jahns and Lancaster (1950, p. 8) describe reeves as "lines, striations, shallow corrugations, or small narrow folds that lie in the plane of the cleavage. . . . Some reeves are simple, closely spaced flexures or crenula-

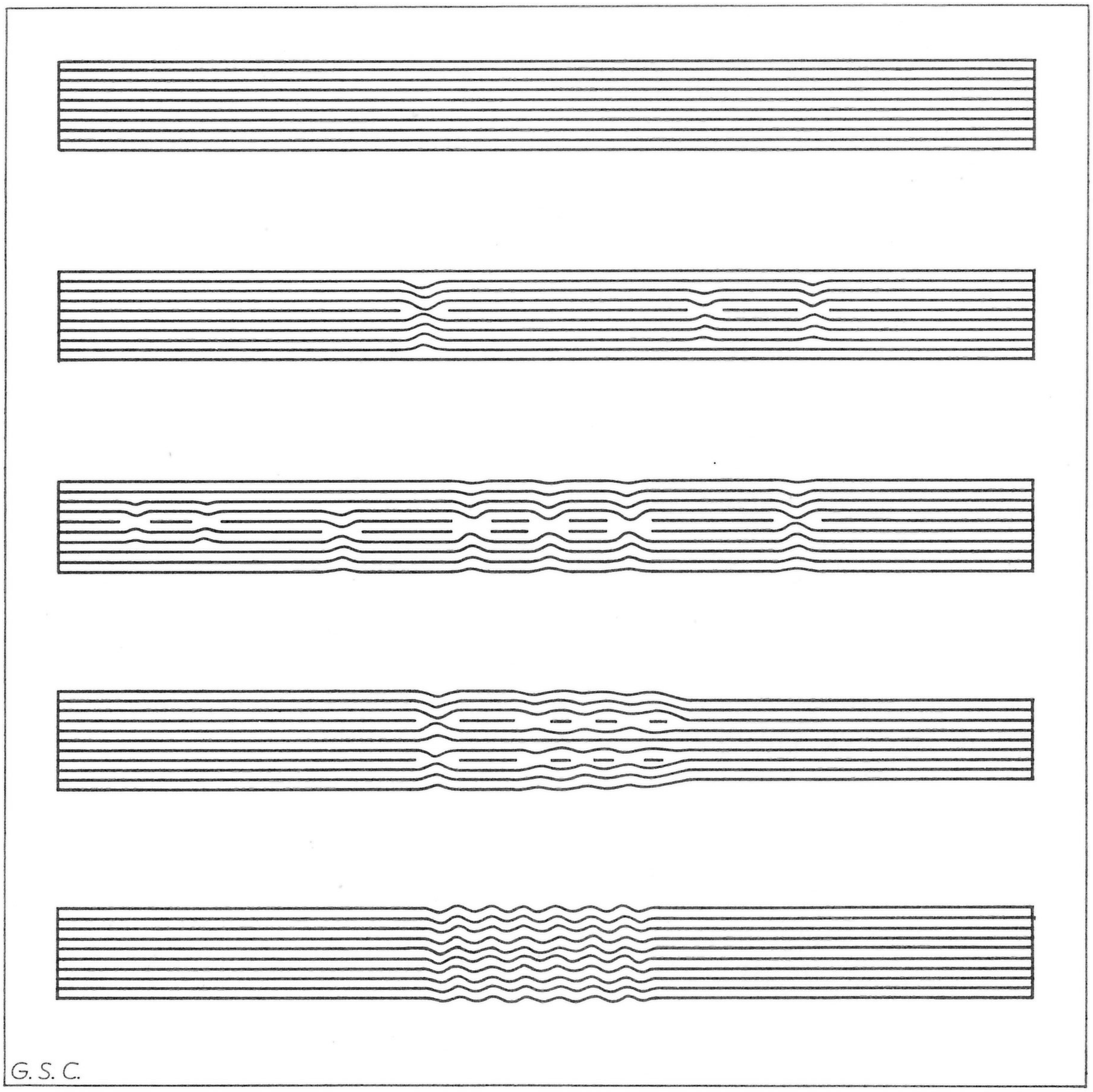

Figure 2. Diagrammatic sections, showing the relation of distribution and depth of reeves to crenulations and discontinuities in muscovite laminae. (From Jahns and Lancaster, 1950)

tions, presumably caused by stress during or after crystallization of the mica. Others, however, are formed by discontinuities in incomplete sheets or laminae". (*See* Figure 2.)

Reeves are oriented perpendicular to the trace of the prismatic and clinopinacoidal faces of the mica crystals and hence are parallel to the rays of the percussion figure. Where two or more are present, they intersect at angles of about 60 degrees. Orientation of reeves with respect to percussion figures is shown in Figure 3 which also shows typical development of 'A' reeves. Much good quality mica can often be obtained from such flat 'A' books. Much 'A' mica, however, is so seriously marred that it must be classed as scrap.

'Herringbone' or 'feather' mica is marked by three sets of reeves, two meeting at 120 degrees flanking a third central line or strip to form a pattern resembling that of a feather or the skeleton of a fish (*see* Figure 3). Books marked by 'herringbone' or a combination of 'herringbone' and 'A' structure seldom contain flat material and hence are processed for scrap only.

Wedge Structure—Wedge structure is caused by the interlayering of tapering laminae or of laminae of unequal sizes. Where such laminae taper from all edges toward the centre, the outward form of the crystal or book may be regular, but due to the complex internal structure it may not yield any sheet mica. Other books may be thick on one side and thin on the other. Wedging is common in 'A' and 'herringbone' mica.

Warping—Much mica is commonly marked by shallow waves or ripples, which are apparently the result of deformation after crystallization. The degree of warping varies considerably from mere shallow, widely spaced waves to sharp buckles or warps (Figure 4). Books that are only slightly waved or waved in only one part, frequently yield good sheet material, whereas those that are highly warped are only good for scrap.

Ruling—Jahns and Lancaster (1950, p. 10) describe ruling as "regular, sharply defined parting planes that intersect the basal cleavage plane at an angle of nearly 67 degrees. They are parallel to the pressure figure. Only one set of these parting planes is present in many books, but two or all three sets occur in others. Their traces on cleavage surfaces intersect at angles of about 60 degrees, and where all three sets are present they commonly separate the sheets into triangular or hexagonal fragments. Many sheets ruled in two directions are similarly separated into rhombic or diamond-shaped fragments or into strips or laths.

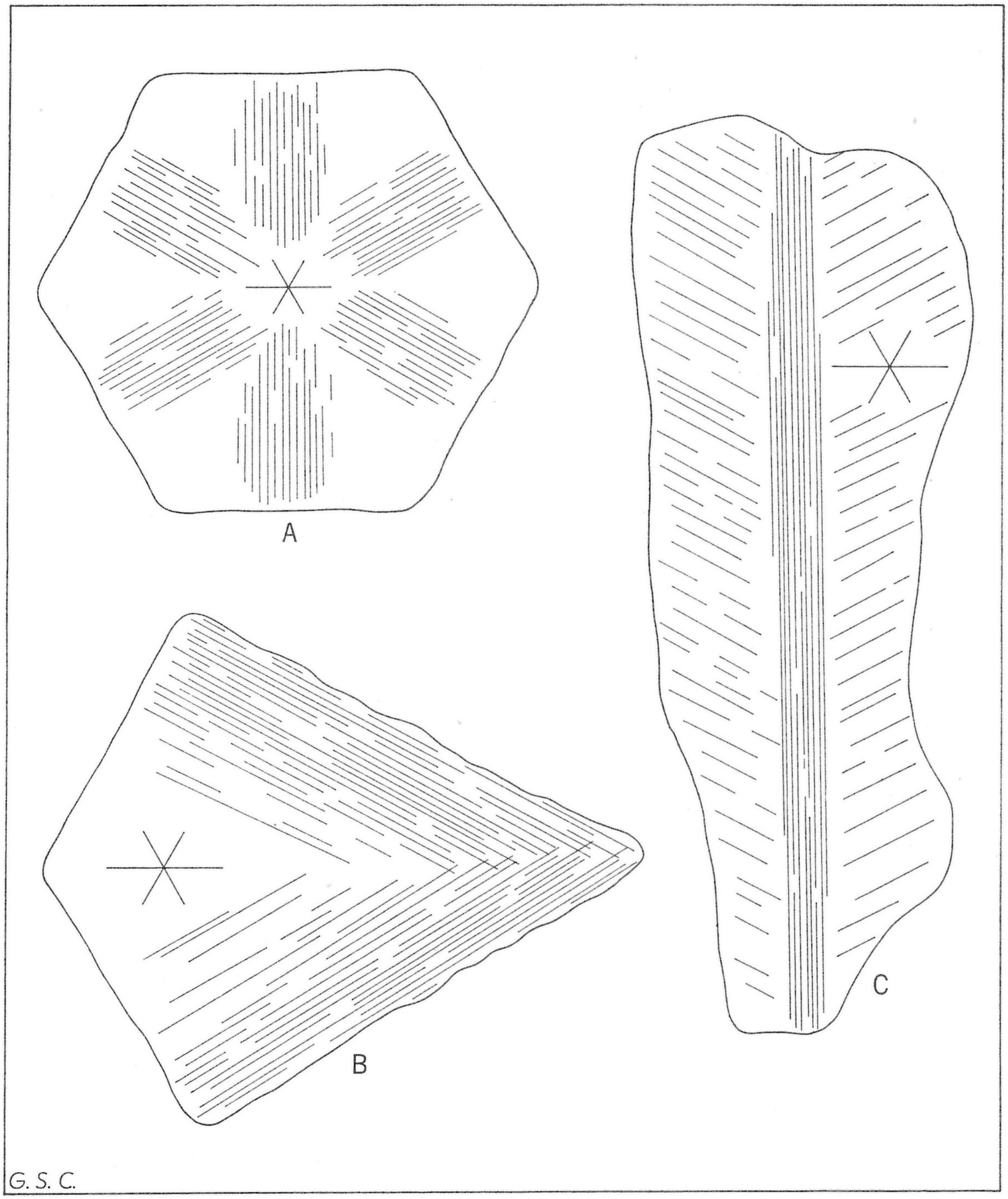

Figure 3. Relation of reeves to crystal directions in muscovite. Orientations are shown by percussion figures. A. Complete directional development of "A" reeves in crystal; B. Typical development of "A" reeves; C. Typical herringbone reeves. (From Jahns and Lancaster, 1950)

"The structure generally continues through the entire thickness of severely ruled books, but in others it is confined to certain layers in which it may extend partly or entirely across the cleavage faces. Where one set of ruling planes is well developed, the mica is thereby separated into strips or ribbons that commonly are less than an inch wide. The ruling in some mica is so closely spaced that individual ribbons are sliverlike or hairlike. Accumulations of such slivers are termed 'hair mica'. Ribbons in some large books, on the other hand, are as much as 4 or 5 inches wide and hence yield satisfactory sheets if free from other defects. Ruling appears in much 'A' and herringbone mica, where it either coincides in direction with the striations and corrugations or forms the cross bar of the 'A'. It is more common, however, in unreeved books, where its distribution is of prime importance in determining the sizes of sheets that can be trimmed out.

"Ruling, warping, buckling, and rippling (Figure 4) are most intense in books that occur near faults or slip joints and plainly are the result of distortion from post crystallization movements. Both percussion figures and ruling are strongly developed in some books that lie near blast holes, where they appear to have been formed by the shock of the blasting. Such ruling generally occurs in small hexagonal or rhombic patterns."

Colour

The general colour features of mica have been described in the foregoing under Physical Features. For more details the reader is referred to Jahns and Lancaster (1950, p. 11).

Colour has had an effect on the merchantability of mica since the days when its chief use depended upon transparency. Thus the lighter browns and greens were more desirable than the darker colours. This applied especially to muscovite, but also, to a lesser extent, to phlogopite. The most valuable type of muscovite was, and still is, ruby mica produced in India. With the advent of ground mica, it was found that the light-coloured varieties produced the whitest product, hence such varieties of scrap sold for higher prices. In later years, however, it has been established that a whiter ground product could be obtained by using a mixture of both ruby and green mica, thus providing a market for a certain amount of green scrap.

The effect of colour upon the dielectric properties of sheet mica is not well established, but in general the trade appears to prefer ruby mica for electrical purposes. In this regard Jahns and Lancaster (1950, p. 12) comment as follows: "In selecting sheet mica for electrical uses during recent years, purchasers have placed varying degrees of emphasis upon the desirability of the so-called ruby micas as contrasted with the green and especially the

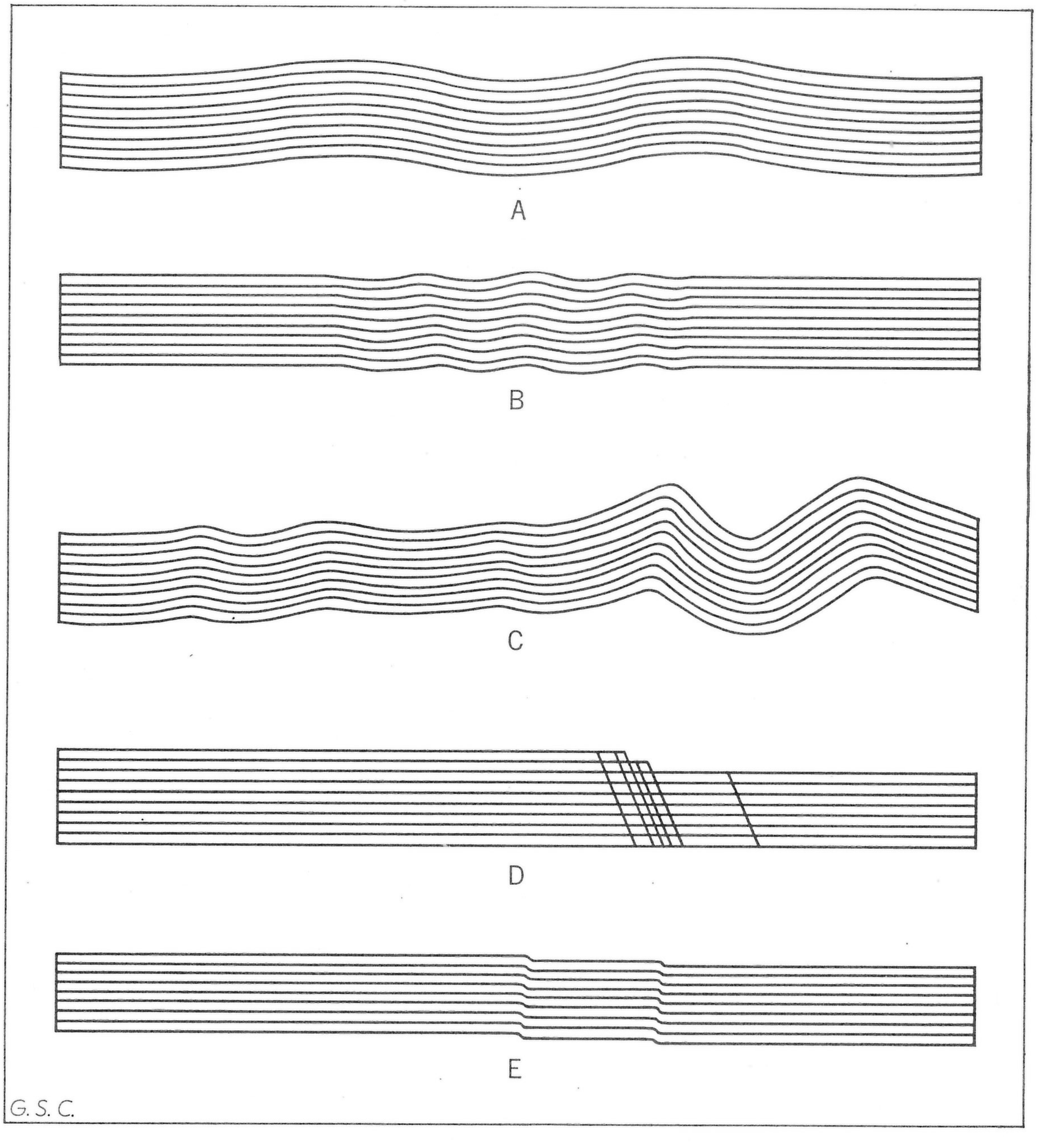

Figure 4. Diagrammatic sections, showing deformation of muscovite laminae. A. Broadly warped or wavy sheets; B. Warped or rippled sheets; C. Gradation of warped mica into buckled or folded mica; D. Mica cut by parting planes (ruling); E. Cleavage-stepped mica. (From Jahns and Lancaster, 1950)

dark green varieties. It has been stated repeatedly that dark or green muscovites usually are poor dielectrics, but the basis for such statements is not entirely clear. At best, they appear to be generalizations extrapolated from scattered and unsystematic data. That they are open to serious question has been plainly indicated during recent years, and their acceptance therefore might well be deferred until the effects of colour have been more fully investigated."

Staining, Intergrowths, and Inclusions

The presence of visible mineral or vegetable impurities in book mica generally reduces its value. Jahns and Lancaster (1950, p. 12) give a detailed description of the various types of impurities and their effect on the value of the mica.

In general, impurities can be divided into two broad classes, primary and secondary, and each of these can be subdivided as follows:

- Primary Impurities
  - Air stain
  - Mottling and vegetable stain (inorganic)
  - Mineral intergrowths and inclusions

- Secondary Impurities
  - Air creep
  - Clay stain
  - Iron stain
  - Manganese stain
  - Vegetable stain (organic)

Primary Impurities

Air-stained mica contains varying amounts of small, rounded or flattened bubbles, which when present in sufficient concentration completely destroy transparency. However, except for certain specialized electrical requirements, air staining does not seriously affect the usefulness of the mica.

Vegetable staining (inorganic) refers to pale green, yellowish green, or greenish brown discolouration produced by minute scales or finely divided aggregates of chlorite, biotite, or material rich in ferrous iron. When the staining is confined to separated spots in a sheet of mica it is termed 'mottled'. Such staining is generally not a serious defect.

Mineral staining, which is caused by inclusions and intergrowths of recognizable mineral grains or crystals is the most serious of the primary impurities. Jahns and Lancaster (1950, p. 13) state that "Among the minerals that occur within books of muscovite are actinolite, albite, allanite, apatite, beryl, biotite, brookite, chlorite, columbite, dumortierite, epidote, fluorite, garnet, hematite, kyanite, magnetite, manganese oxides, marcasite, microcline, pyrite, pyrrhotite, quartz, rutile, sillimanite, sphene, staurolite, thulite, topaz, tourmaline, vermiculite, zircon, and zoisite. The distribution and shape of many of these minerals are influenced or controlled by crystal directions of the host mica. This is especially clear in the case of magnetite, hematite, and some of the manganese oxides but can be demonstrated for other minerals by means of statistical studies only. Probably few of the included minerals are unoriented in the strictest sense.

"Magnetite and hematite are the most common of these included minerals. Small amounts of magnetite do not impair the splitting qualities but thicker inclusions tie the sheets together and thus seriously impair the filming properties. Hematite is the most abundant and widespread inclusion material in commercial muscovite, but its presence does not appear to affect the splitting qualities. However, both hematite and magnetite inclusions seriously impair the dielectric properties of mica, and hence lower its value for electrical purposes."

All of the various other minerals which occur as inclusions in mica, if present in sufficient size and amount, seriously impair the splitting qualities.

Secondary Impurities

Air creep consists of air bubbles or patches between the laminae, generally near the edges of books, and is caused by rough handling during trimming, especially when shears are used. It is generally not a serious defect.

The other secondary impurities result from exposure of the mica to agents of weathering and they occur in mica in surface dumps or in the zone of surface oxidation or meteoric waters. They consist of secondary calcite, chalcedony, clay minerals, hydrous iron oxides, manganese oxides, or other secondary minerals. Where they are deposited between the laminae they must be removed by splitting and trimming thus reducing the value of the mica. Books marred chiefly by silica, calcite, and clay minerals are termed 'clay stained', those that are coloured yellowish, reddish, or brownish by iron oxides are termed 'iron stained' and those contaminated by manganese minerals are termed 'manganese stained'. Mica books occurring at or near the surface are frequently impaired by organic vegetable material, which exists as a surface coating or at times as interlamellar material. Most organic vegetable stain is accompanied by heavy clay and iron stain and books so affected yield little usable sheet material.

Electrical Properties

Muscovite is an extremely poor conductor of electricity, and, even in thin films, has the ability to resist breakdown or rupture under conditions of high voltage or electric field strength. The specific conductance of a sample of mica is measured in terms of the dielectric constant (K), whereas the ability of a sample to resist breakdown is defined as its dielectric strength.

The dielectric constant K is the ratio of the capacitance of a condenser in which muscovite is the non-conducting substance to the capacitance of the condenser in which air (or, more exactly, a vacuum) is the dielectric. Jahns and Lancaster (1950, p. 16) state that: "K for sheet mica ranges from 2.0 to about 8.5 but generally is more than 6.5 with an average of about 7.2." It is a property of great significance for many electrical uses but is so uniformly satisfactory in micas that are otherwise of good quality that limiting values are rarely specified by purchasers.

Dielectric strength is defined in terms of the maximum potential gradient that material of a given thickness can withstand. Any dielectric material used in condensers must possess a low power factor otherwise overheating and damage will result. The power factor of a dielectric is a measure of the loss of electrical energy in a condenser and is expressed in per cent. Good condenser mica has a PF of less than 0.04 per cent at a frequency of 1 megacycle. The 'Q' value, or reciprocal of the PF, is frequently used instead of PF. Good condenser mica has a Q value of at least 2,500.

Grading, Classification, and Preparation for Marketing

The grading, classification, and preparation of sheet mica for marketing is a highly specialized industry requiring a considerable degree of skill and experience on the part of those involved. The failure of many mica-mining enterprises can be directly attributed to improper or uneconomical classification and preparation for marketing. The best mica in the world can be very easily spoiled or downgraded in value by improper or inexperienced handling and preparation.

The following is a brief introduction to the subject. More detailed information has been compiled by Jahns and Lancaster (1950).

Grading and Classification of Sheet Muscovite

The process of grading and classification of sheet muscovite is divided into two parts: (a) visual methods, and (b) electrical methods. The visual method is used for preliminary grading at the mine and for classification of the various products of the mica-preparation shops. Most mica is sold by the producers on the basis of visual classification. The electrical properties and the mechanical perfection (absence of pinholes, cracks, etc.) of mica used by the electrical industry are often further classified and tested by means of precise electrical equipment.

Visual Methods

Visual methods are used to broadly classify sheet mica according to size and quality.

Size Grading—According to Jahns and Lancaster (1950, p. 18) "Size grading of sheet mica is based upon the area and minimum width of the largest rectangle of a given quality that can be obtained from the block."

A size-grading chart of the type adopted by the American Society for Testing Materials for domestic block mica and mica splittings is reproduced in Figure 5. The method outlined by the Society is as follows: "The specimen to be graded shall be laid upon the chart so that it covers point O and has maximum and minimum dimensions extending along and covering lines AO and OB respectively. The specimen should be fitted until its usable area completely covers the largest rectangle determined by a diagonal extending from point O to or beyond a point on any of the curves, Nos. 6, 5½, 5, 4, 3, 2, 1, or A-1(Special). The number of the curve at greatest distance from O cut by the diagonal of the rectangle designates the grade of the specimen."

The size groups for United States domestic and Indian sheet mica are summarized in Table I, and a chart for grading mica according to Indian standard sizes is shown in Figure 6.

Thickness of mica is determined by micrometer. The minimum acceptable is 0.007 inch, except when sold under specific agreement. Uniformity of thickness is judged by viewing the specimen between crossed polaroid sheets.

Quality Classification—Quality classification of sheet muscovite is described by Jahns and Lancaster (1950, p. 18) as follows: "Quality designations for sheet mica vary according to the visual classification used, and a combined visual and electrical classification recently adopted by the Society for Testing Materials yields still another set of terms. Interpretations of visual standards differ from one observer to another, but attempts have been made to define the standards and to describe the methods of determination in such exact terms that the inconsistencies are reduced to a minimum. The Indian standard groups, beginning with the best quality, are clear, clear and slightly stained, slightly stained, fair stained, good stained, stained, heavy-stained, light dotted, black-spotted, and black-stained."

Table I

United States and Indian Size Groups for Sheet Mica, Including Punch and Sheets Larger than Punch, not less than 0.007 Inch Thick

(After Jahns and Lancaster, 1950)

Usual U.S. grades	Usable area in single rectangle, in square inches		Minimum dimension of one side, in inches	Standard India grades
	Minimum	Maximum		
Small punch.[1]	1	1½		6 small
Punch[1]	1½	2½	¾	6
Circle[1]	2½	3	1	5½
1½ by 2 inches	3	4	1	5
2 by 2 inches	4	6		
2 by 3 inches	6	10	1½	4
3 by 3 inches	10	12	2	3
3 by 4 inches	12 by	15		
3 by 5 inches	15 by	24	2	2
	24	36	3	1
4 by 6 inches	36	48	4	A-1 (Special)
6 by 8 inches	48	60	4	Extra special
8 by 8 inches	60	80	4	Extra extra special
8 by 10 inches	80	100	4	Over extra extra special
Larger than 8 by 10 inches	100 plus		4	Over over extra extra special

[1] Ordinarily included under general designation of "punch" which applies to mica yielding usable sheets less than 1½ inches wide and 2 inches long but not less than 1 square inch in area.

In 1938 the American Society for Testing Materials adopted Indian grading as the American standard and designated the seven principal qualities listed below (Jahns and Lancaster, 1950, p. 21).

A.S.T.M. Designation	**A.S.T.M. Description**	**Supplementary Description**[1]
Clear	Free from all mineral and vegetable inclusions, stains, air inclusion, waves, or buckles. Hard, transparent sheets.	Hard and substantially flat. Ten per cent of the largest rectangle may contain small air spots, and the remainder may contain a few small air specks.
Clear and slightly stained	Free from all mineral and vegetable inclusions, cracks, waves, and buckles, but may contain slight stains and air inclusions.	Hard, but may be slightly wavy. The largest rectangle may contain small air specks and one third of it may contain small air spots. One tenth of the rectangle may contain small, light air stains, light vegetable stains, or a few mineral specks.

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[1] Imperfections mentioned are defined at the end of this table (page 17).

A.S.T.M. Designation	A.S.T.M. Description	Supplementary Description[1]
Fair stained	Free of mineral and vegetable inclusions and cracks. Hard. Contains slight air inclusions and is slightly wavy.	Hard, but may be slightly wavy. One fourth of the largest rectangle must be free of all stains except small air specks, and three fourths may contain small air spots. One fourth of the rectangle may contain light air and light vegetable stains or small mineral specks.
Good stained	Free of mineral inclusions and cracks, but contains air inclusions and some vegetable inclusions and may be somewhat wavy.	Hard, but may be wavy though not buckled. The largest rectangle may contain small air specks and small air spots over the entire area. Half of the rectangle may contain light air stains and light vegetable stains, but not more than one tenth may contain dense air stains or mineral spots and lines.
Stained	Free of mineral inclusions and cracks, but may contain considerable clay and vegetable stains and may be more wavy and softer than the better qualities.	May be soft or hard (approximately 75 per cent hard and 25 per cent medium soft) and may be slightly buckled. The entire area of the largest rectangle may contain air specks and stains, but not so densely concentrated as to give a silvery appearance to more than one third of the rectangle. Light vegetable stains or some small mineral specks may be present over the entire area, but not more than one third of the rectangle may contain vegetable stains, lines, or spots.
Heavy-stained	Free from mineral inclusions, but contains more clay and vegetable stains than stained quality and is distinctly inferior as regards rigidity and toughness.	May be soft or hard (approximately 50 per cent hard and 50 per cent soft) and may be slightly buckled (about 10 per cent may be buckled). The largest rectangle may contain dense air stains, and two thirds of the area may contain dense vegetable stains, spots or lines.
Black stained and spotted	Apt to contain some mineral inclusions consisting of magnetite (black), specularite (red), and hydrous iron oxide (yellow).	

Imperfections

(Degree of flatness is determined by observation of light reflected from the mica sheet as the sheet is rotated back and forth.)

Small specks: Size of small pin or needle holes.

Specks: Twice the size of small specks or about the size of periods made by a typewriter.

Small spots: About three times the size of small specks or about one-sixteenth of an inch in diameter.

Spots: Any spots larger than small spots.

Lines: Series of specks or small specks, forming continuous rows: individual specks may be in contact or slightly apart.

Light stains: Stains not sufficiently dense to impair the transparency of block mica when ordinary print is read through the sheet.

Dense stains: Stains so dense that they distinctly impair the transparency of the mica, as roughly determined by the reading test.

Flat: No wave nor ripple of light.

Substantially flat: Only a slight wave or ripple of light.

Slightly wavy: Light appears to rise and fall evenly, without jerkiness, like waves on a pool of water.

Slightly buckled: Light appears to rise and fall jerkily, but the rise and fall from different parts of the sheet do not overlap.

Buckled: Light appears to rise and fall jerkily, with overlap and confusion of motion.

Electrical Methods

The various manufacturers of electrical equipment employ a variety of electrical instruments to test the electrical properties of sheet mica. The methods and instruments commonly used are described by Jahns and Lancaster (1950, pp. 22-24).

The American Society for Testing Materials has devised a method of testing condenser-quality mica based on a combination of visual and electrical tests. The method has been tested commercially and, according to the Society (A.S.T.M. 1946, pp. 705-717) has been "found to be both practicable and reliable". Details of the method are also given by Jahns and Lancaster (1950, p. 25).

Grading and Classification of Sheet Phlogopite

In Canada, size gradings for sheet phlogopite generally conform to those applying to muscovite but are expressed in terms of linear dimensions (in inches). The following grades are in common use:

1 x 1 and 1 x 2, 2 x 3, 2 x 4, 3 x 5, 4 x 6, 5 x 8 and larger.

No formal quality grading which applies specifically to phlogopite has been established but, in general, the soft, light-coloured varieties are regarded as having the best electrical qualities. These grade down to the darker, more brittle varieties in the lower grades. The terms 'light amber', 'medium amber', and 'dark amber' are commonly used in reference to quality.

Preparation for Marketing

The first rough separation of mica is made at the mine. The books are first rough-cobbed to remove obvious impurities, such as quartz and feldspar, which may be adhering to the edges. Scraps, films or books that are too small or too marred by inclusions, cracks, holes, or other imperfections, to yield acceptable sheet or punch stock are discarded as mine scrap. The books are then split or rifted by means of a knife blade into sheets about three-sixteenths of an inch thick. Defective material is removed during this operation, and the product is roughly graded into block, punch, and washer stock, and shop scrap. After rifting, the ragged edges are frequently removed by thumb-trimming and then the blocks are usually trimmed by hand, using a curved knife or sickle. Knife- or sickle-trimming produces curved, bevelled edges which is a much more desirable effect than the straight edges resulting from trimming by shears or by mechanical means.

India mica is knife-trimmed free of all defects, with the product having bevelled edges on all sides. According to Jahns and Lancaster (1950, p. 27) the practice is somewhat different in the United States, where three classes of trimmed sheets are recognized. They comment as follows: "Half-trimmed mica, for example is cut on two adjacent sides with no cracks, reeves, cross grains, nor ribs extending from those sides. Three-quarter-trimmed mica is cut on all sides, with no cracks nor comparable flaws extending from two adjacent sides or into the final pattern area. Only fully-trimmed mica is comparable to India-trimmed material in that it is cut on all sides and contains none of the flaws noted above. Moreover, upper limits generally are set on the number and size of 'V' or figure cuts on any one piece of mica, as well as on the proportion of pieces with such cuts in a given lot of mica."

A large proportion of sheet mica is consumed in the form of splittings or films 0.0007 to 0.001 inch thick, which are used in the manufacture of built-up mica board. As yet no satisfactory substitute for hand-splitting methods of producing splittings has been devised, and the work is usually done in countries where labour costs are low.

Uses

The uses of mica are based on its unique combination of physical, chemical, and electrical properties, or more specifically on its perfect cleavage, flexibility, elasticity, mechanical strength, transparency, lustre, lubricating properties, heat resistance, non-inflammability, chemical inertness, exceptionally low conductivity, high dielectric constant and dielectric strength, and low dielectric loss. Although the degree of emphasis placed on a given property by the purchaser depends on the specific end use involved, the main uses of mica in modern industry are based on the combination of a number of these properties, rather than on any single one. The fact that it is extremely difficult to obtain such a combination in any other naturally occurring material, or in any synthetic product is the main reason why sheet mica has remained indispensable to modern industry.

A very high proportion of all sheet muscovite is used as electric insulating material. It is used in many ways, as washers, discs, and other small punched forms, both singly and as built-up rods or tubes in which the individual pieces are cemented together by some suitable material. Jahns and Lancaster (1950, p. 17) list the following uses: "as tubes, sleeves, studs, washers, bushings, lamination, and thin perforated plates in condensers, transformers, small heating elements, rheostats, fuses, incandescent bulbs, radio and electronic tubes, various types of coils, and acoustic, X-ray, and other specialized equipment". It is used in generators as dielectric separators between the segments. Thin films of 'cigarette' mica 0.0012 inch or less thick are used in aircraft-engine spark plugs, where they are wrapped around rod-like spindles a little more than one-eighth of an inch in diameter. Thin splittings 0.001 inch thick, obtained mainly from India and Madagascar, are used to form mica board which consists of layers of splittings bonded together by thermosetting binders of various types, depending on the end use of the product. This mica board is hard and compact, and can be sawn, punched, or moulded into any required form; it has a wide variety of uses in the electrical industry.

Prices

Prices of sheet mica vary constantly according to supply and demand, and market quotations are usually only an approximate indication of the actual value. As previously mentioned, accurate grading of sheet mica is difficult, and can only be done properly by an experienced mica dealer versed in market requirements. Since all purchases of sheet mica are made by sample, prospective operators would be well advised to submit samples of their mica before undertaking expensive mining operations.

The following tables show approximate 1955 prices of sheet muscovite and phlogopite.

Table II

Approximate 1955 Prices of Domestic Canadian Sheet Phlogopite (Well-trimmed Block)

Grade	Price per pound
1 × 1—1 × 2	$0.30
1 × 3	0.70
2 × 3	1.30
2 × 4	1.65
3 × 5	2.15
4 × 6	2.75
5 × 8	3.50

Table III

Approximate 1955 Prices of Madagascar Sheet Phlogopite, as Sold by U.S. Dealers to U.S. Manufacturers

Indian Standard Grade	Price per pound
EES	$8.50
ES	6.75
Al	6.00
1	5.50
2	4.95
3	3.95
4	2.95
5	1.95

Table IV

Approximate 1955 Prices of India Ruby Block Micas, as Sold by U.S. Dealers to U.S. Manufacturers

Indian Standard Grade	Clear and Slightly Stained	Fair Stained	Good Stained	Stained
1	$25.00	$20.00	$15.00	
2	*	17.50	12.60	
3	*	15.00	11.20	$4.25
4	*	12.00	9.25	3.55
5	*	8.20	6.15	2.65
6	*	3.00	2.26	1.45

Table V

Prices (Aug. 1955) of Brazilian Pasada Trimmed (Half-trimmed) Block Muscovite, f.o.b. New York, Duty Paid

Indian Standard Grade	Price per pound	
	Stained	Heavy Stained
Al	$6.60	$4.94
1	5.54	4.15
2	4.64	3.48
3	4.04	3.03
4	3.15	2.36

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*Approximately 25% higher than fair stained.

Chapter II

ATOMIC STRUCTURE OF THE MICA-GROUP MINERALS

Silicate Structure

The skeleton of all silicate minerals is composed of atoms of silicon and oxygen arranged in such a way that one silicon atom lies between four oxygen atoms. This arrangement appears to be common to all silicates and the bonds between silicon and oxygen are so strong that the four oxygen atoms are always found at the corners of a tetrahedron of nearly constant dimensions and regular shape no matter what the rest of the structure may be like. This silicon-oxygen tetrahedron (*see* Figure 7) may thus be considered to be the basic building unit in all silicate minerals, with the various silicon-oxygen frameworks or skeletons of the minerals being formed by linking together two or more tetrahedra. The ways in which these tetrahedra are linked together are characteristic of different groups of minerals. Thus in the micas and related minerals they are linked together to form sheets. This is accomplished by linking three corners of each tetrahedron to neighbours (*see* Figure 8). The result is a hexagonal network like that of wire netting. Each silicon-oxygen tetrahedron has three shared and one free oxygen atom and thus has a composition of $(1Si+\frac{3}{2}O+\frac{2}{2}O)$ or $(Si+\frac{5}{2}O)$. In a sheet the tetrahedra extend indefinitely in two directions so that the composition of the sheet is written $n^2\ (Si+\frac{5}{2}O)$ or $n^2(Si_2O_5)$ which has a valence or electrical charge of minus 2. The unit cell of these minerals has been shown to contain 12 oxygen atoms of which 10 are contained in the silicon-oxygen tetrahedra, so that in writing the formula for the minerals the simple composition of the sheet must be multiplied by 2 in order to provide 10 oxygen (O) giving $n(Si_4O_{10})$. Also in some of the minerals, notably the micas, certain silicon (Si) atoms (approximately one quarter but sometimes one half) are replaced by aluminum (Al) atoms. In these cases the composition of the sheet is changed to $n(Al\ Si_3O_{10})$ or $n(Al_2Si_2O_{10})$ with valencies being minus 5 or minus 6 as the case may be.

Structure of the Mica Minerals

The silicon-oxygen sheets described in the foregoing section form the basis of most of the flaky or sheet silicate minerals. With the exception of replacement of silicon (Si) atoms by aluminum (Al) atoms in certain cases,

Figure 7

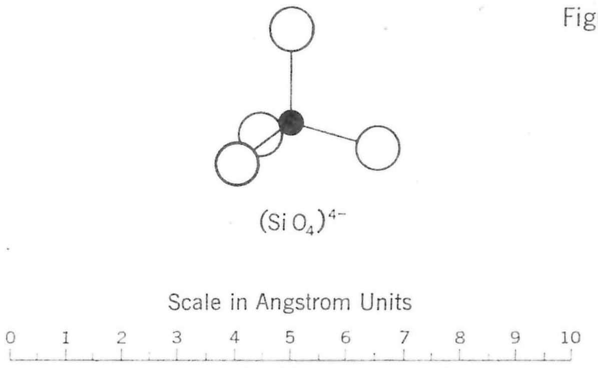

Figure 7. Silicon-oxygen tetrahedron. (After Bragg, 1937)

Figure 8 (a)

Figure 8 (b)

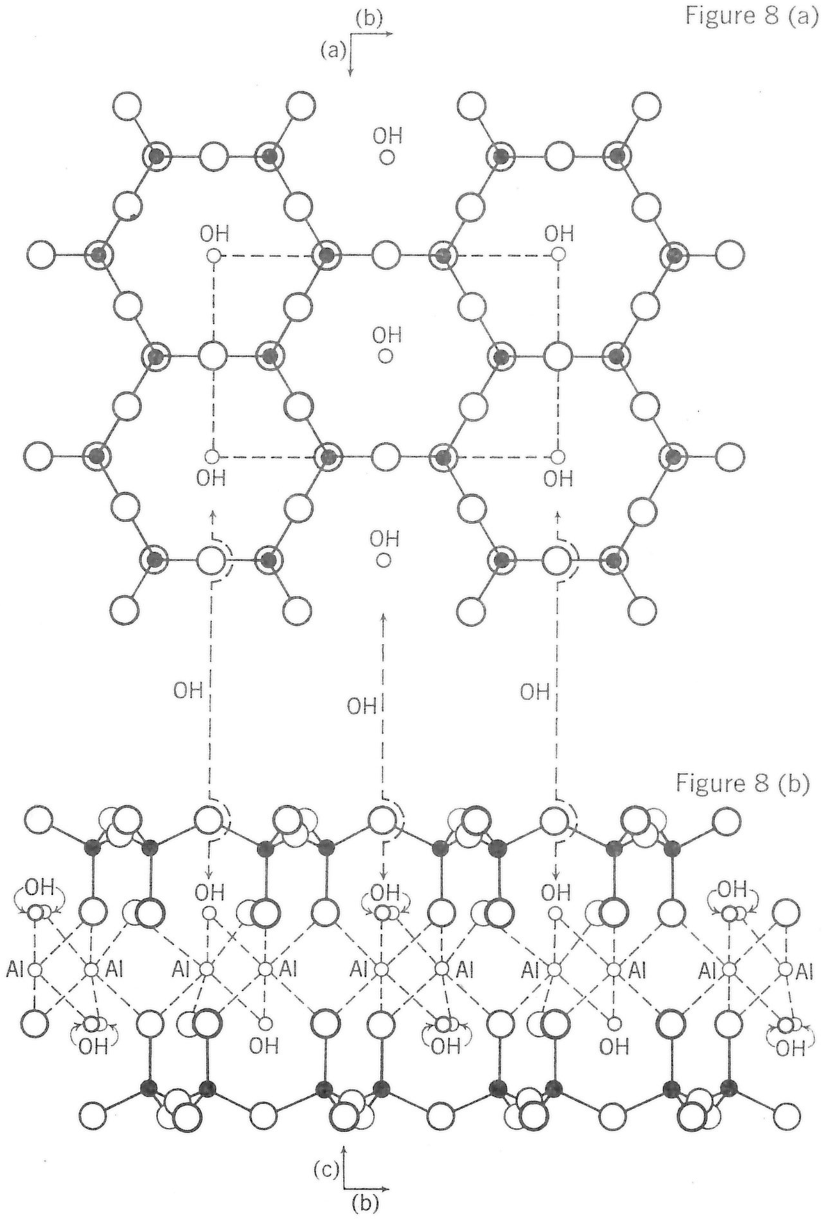

Figure 8.

(a) Atomic arrangement in a sheet of linked silicon-oxygen tetrahedral groups, with hydroxyl at the centre of each ring of 6 vertices.

(b) Two of the above sheets seen endwise, with their vertices turned inwards. The layers of vertices and hydroxyls pack into each other providing situations for aluminum (Al) or magnesium (Mg) atoms. The whole forms a firmly bound double sheet. Certain oxygen (O) and hydroxyl (OH) atoms which would otherwise be superimposed have been slightly displaced. (Ref. Bragg, 1937)

the composition of the sheets is the same in all of these minerals. The differences between them arise from differences in the way the sheets are stacked on one another, and in the different ways in which the sheets are bound together.

In the following list of minerals the formulas have been reduced to an ideal type. Actual compositions are, however, very complex due to extensive isomorphous substitution.

Mica Group

Muscovite	$KAl_2\ (Al\ Si_3O_{10})\ (OH)_2$
Paragonite	$NaAl_2\ (Al\ Si_3O_{10})\ (OH)_2$
Phlogopite	$K\ Mg_3\ (Al\ Si_3O_{10})\ (OH)_2$
Biotite	$K\ (Mg,Fe)_3\ (Al\ Si_3O_{10})\ (OH)_2$
Lepidolite	$K\ Li_2Al\ (Si_4O_{10})\ (OH)_2$
Zinnwaldite	$K\ LiFeAl\ (Al\ Si_3O_{10})\ (OH)_2$
Pyrophyllite	$Al_2(Si_4O_{10})\ (OH)_2$
Talc	$Mg_3\ (Si_4O_{10})\ (OH)_2$

Clintonite Group (Brittle Micas)

Margarite	$CaAl_2(Al_2Si_2O_{10})\ (OH)_2$
Chloritoid Clintonite	Fe and Mg partly replace Ca and Al
Vermiculite	$(MgFe)_3\ (Si,Al_4O_{10})\ (OH)_2\ 4H_2O$

It will be seen that in the above formulae, the groups $(Al\ Si_3O_{10})$ and (Si_4O_{10}) represent the contribution of the sheets of linked tetrahedra.

The general structural scheme of the above minerals is as follows: Commencing with the hexagonal network of linked tetrahedra (Figure 8(a)), two of these sheets are placed together with the vertices of the tetrahedra pointing inward as show in Figure 8(b). These vertices are cross-linked by aluminum (Al) atoms in muscovite or by magnesium (Mg) and iron (Fe) atoms in phlogopite and biotite. Hydroxyl (OH) groups are incorporated, linked to aluminum (Al) in muscovite or to magnesium (Mg) and iron (Fe) in phlogopite and biotite. This forms a firmly bound double sheet, with the bases of the tetrahedra on each outer side. The structure is a succession of such double sheets, with cations—usually potassium (K) but sometimes sodium (Na)—between them. The double sheet is shown in detail in Figure 8(b). In the structure as shown, there is room for a hydroxyl group, inside each ring formed by the oxygen atoms at the vertices of the tetrahedra. The lower

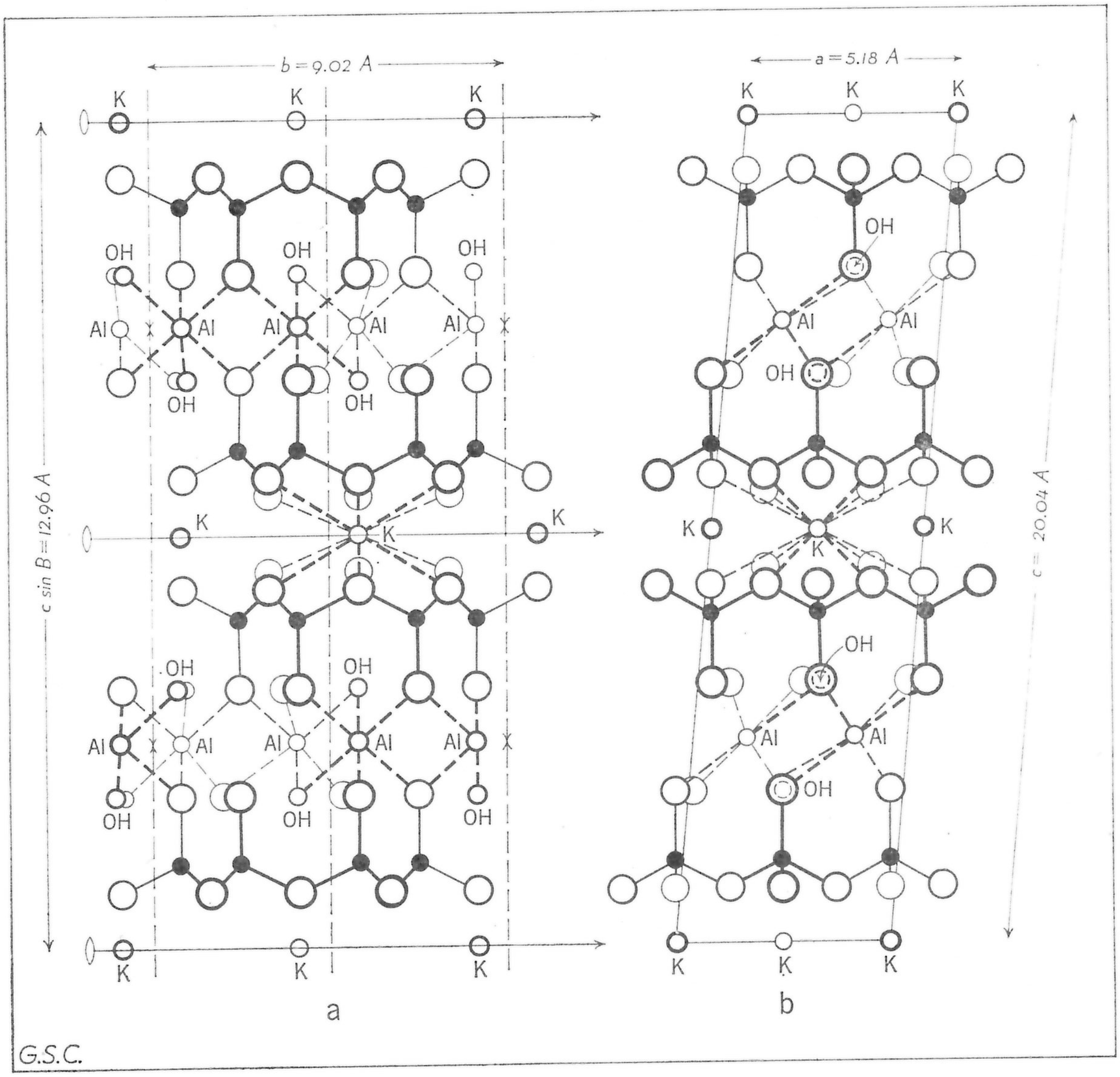

Figure 9.

(a) Atomic structure of muscovite projected on a plane normal to the "a" axis. The double sheets are seen, with potassium (K) atoms between them surrounded by 12 oxygen atoms.

(b) The same structure projected on (010). Note the staggering of the double layers which is responsible for the monoclinic angle of about 95 degrees. Only half of the atoms are included. (Ref. Bragg, 1937)

oxygen atoms and hydroxyl groups form a close-packed layer, with atoms at the corners of equilateral triangles. This close-packed layer fits into a similar layer of the opposite sheets, each atom of one layer resting upon three atoms of the opposite layer. This produces a staggering of the tetrahedral networks as shown in Figure 8(a). The staggered arrangement destroys the hexagonal symmetry and determines the monoclinic angle of the mica. Aluminum (Al) or magnesium (Mg) atoms occur between these two layers, as shown in Figure 8(a), in such a way that each aluminum or magnesium atom is closely surrounded by four oxygen (O) atoms and two hydroxyl (OH) groups, and is joined to them by chemical bonds. They are thus said to be in 6 coordination. In Figure 8(b) aluminum (Al) atoms are shown in two thirds of the positions, which represents the arrangement in muscovite. In phlogopite and biotite all the positions are filled with magnesium (Mg) or iron (Fe) atoms.

The complete unit cell of muscovite is shown by dotted lines in Figure 9(a), illustrating the structure projected onto a plane perpendicular to the *a* axis; the bases of the tetrahedra are symmetrically opposed as mirror images across a central plane, and opposite hexagonal rings of oxygen atoms thus outline a large cavity in which a potassium atom is situated, surrounded and bonded to 12 oxygen atoms (12 coordination). In this way the double layers are firmly held together. In most of the micas the cation present is potassium, but in paragonite it is sodium. In margarite, one of the brittle micas, the sheets of linked tetrahedra have the composition $(Al_2^{+6}Si_2^{+8}O_{10}^{-20})^{-6}$ instead of $(Al^{+3}Si_3^{+12}O_{10}^{-20})^{-5}$ as in normal micas. The negative charge on the sheet(valence) is thus twice as great as in the micas and is balanced by inserting divalent calcium atoms between the sheets in place of monovalent potassium or sodium.

i.e. $Ca^{+2}[Al_2^{+6}(Al_2Si_2O_{10})^{-6}(OH)_2^{-2}]^{-2}$
$K^{+1}[Al_2^{+6}(AlSi_3O_{10})^{-5}(OH)_2^{-2}]^{-1}$

The composition of mica in terms of the number of atoms in the various parts of the structure may be summarized as follows:

12 (O, OH, F) comprising 10 oxygen and 2 (OH, F);
four tetrahedral positions (4 coordination) occupied by Si and Al—i.e. one at centre of each tetrahedra;
two to three octahedral positions (6 coordination)—between sheets of linked tetrahedra—occupied by Mg, Al, Fe, Ti, and Li;
zero to one position for large cations—between double layers occupied by K, Ca, or Na.

Comparison of Structure of Micas with that of Talc and Pyrophyllite

Talc and pyrophyllite have structures much similar to that of mica. The essential difference appears to be that the composition of linked tetrahedra is represented by (Si_4O_{10}), as compared to $(AlSi_3O_{10})$ in mica. This has the effect of making the double sheets neutral (*see* formula below) and hence no alkali or other ions are required between the double layers to balance a negative charge.

Pyrophyllite $[Al_2{}^{+6}(Si_4O_{10})^{-4}(OH)_2{}^{-2}]^0$
Talc $[Mg_3{}^{+6}(Si_4O_{10}{}^{-4}(OH)_2{}^{-2}]^0$

In talc, magnesium atoms fill all the six coordinated positions between the sheets of linked tetrahedra, as is the case in phlogopite; whereas in pyrophyllite, like muscovite, aluminum (Al) fills only two thirds of the six coordinated positions.

Relationship of Atomic Structure to Physical Properties

Pauling (1930, p. 128) explains the relationship of cleavage and hardness in mica and related minerals to the atomic structure as follows: "To tear apart one of the pseudo-hexagonal layers it is necessary to break the strong silicon-oxygen, (Si-O), aluminum-oxygen (Al-O) etc., bonds; as a consequence these individual layers are tough. But they can easily be separated from one another, giving rise to the pronounced basal cleavage shown by all these minerals. In talc and pyrophyllite the layers are electrically neutral, and are held together only by stray electrical forces. These crystals are accordingly very soft, feeling soapy to the touch as do graphite crystals. To separate the layers in mica it is necessary to break the bonds of the univalent potassium ions, so that the micas are not so soft, thin plates being sufficiently elastic to straighten out after being bent. Separation of layers in the brittle micas involves breaking bonds of bivalent calcium ions; these minerals are hence harder, and brittle instead of elastic, but still show perfect basal cleavage. The sequence of hardness is significant; on Mohs scale it is: Talc and pyrophyllite, 1-2; the micas, 2-3; the brittle micas, $3\frac{1}{2}$-6."

Isomorphous Substitution in Micas

Throughout the foregoing discussion of the structure of the mica and related minerals, we have considered only the ideal compositions as established by their atomic structure. These, in effect, are relatively simple, whereas in actual fact the true compositions of the minerals are highly complex due to extensive and varied substitution of atoms of one mineral by atoms of certain other minerals. This phenomenon is termed isomorphous substitution. Such substitution appears to depend more upon ionic size than upon valency. The simplest cases occur when the ions are equal both in charge (valency) and in ionic size, e.g. magnesium and iron which are readily interchangeable. But substitution between ions of similar ionic size but dissimilar valence appears to be much more easily accomplished than between ions of similar valence but dissimilar atomic radii. Thus replacement between sodium and calcium is much more common than between sodium and potassium, because sodium and calcium have the same ionic radii, whereas potassium is considerably larger. However the interchanges of ions of different valency are always subject to the condition that the total positive and negative valencies must balance. Moreover, there is a limit beyond which substitution cannot go without destroying the stability of the mineral structure. Thus in mica, to maintain stability the structure requires at least two silicon ions in every four tetrahedral positions.

Before the atomic structure of minerals was properly understood, the mineralogists of the time attempted to explain complex compositions by devising formulae for 'end members', such as albite and anorthite in the plagioclase series, regarding the minerals as an 'isomorphous mixture' of these ideal compounds. As Bragg (1937, p. 37) states: "though successful in simple cases, this attempt is based on a principle which is fundamentally wrong. It implies the existence of a chemical 'molecule', in which a definite number of atoms form a characteristic sub-group in the structure. Molecules do not exist in structures such as minerals, which are continuous.

"In cases of complex substitution, such as in the mica group or amphiboles, the variations of replacement are so extensive that it is almost impossible to frame a list of end-members which covers all the permutations. On the other hand, when the structure is taken into account the apparently bewildering varieties of composition are seen to fall into an extremely simple scheme. Thus, as a result of the study of the atomic structures of the minerals, it has been possible to assign ideal formulae, which serve as a basis for distributing the atoms, shown to be present by the chemical analyses of the specimens, amongst the situations characteristic of the type of structure. The formula thus obtained may then be compared with the ideal one for the mineral in question, thereby clearly indicating the nature and extent of substitution present."

The analyses shown in Table VI provide examples of isomorphous substitution present in the micas.

Table VI

*Analyses of Type Micas**

Element	Margarite		Muscovite		Phlogopite		Biotite		Phlogopite	
Si	2.12	4	3.00	4	2.79	4	2.80	3.97	3.02	4
Al	1.88		1.00		1.21		1.17		0.98	
Al	1.92	2.16	1.84	2.05	0.28	3.06	—	2.78	0.14	3.08
Ti	—		—		0.04		0.09		—	
Fe	0.12		0.05		—		0.40		0.02	
Fe	—		0.07		0.14		0.80		0.04	
Mg	0.03		0.04		2.60		1.49		2.88	
Mn	0.01		—		—		—		—	
Li	0.08		0.05		—		—		—	
Ca	0.71	0.95	0.01	0.83	—	1.06	—	1.13	0.03	0.86
Na	0.24		0.08		0.12		0.06		0.05	
K	—		0.74		0.94		1.07		0.78	
H	2.02		2.22	2.25	2.08		1.75		0.55	1.74
F	—		0.03		—		—		1.19	
O	12.04		11.99		12.2		11.85		10.80	
O+F	12.04		12.02		12.2		11.85		11.99	

* Figures indicate number of atoms of each element present in the unit cell divided by four, so as to correspond to the simple mica formulae and are based on the known size of the cell, the density of the specimen, and the percentage composition by weight. The elements are arranged into groups which the analysis of the structure distinguishes. (After Bragg, 1937).

Chapter III

GEOLOGY OF MICA DEPOSITS

Sheet mica deposits can be divided into two distinctly different types, according to their different modes of origin: (a) those associated with bodies of granite pegmatite, and (b) those associated with what has been called metamorphic pyroxenite, which usually occur in or near bodies of limestone or calcareous sedimentary rocks.

Since the mode of occurrence in each case is quite different it is necessary to describe each type separately.

Occurrence, Origin, and Distribution of Mica Deposits Associated with Granite Pegmatites

Granite pegmatite bodies constitute the only source of commercial sheet muscovite. While muscovite is one of the common constituents of many pegmatites, only in rare cases is it present in commercially exploitable concentrations. However, in all cases its distribution, origin, and occurrence is dependent on that of the pegmatitic body in which it occurs, so that a brief résumé of the geology of granite pegmatites is a necessary preliminary step in the description of the geology of muscovite deposits.

Origin of Granite Pegmatites

Significant Features of Granite Pegmatite Occurrence

Before considering the various theories of origin the writer wishes to set forth the following summary of the significant features of granite pegmatite occurrence, based on a study of the literature and supplemented by personal experience.

(1) All granite pegmatites are similar in that they are composed essentially of quartz and feldspar, with more or less muscovite, tourmaline, garnet, and other rarer minerals.

(2) They are characterized by uneven textures, that in general, are coarse.

(3) A small percentage of granite pegmatites exhibit regular internal zoning that is reflected in units of different composition and texture.

(4) Fracture filling and replacement of earlier crystallized minerals is common in some granite pegmatites and absent in others. In many cases the source of the solutions effecting the replacement is a matter of conjecture.

(5) In competent rocks such as granite, granite gneiss, and quartzite, granite pegmatites occupy fractures that commonly transect foliation or bedding planes. In incompetent rocks such as schists, they are, as a rule, conformable with foliation, although many exceptions are known.

(6) Almost all granite pegmatites occur in metamorphic terrains composed of meta-sedimentary and meta-volcanic rocks intruded by numerous granitic bodies.

(7) Many pegmatite bodies appear to be genetically related to nearby granitic intrusions, while many others exhibit no such relationship, being far removed from known intrusive bodies.

(8) The granite pegmatites associated with any one intrusion commonly exhibit marked similarity in mineralogy, which may or may not show a definite spatial relationship to the border of the intrusion.

(9) In some cases mineral content of granite pegmatites appears to be influenced by the composition of the enclosing rocks.

(10) Some granite pegmatites have exerted a marked effect on the wall-rocks, as evidenced by the pronounced and varied alteration that has taken place, while others appear to have exerted no effect whatsoever.

Some of the above points require amplification, and substantiation.

Many examples in support of the statement that most granite pegmatites occur in metamorphic terrains are available in geological literature. In Canada, by far the greatest development of granitic pegmatites occurs in the areas underlain by rocks of the Grenville series and in areas underlain by Grenville type rocks, which are typical metamorphic terrains. In the Yellowknife area, Northwest Territories, the pegmatites occur in the meta-sedimentary and meta-volcanic rocks of the Yellowknife group (Rowe 1952, p. 10), or in the outer fringes of the granitic bodies that intrude the group. Also in south-central British Columbia, in the area underlain by the para-gneisses and schists of the Shuswap complex, pegmatites are common. Similar conditions pertain to almost all areas in this and other countries where pegmatites are common. In contrast, pegmatites are uncommon in areas that are predominantly underlain by granitic plutonic rocks. An excellent example is the Coast Range region of British Columbia where the work of various members of the Geological Survey of Canada and other geologists, has shown pegmatites to be almost non-existent. The reason for this lack of pegmatites in the coastal Cordilleran region is not apparent. However, the very fact that one type of terrain contains abundant pegmatites whereas the other does not, is indicative of some fundamental difference, which at the present stage of our knowledge is undeterminable.

The genetic relationship between pegmatites and granitic intrusive bodies and the contrast between groups of pegmatites associated with various intrusive bodies has been widely discussed by many geologists. In this connection Cameron *et al.* (1949, p. 7) have pointed out that "there are many contrasts in mineralogy, texture, and structure, among groups of pegmatites in different regions, and even between groups that lie within a single region, but associated with different intrusives. . . . Differences in physical conditions of formation, differences in degree of reaction of pegmatite solutions with wall rocks are undoubtedly responsible for some of the contrasts between groups of pegmatites, but it is evident that intrinsic differences in compositions of pegmatitic solutions given off by various magmas have played a leading role." Cameron cites many examples in support of this statement. In Canada several examples indicate much the same conclusion. In the Haliburton-Bancroft area there are numerous bodies of nepheline syenite, with which are associated many nepheline syenite pegmatites (Adams and Barlow, 1910, p. 302). Corundum is present as an accessory mineral in both the intrusive bodies and the pegmatites. In the same general area are numerous intrusive bodies of pink granite which, in the case of the Methuen batholith (Satterly, 1943, p. 18) grades outward into border phases of pink syenite. Granite pegmatites are associated with the granitic phase, and syenite pegmatite with the pink syenite border phases. According to Satterly (1943, p. 18) syenite pegmatite grades into granite pegmatite in several places. In the Wilberforce area, Cardiff township, Ontario, there are many apatite-fluorite-calcite 'veins' which Satterly (1943, p. 31) states "at most localities are fairly intimately associated with hornblende-syenite-pegmatite dikes." These pegmatites are apparently associated with nearby pink granite which contains fluorite as an accessory mineral.

The spatial relationship of certain pegmatites with respect to intrusive bodies, and zonation of mineral assemblages of the pegmatites with respect to associated intrusions, is especially well illustrated by the beryl-tantalum pegmatites of the Yellowknife-Beaulieu region, Northwest Territories. Rowe

(1952, p. 10) states "the pegmatites of the region that carry one or more of the minerals beryl, columbite-tantalite, spodumene, and amblygonite occur only in the aureoles of high-grade meta-sedimentary rocks that surround the batholiths and smaller bodies of granite, or in the granodiorite intrusive bodies of granite." In the same paper he notes a regular regional zonation of the mineral content of the pegmatites outward from the Redout Lake granite which he describes as follows: "This zonation occurs between Redout and Ross Lakes, and features five zones. The first zone, closest to the granite, contains large, irregularly shaped pegmatites that have poorly developed internal structure, and that contain graphic granite. The second zone is composed of pegmatites containing graphic granite and beryl. In this zone, the pegmatites tend to be lenticular and have a somewhat better developed internal structure. The third zone contains many pegmatites that have beryl as a component, but have no graphic granite. These pegmatites are regular in shape, are much smaller and display a readily recognizable internal structure. The pegmatites of the fourth zone are structurally similar to those of the third, but many contain columbite-tantalite as well as beryl. The fifth zone, the one farthest from the granite, features pegmatites that are spodumene-bearing."

Tremblay (1950, p. 41) during his work in the Fiedmont map-area, Abitibi county, Quebec, noted a somewhat similar spatial relationship between the pegmatites of the area and bodies of muscovite granite. As in the Yellowknife-Beaulieu region some of the pegmatites of the Fiedmont map-area contain varying amounts of spodumene, columbite-tantalite, beryl, lepidolite, and other rare minerals. Tremblay observed a zonation of these minerals outward from the granite that is similar to, but not as regular or complete as that found by Rowe in the Yellowknife-Beaulieu region. Cameron (1949, p. 7) noted similar systematic variation in pegmatite composition with distance from the associated, presumably related, intrusives, and mentions examples where this has been observed by other workers.

The examples cited are sufficient to indicate the close association between pegmatites and intrusive bodies, lending strength to the theory that they are genetically related. The examples also show that systematic variation in the mineralogy of pegmatites with distance from the source is by no means uncommon. However, as Cameron (1949, p. 8) points out "so few districts have been studied comprehensively that conclusions as to the importance of this regional zoning must be accepted with reservation. . . . The concept of zonal distribution is appealing in its simplicity, but it may be that factors other than distance are of equal or greater importance in controlling the distribution of types of pegmatites."

Relationship of Type of Pegmatite to Type of Wall-rock

Much has been written on the relationship between mineralogic types of pegmatites and the composition of the enclosing wall-rocks, especially with respect to mica-rich pegmatites. (*See* Occurrence and Origin of Muscovite in Mica-rich Pegmatites, page 37). However, in some instances wall-rock composition has, apparently, had a marked effect on the composition of non-micaceous pegmatites. For example in part of the Revelstoke area, British Columbia, the pegmatites that occur in kyanite-rich paragneisses and schists are themselves kyanite bearing, whereas pegmatites in another part of the area occurring in tourmaline-rich meta-sedimentary rocks all contain tourmaline.[1]

Theories of Origin of Pegmatites

Any comprehensive theory of origin of pegmatites must account for all the characteristic features of pegmatites discussed in the previous section and must account for the wide variation in pegmatite geology and mineralogy.

The earlier theories of origin are excellently summarized by Johannsen (1932, pp. 72-84). Flawn (1951, pp. 180-183) gives an excellent résumé of the current theories, parts of which are included in the following.

Currently there are three main schools of thought on pegmatite formation, and within each school, at least one theory of origin is prevalent. The following is a brief summary of the various theories.

1. *Granitization Theory*: Pegmatites represent zones of selective metasomatism in which volumes now occupied by pegmatite were formerly occupied by country rock.
2. *Palingenesis Theory*: Partial melting of crustal rocks under deep-seated conditions with subsequent injection into overlying rocks.
3. *Open System Theory*: Formation by crystallization from solutions moving through an open system. Fluids considered by some workers to be tenuous aqueous solutions and by others to be magmatic solutions.
4. *Magmatic Theory*: Injection of a granite rest magma into a closed or restricted system with subsequent crystallization producing, where conditions are favourable, a systematic sequence of mineralogical and textural units. Early-formed units may be modified by remaining pegmatite fluid due to changes in physical conditions.

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[1] Jones, A. G.: personal communication.

Nature of Pegmatite Fluid

Very few if any actual facts are known about the nature of the pegmatite fluid. However, from the experimental work of Goransen, Smith, Tuttle and Friedman, and others, combined with the knowledge of the general composition of pegmatites, it is possible to arrive at some reasonable conclusions.

From Goransen's work (1931, pp. 481-502) it is known that up to 10 per cent water is soluble in a granite magma, under conditions of high temperature and pressure. Smith (1948, pp. 535-546) has calculated that with 2 per cent water in the original magma the rest magma contains 20 per cent water after 50 per cent crystallization, 50 per cent water after 96 per cent crystallization, and 67 per cent water after 97 per cent crystallization. The results of pressure-bomb experiments led Smith (1948, p. 535) to conclude that the rest magma, near the end of magmatic crystallization is composed of two immiscible liquids, one a tenuous water solution, and the other a silicate solution with the soluble components being partitioned between the two liquids in such a way that the majority of ionic and metallic elements are confined to the water solution, and the more homopolar ones to the siliceous liquid. Temperature range of such a system is considered to be between 290 and 550°C. Tuttle and Friedman (1948, p. 926) likewise found two somewhat similar liquid phases during experimental work with the system H_2O-Na_2O-SiO_2 at temperatures ranging from 250 to 350°C. Tuttle and Bowen (1949, p. 1925) have shown that the transition from high- to low-temperature albite, in the presence of fluxes, may take place as low as 700°C. Pegmatite albite is the low-temperature type. Pegmatite quartz is also the low-temperature form, with temperature of formation below 600°C. On the basis of liquid inclusion experiments on pegmatite quartz, Ingerson (1947, p. 387) states that temperature of formation is less than 250°C.

Briefly then, it is generally concluded that a granitic rest magma, near the end of magmatic crystallization is highly aqueous. It was likewise concluded by most contemporary workers that the temperature of formation of pegmatites is considerably lower than it was previously thought. The range is now thought to be from about 250 to 550°C. Most workers consider the rest magma to be a two-component system, that is crystals and aqueous liquid, and that pegmatites and hydrothermal veins are formed by crystallization from this liquid. Pegmatites are generally considered to have been derived somewhat earlier than quartz veins. However, there does not seem to be any general agreement among those who support this theory, of just how this is accomplished. Smith's theory of two immiscible liquids supplies a very feasible origin for both pegmatites and hydrothermal veins, and for the differences in their composition. His conclusions are supported by much experimental data, and therefore deserve careful consideration.

Emplacement

The unique physical characteristics of pegmatite bodies are indicative of a unique environment of emplacement, entirely different from that of any other type of igneous dyke. From a study of these physical characteristics it is possible to arrive at certain fairly definite conclusions as to the nature of this environment. The features of pegmatites that are pertinent are—

1. Coarse and irregular grain size, with euhedral crystals commonly developed.
2. The presence of well-developed mineralogical and textural zones in some pegmatites.
3. The irregular shapes of many bodies of pegmatite and their intimate penetration in the host rock.
4. The universal absence of chilled margins, and the common presence of well-developed wall-rock alteration.
5. The common presence of fragments of wall-rock in the body of the pegmatite exhibiting various stages of digestion.
6. The influence of wall-rock composition on the composition of pegmatites as evidenced by the presence, in some cases, of certain minerals peculiar to the host rocks—for example, kyanite in kyanite gneiss.

In order to produce the features noted in 1 and 2 above the crystallization of pegmatites must have occurred from solution under very stable conditions of temperature and pressure, and these stable conditions must have pertained over a great length of time. As Flawn (1951, p. 185) points out such conditions could pertain in a deep-seated environment, where pegmatite fluid and host rock were at approximately the same temperature, and where no chilling and resulting precipitate crystallization would be expected. Intimate penetration of the host rock with accompanying dilation would only occur if a very tenuous fluid was injected, under high pressure, into preformed openings in the host rock.

The fact that most pegmatites exhibit evidence of only one major sequence of uninterrupted crystallization indicates that crystallization in most cases took place in a closed system, and that the injection was a one-pulse affair. Where evidence of multiple crystallization is present, it would appear that reopening and further injection of fresh fluid, of somewhat different composition, occurred during the period of crystallization. Depending on the timing relative to the stage of crystallization, and the differences in composition of the fluids, this could produce a variety of effects ranging from simple multiple crystallization with regular and similar discontinuity in crystal structure exhibited by all crystals of the same mineral, to extensive re-solution giving rise to varied replacement phenomena.

Crystallization

The features of pegmatites noted in 1 and 2 of the foregoing are likewise indicative of special conditions pertaining during the period of crystallization. These are: (*a*) a limited number of centres of crystallization, (*b*) a very slow and prolonged period of crystallization from a tenuous or low-viscosity liquid, and (*c*) an extremely delicate balance of solubility relations between the various pegmatite constituents.

The origin of the zones and the sequence of crystallization of the mineral components in zoned pegmatites has been extensively studied and reported by Cameron *et al.* (1949, pp. 97-106). They conclude "as a working hypothesis, that zones have developed from walls inward, essentially by fractional crystallization and incomplete reaction in a restricted system."

Conclusions

(*a*) The relatively high concentrations of rare elements contained in zoned pegmatites as compared to the low concentrations present in normal granitic rocks require some method of concentrating them into a residual fluid from which the pegmatites are produced. Such a fluid might result from fractional crystallization of (1) an original granitic magma, or (2) a granitic magma formed by palingenesis or anatexis of a large mass of crustal rocks, or formed in advance of a wave of granitization. In each case the resulting product would be similar and it is impossible by examination of the crystallized product, to determine which process prevailed.

(*b*) The exact nature of the pegmatite fluid has not been established to the mutual satisfaction of all concerned. Some geologists consider it to be a water-rich, silicate solution. Smith (1948, p. 535) thought that it was a more or less anhydrous, residual silicate solution, formed in the presence of an immiscible water solution. Of the two theories, the latter best explains the significant features of pegmatite geology. It envisages the progressive partitioning of the soluble components between the two liquids in such a way that the very ionic components such as alkali halides, sulphides, sulphates, and carbonates are confined to the water solution, whereas the more homopolar components are confined to the more viscous silicate solution. Such a partitioning of the components is in accord with the observed compositions of the products of crystallization of these solutions, namely, hydrothermal quartz veins from the water solution, and pegmatite bodies from the siliceous solution.

(*c*) It seems probable that the pegmatite fluid was emplaced by injections in a deep-seated environment where conditions of high pressure and moderately high temperature prevailed over a long period of time. In many cases, injection was a one-pulse affair, but reopening and reinjection seems to have occurred in some instances.

(*d*) Pegmatite bodies appear to have formed in situ, by fractional crystallization of the injected fluid. Under favourable physical and chemical conditions this process has produced successive layers or zones of mineralogical and textural composition.

(*e*) The amount of stoping, digestion and interaction between fluid and wall-rock that took place during injection and later crystallization varied greatly, probably depending on physical character of the wall-rocks, and on the difference in composition between the wall-rocks and the pegmatite fluid.

Occurrence and Origin of Muscovite in Mica-rich Pegmatites

In the foregoing it has been shown that the main area of disagreement between the proponents of the various theories of origin of granite pegmatites, is in the method or mechanics of producing the pegmatitic fluid. Whether the method be differentiation of a magma, granitization, or palingenesis, the resulting fluid is of much the same composition, and the method of emplacement, except as envisioned by those granitizationists who believe in selective metasomatism, is much the same. However, on investigation of the origin of the high concentrations of muscovite in muscovite-rich pegmatites, we find a further divergence of opinion, with two widely opposed theories currently prevalent. The most accepted theory—and the one accepted by most North American pegmatite geologists—is that the composition of pegmatites, including mica content, depends upon the chemical character of the source magma and the stage of crystallization of the batholith at the time of withdrawal of the pegmatite fluid. The other theory, supported by many European, African, and Indian geologists, contends that the character of the host rocks plays a controlling role in determining whether or not a particular pegmatite is mica-rich. Mode of origin of the pegmatite fluid is not considered to be of primary importance as far as mica deposits are concerned.

Occurrence

Throughout the world most pegmatites that have been mined successfully for mica occur in mica schists and gneisses, and in mica-bearing quartzites. In many cases however, the host rocks are hornblende schists and gneisses or mixtures of mica schists and hornblende schists, granites and granitic gneisses, and in one instance at least, norite.

Dunn (1942, p. 17) referring to the Indian mica deposits states, "So far as the mica belt (Bihar belt) has been surveyed to date it has become clear that payable mica-bearing pegmatites never occur in the granite, but only within the various grades of mica schists and mica gneisses." Holland (1902, p. 40), one of the earlier Indian workers, came to a similar conclusion. Bouladon *et al.* (1950, p. 229), have observed that all the pegmatites of the Tazenakht region, French Morocco, that have been exploited for their mica content, occur in schistose rocks (mica schists and migmatites) rich in muscovite. In the Kolotovha deposits of the Mama-Vitim mica-bearing region of U.S.S.R., exploitable deposits are restricted to the pegmatites occurring in gneisses. Cameron *et al.* (1949, p. 8), regarding mica deposits of the United States, say, "There is no doubt that most productive sheet-mica-bearing pegmatites of the country occur in mica schists and mica-bearing quartzites." They go on to point out that while this is true, exceptions are common so that no sweeping generalizations are justified by present knowledge. In Canada the same general association appears to be the case. The deposits of the Eau Claire district of Ontario that contain commercial or near-commercial quantities of mica, are all found in roof-pendant bodies of garnetiferous hornblende gneiss which occur in younger gneiss. The muscovite-bearing pegmatites of the Cariboo Lake district, McKonkey township, Parry Sound county, Ontario, are restricted to a small stock-like body of norite. A few miles to the northeast another similar norite stock also contains muscovite-rich pegmatite bodies. The gneissic granite surrounding the norite bodies is cut by smaller, more irregular pegmatites, which do not appear to contain the high concentration of mica found in the bodies of norite. Again in Bergeronne township, Saguenay county, Quebec, pegmatite bodies containing commercial or near-commercial percentages of muscovite appear to be confined to the mica schists and gneisses, and to the micaceous quartzites, whereas the pegmatites in the granitic rocks do not contain appreciable mica.

On Baffin Island, Fortier[1] reports that the pegmatites cutting micaceous quartzites contain muscovite in worth-while quantities, whereas those cutting nearby granitic rocks are almost, if not entirely, devoid of muscovite.

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[1] Fortier, Y. O.: personal communication.

The foregoing summary of world-wide occurrences of mica-rich pegmatites does not furnish any overwhelming evidence in favour of either theory. It can only be said that in some cases wall-rock composition appears to have an effect on mica content, whereas in others it does not.

Geochemical Considerations

Many examples are known where muscovite, plagioclase, potassium feldspar, and quartz have crystallized simultaneously, and thus, presumably under the same conditions of temperature and pressure. It would also seem logical to assume that similar pressure and temperature conditions pertained during crystallization of similar, but comparatively muscovite-free pegmatites. If such is the case it would appear that pressure and temperature do not play a critical role in determining whether or not muscovite crystallizes from any given pegmatite liquid.

Availability of the necessary elements to form the crystal lattice of muscovite would be a prime factor controlling crystallization. Since muscovite and potassium feldspar have identical chemical compositions, except for the OH ions required in the former, any pegmatite fluid capable of crystallizing potassium feldspar would also be capable of supplying all the components required in muscovite as long as sufficient OH ions were present. Thus it would seem that the presence or absence of OH ions is a possible controlling factor. If the pegmatite fluid is considered to be a highly aqueous solution, it must of necessity contain an excess of OH ions, and this argument is not valid. If however we consider that the pegmatite fluid is derived from a residual silicate solution as suggested by Smith (1948, p. 535), it would be deficient in OH ions, and the pegmatites crystallized therefrom would not normally contain hydrous minerals. Such is known to be the case in most common pegmatites. However, where the host rocks contained sufficient OH ions either as interstitial water, or as OH ions in hydrous minerals, they would provide an available source of the OH ions required to form muscovite. Such a concept might possibly explain many of the features of mica-rich pegmatites which at present appear to be incomprehensible.

Internal Structure of Granite Pegmatites with Respect to Distribution of Muscovite

Most, if not all deposits of sheet muscovite occur in complex or zoned pegmatite bodies, and their successful development and exploitation depends to a great extent upon a clear understanding of characteristic structural features exhibited by such bodies, and upon the ability of the individual to recognize these features when they are encountered, as the distribution of mica in any given body is related to, and frequently controlled by the distribution of one or more of the structural or textural units.

The presence of distinct lithological and structural units within pegmatite bodies has been recognized for many years, but until quite recently no serious attempt was made to define such units, or to establish a classification upon which further work could be based. During the period 1939 to 1946 the United States Geological Survey conducted a systematic and detailed survey of many pegmatite bodies throughout the United States. The results of this work, later reported by Cameron *et al.* (1949, pp. 1-115), represent by far the greatest advance yet achieved in our knowledge of pegmatite geology. The following is in essence a condensation of this work, augmented by information gained during the present study of Canadian mica deposits.

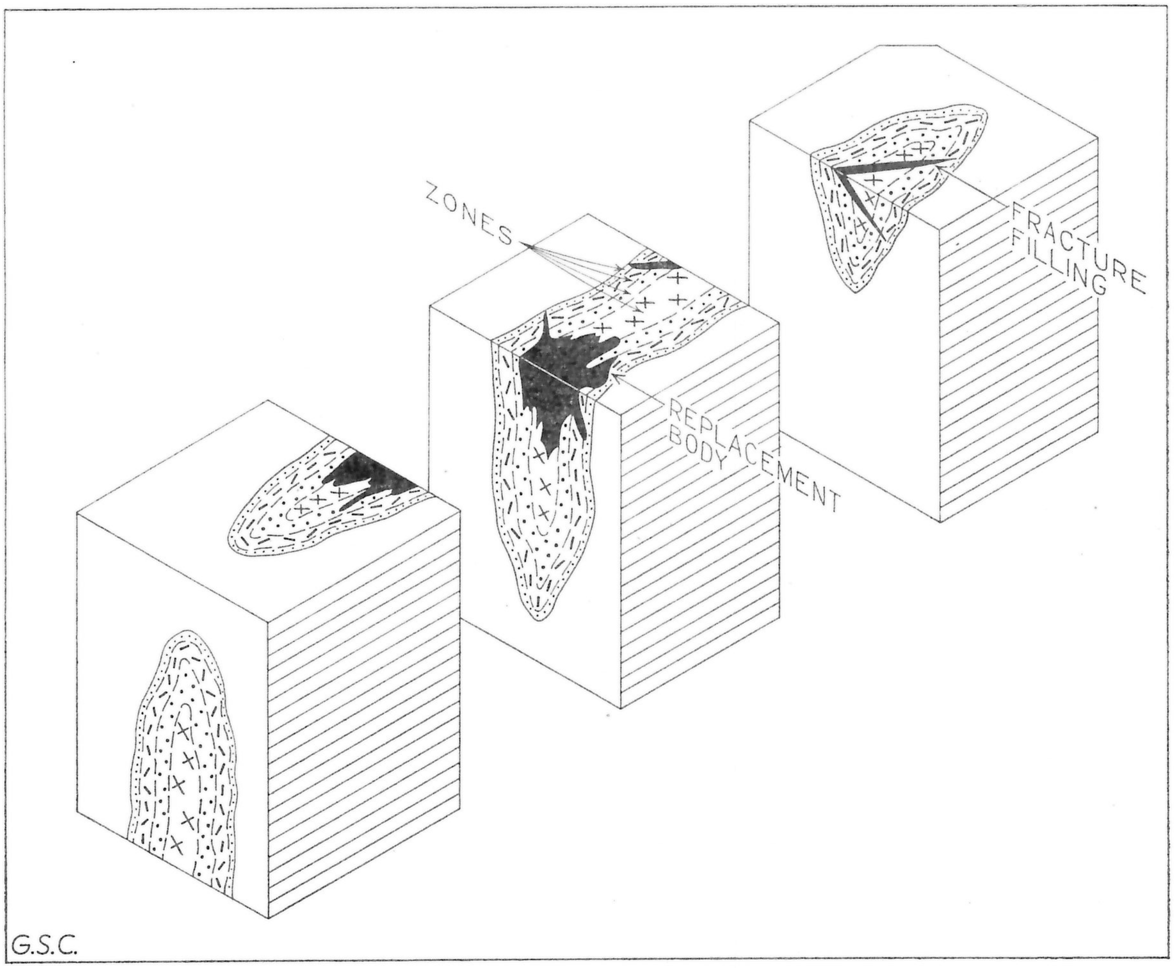

Figure 10. Idealized diagram showing relationships of units within pegmatites. (Cameron, 1949)

Internal Structure of Zoned Pegmatite Bodies

Lithological and Structural Units

Three basic lithological and structural units are found within pegmatite bodies. They are defined by Cameron *et al.* (1949, p. 14) as:

> "1. Fracture filling are units, generally tabular, that fill fractures in previously consolidated pegmatite.
>
> 2. Replacement bodies are units formed primarily by replacement of pre-existing pegmatite, with or without obvious structural control.
>
> 3. Zones are successive shells, complete or incomplete, that reflect to varying degrees the shape or structure of the pegmatite body. Where ideally developed they are concentric about an innermost zone or core. Some concentric units, however, are not zones, but belong in the categories above."

The general relationships of the three groups of units are shown diagrammatically in Figure 10.

Zones are usually the most important of the three units, both quantitatively and economically, but in some pegmatite districts, replacement units are common and of major economic importance.

Irregularity of grain size is a recognized characteristic of all pegmatite bodies, the term pegmatitic texture connotes such irregularity, but only in a general way which is inadequate for the purpose of description. For this reason Cameron *et al.* (1949, p. 16) have established the following size classification that will be used for all pegmatite descriptions in this report.

Term	*General grain size*
Fine	less than 1 inch
Medium	1 inch to 4 inches
Coarse	4 to 12 inches
Very coarse	greater than 12 inches

General Features of Zones

Cameron *et al.* (1949, pp. 16-19) describe the general features of zones as follows: "Zones reflect the shape or structure of the containing pegmatite body, and where ideally developed in a pod-shaped pegmatite they are shells concentric about an innermost zone or core. In most pegmatites, however, one or more are incomplete or discontinuous, and occur as pods, straight or curving layers and lenses; pipelike, troughlike or hoodlike bodies; chains of lenses; or as more irregular bodies. There are all gradations between complete zones and those that are developed only along one side or at one end of a pegmatite body, but whether complete or incomplete, the zones in a given pegmatite consistently reflect the form and structure of that body, commonly in considerable detail.

"Two or more zones that are clearly defined in parts of a given pegmatite may appear elsewhere to merge along their dip or strike into a single unit whose composition corresponds to the bulk composition of the zones combined. The position of this single unit with respect to the adjacent zones is the same as that occupied jointly in other parts of the pegmatite by the zones into which the single unit can be traced. Such 'telescoping' of zones is most common in podlike pegmatites and in some elongate pegmatites with local bulges or more irregular protuberances; . . . This feature is not to be confused with the simple tapering out of one zone between two more continuous units.

"Zones vary greatly in distinctness. In some pegmatites mineralogical or textural contrasts between zones are so sharply defined that the zonal structure is evident even from casual inspection. In others, zonal structure becomes evident only after detailed study, large-scale mapping and careful structural analysis.

"Although the definition of zones specifically excludes units developed by replacement of pre-existing pegmatite, the outermost zones of some pegmatites may well have been developed, entirely or in part, through replacement of country rock. The distinction between zones and replacement bodies as defined here is not always easily made, even though the two kinds of units are fundamentally different in genesis and significance. Some replacement bodies, especially those controlled by zonal structure, are concentric about the pegmatite core. The designation of some units as zones therefore must be tentative, pending conclusive determination of their origin."

Cameron *et al.* (1949, p. 20) have classified zones as (1) border zones, (2) wall zones, (3) intermediate zones, and (4) cores.

Border or outermost zones are usually thin, relatively fine-grained selvedges, and are economically unimportant. They are commonly characterized by a high concentration of biotite. Wall zones, next inside the border zones, generally are coarser and much thicker. The innermost zone or core, in most cases occurs at or near the centre of a pegmatite body, commonly as an elongate lens or as a series of disconnected segments. Any zone between the core and wall zone is an intermediate zone. There is no theoretical limit to the number of intermediate zones, but few pegmatites contain more than three.

The outer zones of a pegmatite are generally much more regular and continuous than the inner zones. Many intermediate zones are lenticular, and many are so unevenly or incompletely developed that the pegmatites are markedly asymmetric in internal structure.

Many large pegmatites in which zonal structure is not well developed, contain scattered pods or lenses of coarser texture which themselves exhibit zones outward from the centres. The sequence of these zones is consistent in any given pegmatite, and follows the normal zone sequence for the district. According to Cameron (1949, p. 21), "Every gradation between pod-bearing pegmatites with discontinuous cores has been observed."

In some zoned pegmatites that contain wall-rock inclusions or wall-rock septa, the normal zones are complicated by others which developed with respect to the inclusions or septa. Such zones, especially border and wall zones, closely reflect the position and shape of the included material.

Probably the most important thing that must be realized when dealing with zoned pegmatites is, as Cameron so aptly points out, "It is impossible to understand the internal structure of a zoned pegmatite from a two dimensional exposure. Successive horizontal or vertical sections commonly yield different zonal patterns, even in deposits of very regular structure. . . . Interpretation of the size, shape, and attitude of the pegmatite body commonly are good clues to the distribution of zones within it. In many pegmatite mining districts, it is most important to recognize the probable presence of additional zones not exposed at the surface and to predict the downward distribution of zones that do not appear there. Correlations of zonal structure with other structural features in both pegmatite and wall-rock are therefore desirable."

Distribution of Muscovite with Respect to Zones

In most zoned pegmatite bodies the greatest concentration of muscovite is usually found in the wall zone, although in many such zones it is absent.

Cameron *et al.* (1949, p. 42) state: "Wall zones are normally coarser-textured than border zones and finer grained than intermediate zones, but certain wall zone minerals, such as muscovite, tourmaline, or beryl may be much coarser than the surrounding minerals, although few exceed 12 inches in maximum dimension. The minerals commonly present in wall zones include plagioclase, perthite, quartz, muscovite, and tourmaline. Biotite, apatite, and other phosphate minerals, columbite-tantalite, garnet, and beryl are less common. Typical wall zones are composed essentially of plagioclase and quartz; plagioclase, quartz, and muscovite; plagioclase, perthite and quartz; perthite and quartz; plagioclase, perthite, quartz, and muscovite. In each pegmatite district one or more of these types predominates. . . . In general the pegmatites that contain abundant book (sheet-bearing) muscovite in the wall zones have plagioclase (andesine to median albite) and quartz associated with the mica."

The sizes of wall zones vary greatly as do their shapes and distribution within any given pegmatite body. In many simple lenticular or tabular pegmatites the wall zones are continuous envelopes enclosing inner zones. In some instances the wall zones (including border zones) comprise the whole body, while in others this only appears to happen where the total thickness of the body is less than the combined thickness of the wall and border zones in the thicker parts. In a pegmatite body of complex shape the wall zone is commonly, but not always, asymmetrically developed, or in some instances, even discontinuous. It is often much thicker along the keel and sides than on the crest or hood of the body. However, the converse of this is not uncommon. In some cases it is commonly much thicker along one wall than the other, especially when the body has an appreciable dip. In still other cases, wall zones are thickest in the vicinity of rolls or swells, bulges, or sudden changes in strike or dip of the wall-rocks.

The concentration of muscovite in any given wall zone is not necessarily constant. In most workable deposits the mica-rich parts are confined to shoots, or lenses which commonly bear a definite structural relationship to the structure of the wall zone itself. The concentration of mica is not necessarily greatest where the wall zone is the thickest. In some deposits the greatest concentration occurs on the hanging-wall side, whereas in others it is on the foot-wall. However, it is not possible to establish any general rule governing the distribution of mica-rich shoots within wall zones, beyond saying that where one does occur it will probably conform to the shape of the enclosing zone.

Intermediate zones generally contain a lower percentage of muscovite than wall zones, but since the texture is usually coarser than that of wall zones, crystals of muscovite, when present, are commonly larger and more idiomorphic than those found in wall zones.

Intermediate zones vary in composition much more than wall zones. According to Cameron *et al.* (1949, p. 48), "In lithium free pegmatites, the intermediate zones are rarely more than three in number and generally are composed of perthite or combinations of plagioclase, quartz, perthite, muscovite, and biotite. In lithium-bearing pegmatites the outer intermediate zones are formed of these same minerals, but in addition contain amblygonite, spodumene, or lepidolite, or these minerals in various combinations."

Core zones do not commonly constitute an important source of sheet muscovite, but in some rare instances, as in some of the pegmatite bodies of the Spruce Pine district of North Carolina, they yield a high proportion of sheet mica. In general, mica is more commonly present in the cores of pegmatites that contain only two zones, in which case the cores are commonly composed of medium- to coarse-grained plagioclase, potash feldspar, quartz, mica and tourmaline.

Irregularities in shape of a pegmatite caused by pinching or swelling, rolls, or branching segments are commonly reflected in the shape of the core. In long, sinuous, or tubular pegmatites, a series of lenticular core segments occurs near the centre of the body, particularly in the wider parts or at the intersection of branches.

The mineral composition and texture of cores vary from pegmatite to pegmatite, and from district to district. However, Cameron *et al.* (1949, p. 58) have been able to show that, in general, the cores of pegmatites in any given pegmatite district are similar in composition and texture. Thus, "In New England the common cores of polyzonal pegmatites are massive quartz, massive perthite, or quartz with scattered giant crystals of perthite. In the Southern States the common cores in polyzonal pegmatites are quartz or quartz-perthite pegmatite. In the Black Hills of South Dakota the common cores of sheet-mica-bearing pegmatites are quartz or quartz-perthite-plagioclase pegmatite." In general, there seems to be a rough correlation between the size of a well-zoned pegmatite and the size of the crystals in the core.

Occurrence, Distribution and Origin of Phlogopite Deposits

Occurrence and Distribution

The occurrence and distribution of phlogopite deposits are universally similar. They always occur in areas of highly metamorphosed sedimentary rocks that have been intruded by large and small bodies of pegmatite-rich granitic rocks. Within such areas, the phlogopite deposits are invariably associated with bodies of diopsidic pyroxenite which, in turn are commonly associated with bodies of crystalline limestone. This association of phlogopite, pyroxenite, and limestone is so characteristic that it serves as a fundamental guide to those in search of phlogopite deposits.

Pyroxenite

The bodies of pyroxenite which contain, or with which are associated, commercially important concentrations of phlogopite occur as irregular masses or bands elongated in the direction of the enclosing rocks. Less commonly they occur as dyke-like masses which transect the strikes of the enclosing rocks. The pyroxenite masses are variable in composition, texture, and colour. In most cases diopside is the major mineral constituent and phlogopite and apatite the most common and widespread accessory minerals. Tremolite, scapolite, and plagioclase are less common but are nevertheless widespread. Pyrite, pyrrhotite, sphene, and carbonate are widespread, but not usually abundant. In some places, hornblende occurs as an alteration product of pyroxene and as euhedral crystals in some calcite-rich veins.

The texture of the pyroxenite appears to vary with the percentage of phlogopite and apatite. In general it is a fine-grained, compact, tough and hard rock, largely composed of uniform grains of diopside ranging from 1 millimetre to 5 millimetres in length. In such cases the percentage of mica and apatite is very low, and the rock is considered by some operators to be 'dry' or unfavourable for the occurrence of phlogopite and apatite deposits. The type generally regarded to be more productive is softer, looser in texture, and more easily drilled: grain size is larger, and the rock contains scattered coarse flakes of phlogopite, generally in booklets several times the diameter of the associated pyroxene, as well as individual crystals of apatite, phlogopite, and carbonate. The size of the pyroxene grains commonly increases in the vicinity of such pockets. In most cases, the walls of the pockets are lined with large, singly terminated, euhedral pyroxene crystals.

The colour of the pyroxenite is largely dependent on the colour of the pyroxene itself. This varies from black, through various shades of green, to light greenish grey. According to Wilson (1937, p. 253), "By far the greater part of the pyroxenite has a medium grey-green colour. However, where it occurs in bodies enclosed in limestone the diopside is a white or pale grey colour, and where it occurs completely enclosed in igneous intrusives it is commonly dark green."

Phlogopite Deposits

Phlogopite deposits may be broadly classified under the following headings—

1. Vein and pocket deposits occurring within bodies of pyroxenite.
2. Vein or dyke deposits occurring within gneiss or other country rocks, marginal to bodies of pyroxenite and contact metamorphosed limestone.
3. Disseminated deposits with phlogopite occurring rather evenly distributed throughout bodies of contact metamorphosed limestone.

The first class is by far the most common, and is the only one which has yielded important amounts of phlogopite. Spence (1929, p. 41) distinguishes two types of deposits within this class. The first and economically the most important type he calls 'vein' deposits, which are characterized by persistence and regularity in width, strike, and dip, and by the common occurrence of a system of parallel or nearly parallel, single leads with well-defined walls. Vein matter consists of mica crystals, calcite, and apatite in variable proportions. Spence's second type consists of highly irregular discontinuous bodies called 'pocket' deposits. Vein matter is similar to that present in the 'vein' deposits, but contacts with the surrounding pyroxenite are usually gradational. Deposits of this type found in Portland township, Papineau county, Quebec, contain much apatite, with minor phlogopite and calcite. Elsewhere many such deposits consist almost wholly of mica, occurring as masses of closely intergrown crystals.

Vein or dyke deposits in gneiss bordering bodies of pyroxenite, or in some cases, contact metamorphosed limestone, are common but generally not of significant economic importance. According to Wilson (1937, p. 254) such deposits "consist chiefly of diopside and calcite, the former generally predominating". In the Stanleyville area, Ontario, many deposits of this type consist almost entirely of intergrown crystals of phlogopite.

The disseminated deposits do not constitute a source of phlogopite but in certain cases the contained mica has been altered to vermiculite, which is of economic importance.

Internal Structure

The internal structure of phlogopite deposits is commonly heterogeneous, with the various mineral components arranged in a disorderly manner. However, in some deposits in the Quebec district the mica is concentrated in irregular wall zones with the inner or core zone being largely composed of coarse pink calcite. In a few cases an intermediate zone of apatite has been observed between the mica and the calcite. Currie (1951, p. 774) noted this type of zoning in all the deposits he examined in North Burgess township.

Physical Features

Phlogopite commonly occurs as intergrowths or masses of poorly formed, warped and broken crystals, as in the almost monomineralic vein-type deposits of the Stanleyville area, and in many of the vein-type deposits which exhibit the zoning features described in the foregoing. Where mica occurs scattered throughout bodies of calcite or calcite and apatite, the crystals are commonly well formed and yield the best sheet mica. However, even in this type the mica is commonly reeved, and the larger books are commonly slightly waved so that relatively little sound, perfectly flat, large mica is obtained.

The colour of the phlogopite appears to be related to the colour of the pyroxene with which it is associated. Wilson (1937, p. 253) states: "the phlogopite associated with white or pale grey diopside is light coloured resembling muscovite, and that in dark green diopside, dark brown resembling biotite". He further states that phlogopite associated with the common, medium grey-green diopside is the typical medium amber variety.

Origin of Pyroxenite

Two contrasting theories of origin of pyroxenite have been advanced by the geologists who have studied the phlogopite-apatite deposits. One theory, supported by a number of the earlier workers, and more recently by Spence (1929, p. 40), classed pyroxenite as a normal basic igneous rock. The other, proposed by some of the earliest workers and readvanced in a somewhat modified form by Wilson (1937, p. 254) considered it to be a metamorphosed sedimentary rock. Adams and Barlow (1910, pp. 88-93) have described the occurrence of green pyroxene rock at or near the contact of limestone and granite gneiss in the Haliburton-Bancroft area. They ascribed the origin to contact metamorphism. The occurrences they describe coincide to the phlogopite-apatite deposits in Burgess and Loughborough townships of Ontario, and those in Quebec. Wilson (1914, pp. 159-161) ascribed the formation of the pyroxenite associated with phlogopite-apatite deposits to interaction between limestone and pegmatite solutions derived from nearby intrusive rocks. He distinguished pyroxenites of this origin as 'metamorphic pyroxenites'. Later workers such as W. W. Moorhouse (unpublished report) working in the Portland township apatite belt, and Currie (1951, pp. 765-778) have come to the same conclusions. Gevers (1948, pp. 144-145), in his description of the vermiculite-diopside-apatite deposits at Loolekop, North East Transvaal, states that the diopside, phlogopite and apatite with which the vermiculite is associated were formed by contact metamorphism of dolomitic limestone.

The original igneous theory as conceived by Spence (1929, pp. 40-41) and earlier workers, has been restated in a somewhat modified form by Landes (1938, p. 388) as follows: "The theory advanced in this paper as best fitting the observations made in the field and laboratory is that a granite pegmatite magma, unusually rich in phosphorous, became contaminated with dolomite or dolomitic limestone at much deeper levels than the present surface, where the temperatures were considerably higher. This contaminated magma moved upward into the rock now exposed, and crystallized. Diopside (pyroxenite) was the earliest product, followed by microcline and several associated minerals. Finally, aqueous solutions from the deeper crystallized magma introduced a hydrothermal phase in the already solidified parts of the pegmatite, during which calcite, apatite, phlogopite, and many other minerals were deposited."

Evidence obtained by the writer during the current work tends to corroborate the theory of contact metamorphic origin, and the following points are presented in its support.

1. Numerous cases of pyroxenite occurring at the contact between limestone and pegmatite, and between limestone and pegmatized gneiss have been observed by many workers. For example, Adams and Barlow (1910, pp. 88-91) and Currie (1951, p. 770) cite several cases which exhibit features typical of contact metamorphism.

2. All gradations between pure crystalline limestone and granular green pyroxenite were observed by Adams and Barlow (1910, p. 89). Moorhouse noted the presence of "limestone bands containing disseminated pyroxene (diopside) crystals on the Brazeau property, West Portland township, Quebec". Baker (1916, pp. 28-31) also noted the common occurrence of gradation of apatite-phlogopite deposits into limestone. The limestone on the John Byrne vermiculite property near Stanleyville, Ontario, contains abundant disseminated (in part vermiculitized) phlogopite, tremolite, and diopside.

3. The transgressive relationship of some pyroxenite bodies to the country rock was considered by Spence and Landes to be indicative of intrusive origin. However, the apparent intrusive character of some bodies of crystalline limestone of the Grenville series has been observed by many geologists, hence pyroxenite derived from such limestone would also exhibit transgressive relationship to the country rock which would not be indicative of intrusive origin.

4. Spence (1929, p. 40) states that, "the pyroxenite exhibits sharp, frozen contacts with the enclosing gneiss or limestone". Moorhouse was unable to find evidence in the West Portland area substantiating this statement. Currie (1951, p. 772) was in agreement with Moorhouse in this regard. Adams and Barlow (1910, p. 91) do not mention a single example of sharply frozen contacts, but give many instances of gradual transition from limestone to pyroxenite.

5. Pyroxenite exhibits no inclusions of host rock, as might be expected if it were of intrusive origin.

6. The minerals commonly associated with pyroxenite are characteristic of contact metamorphic zones—that is scapolite, phlogopite, apatite, sphene, and tremolite.

7. The general parallelism of the pyroxenite bands (bodies) with the structure of the enclosing rocks that has been noted by all workers is strongly suggestive of a metamorphic rather than an intrusive origin.

8. Landes (1938, p. 388) considered that the calcite, phlogopite, and apatite were deposited within the already-crystallized pyroxenite during a late hydrothermal phase. Moorhouse (unpublished report) and Currie (1951, p. 775) were of the opinion that the carbonate in these deposits is residual and represents limestone recrystallized but not converted to silicates or phosphates. Currie advanced several lines of evidence to support this view: (*a*) "The pink or flesh colour, characteristic of the calcite in the pits, is also seen in true limestone marginal to pyroxenite and grades outward from the latter to typical white limestone". (*b*) "The occurrence of rounded buttons of pink calcite completely enclosed by apatite crystals points to replacement of calcite by apatite".

9. The results of a series of experiments made by Currie (1951, p. 777), along the lines of those of Smith (1948, p. 535), appear to indicate that more than two-thirds of the phosphorous present in the granitic rest magma would be partitioned in the silicate-rich fraction. Hence, if one concedes that this fraction is the source of the pegmatitic fluid, then it, and not the hydrothermal fraction as postulated by Landes (1938, p. 388), would carry the larger amount of phosphorous, and would thus constitute the source of the apatite.

Origin of Phlogopite Deposits

In the foregoing, the evidence presented in favour of the development of the pyroxenite bodies by contact metamorphism also favours a similar origin for much of the phlogopite and apatite, especially where they occur as disseminated flakes and crystals throughout bodies of pyroxenite and bodies of less severely metamorphosed limestone. In these instances there seems to be little doubt that the phlogopite and apatite were formed contemporaneously with the pyroxene, under the influence of high-temperature metasomatism. Similarly there appears to be considerable evidence to support a contemporaneous contact metamorphic origin for the pocket-type deposits that occur within the pyroxenite. Such features as gradational contacts between the deposits and enclosing pyroxenite, and the highly irregular, pockety nature of the deposits, are characteristic of contact metamorphic origin, with the deposits forming more or less contemporaneously with the surrounding pyroxenite.

However, the structural and physical features of vein-type deposits, notably their constancy in width, strike, and dip, and the abundance of a number of parallel to sub-parallel 'veins' within a single pyroxenite body are more suggestive of injection of solutions and subsequent crystallization in pre-formed fractures within an earlier-formed part of the pyroxenite body, rather than contemporaneous formation with the pyroxenite. A similar mode of origin must also be postulated for the vein-type deposits which occur in the country rocks adjacent to pyroxenite bodies.

In summary, the evidence presented above would appear to indicate that many of the phlogopite and apatite deposits were formed contemporaneously with the pyroxenite by contact metamorphism, whereas others appear to have been formed after the surrounding pyroxenite. This situation poses the question of whether or not the solutions responsible for the formation of the post-pyroxenite bodies were derived contemporaneously from the same source as those which produced the earlier-formed pocket deposits. If not, they must be ascribed to a phase of hydrothermal or pegmatitic activity.

According to Currie's experiments (1951, p. 777), the relatively high phosphorous content of the solutions would appear to indicate that they were related to pegmatitic rather than hydrothermal activity.

Apart from the fact that the vein-type deposits seem to have been formed later than the other types, evidence as to the age and source of the solutions responsible for their formation is inconclusive. It is known that post-pyroxenite pegmatite activity occurred, since stringers and bodies of pegmatite are known to cut pyroxenite and apatite deposits. However, Moorhouse found no evidence of more than one generation of pegmatites. It must therefore be concluded that either of the following theories of formation of vein-type deposits is possible.

1. Deformation and fracturing may have occurred at a late stage in the development of the pyroxenite but before complete crystallization of the pocket-type deposits, causing the remaining fluid to be injected into fractures within the already-formed parts of the pyroxenite, and also into fractures in the adjoining country rocks.

2. Deformation and fracturing may have occurred at some time after the formation of the pyroxenite and associated pocket deposits. Solutions similar to those which previously gave rise to the pyroxenite and pocket deposits, but related to a later and separate phase of pegmatitic activity, were then injected into these fractures forming the 'vein' deposits.

Other Varieties of Mica

Substantial deposits of both biotite and lepidolite occur in Canada, but since neither variety is of importance as sheet mica, details of the various occurrences are not included in this report.

Information on Canadian deposits of biotite and lepidolite is given by Spence (1929, pp. 86-95); and on lepidolite, by Rowe (1952).

Chapter IV

GEOLOGY OF VERMICULITE DEPOSITS

Vermiculite is a micaceous mineral that possesses the characteristic property of exfoliation upon sudden heating to a high temperature. While it has been definitely established that vermiculite exists as a distinct and separate mineral, the name is commonly applied to any and all minerals or combinations of minerals that possess any degree of the property of exfoliation, and also to the expanded commercial material. In this report, the term vermiculite when used without qualification, will therefore refer only to the actual mineral.

The degree of linear expansion upon exfoliation varies considerably from one specimen to another. The maximum is about thirty times. The expanded product is very light, having an apparent density of from 4 to 20 pounds per cubic foot, depending on the degree of expansion and the grain size. It also has a very low coefficient of thermal conductivity, and therefore constitutes a high-grade, lightweight, thermal insulator for which there is a large and ever-increasing market.

At present the major world producers of vermiculite are the United States and South Africa (U.S.S.R. excepted). As yet Canada has no known commercial deposits, although in recent years significant amounts of the mineral have been discovered at various localities in southeastern Ontario and British Columbia.

With the exception of the large deposits at Libby, Montana, virtually no vermiculite occurrences have been explored to any appreciable depth. For this and other reasons much controversy and much uncertainty has arisen as to the origin of the mineral. Many geologists and probably most mining men consider that vermiculite is an alteration product of mica, formed by the action of meteoric waters; others believe that the alteration is the result of hydrothermal processes. While this controversy may appear to some to be concerned with a mere scientific technicality, it nevertheless has an important bearing on the possible size of any given deposit. If the former theory is true, all deposits must be considered to be confined to the zone of circulating meteoric waters. If, however, the hydrothermal theory of origin is correct this limiting factor on the size of deposits is automatically removed. The problem of determining the mode of origin is therefore of major importance in assessing Canada's potential resources of vermiculite and allied minerals. The writer bases the conclusions in this report on information obtained from literature on the subject, supplemented by knowledge gained by examination of Canadian occurrences, and laboratory work.

Mineralogy of Vermiculite

Vermiculite was first described and named by Webb (1824, p. 44). Subsequent descriptions were made of many other minerals having similar properties—all of which were generally known as vermiculites.

Following the advent of X-ray crystallography and the elucidation of the mica structure by such workers as Maugin (1928) and Pauling (1930), the structure of the vermiculite minerals was investigated by Gruner (1934, 1939), Kasanda and Barth (1935), and Hendricks and Jefferson (1938).

From the findings of these workers it is now known that vermiculite exists as a distinct mineral, that can be represented by its own structural formula, and that it is almost always an alteration product of one or other of the mica minerals. The great variety of names and the apparent disparities in composition between the various specimens have undoubtedly originated from the fact that in many cases the alteration from mica to vermiculite did not proceed to completion. Since this alteration is accompanied by colour change as well as progressive changes in the physical properties, an almost infinite variety of physical characteristics and chemical compositions are possible, although the end product is identical in all cases where alteration is from mica.

Physical Properties

The physical properties of vermiculite may vary considerably, depending on the degree of alteration and the composition of the original mineral involved. Colour varies from a light silvery or golden tan in true vermiculite, through various shades of brown, red-brown, and in some cases green, to almost black. The mineral has a dull or drab lustre and feels soft and somewhat soapy or talcose. Hardness varies from 1.5 in true vermiculite to 2.5 to 3.0, depending on the type of mica from which it was derived. Specific gravity likewise ranges from a theoretical value of 2.13 (Gruner) to that of the original mica concerned. Cleavage is perfect basal as in mica, but unlike mica the laminae are inelastic, soft, and pliable. Crystals are usually irregularly warped and exhibit a characteristic bloated or puffed-up appearance. True vermiculite is opaque even in thin laminae.

Structure and Composition

While the basic structure of vermiculite, which is related to and derived from minerals of the mica group, is similar to that of the parent minerals, there is an essential difference in the manner in which the double layers of linked silica tetrahedra are joined together. According to Gruner (1934, p. 574) the vermiculite structure consists of double sheets of linked tetrahedra, as in mica, between which are interstratified layers of water molecules. The change from mica to vermiculite involves a complete loss of K^+ ions from between the double sheets, and their replacement by water molecules. The latter, due to their large size, give rise to an expanded structure. Gruner felt that the additional changes involved consist of the oxidation of Fe^{++} to Fe^{+++} ions, some of which continue to occupy octahedral or intralayer positions in the structure, while others replace some of the silicon atoms in the tetrahedra. The structural formula as proposed by Gruner (1934, p. 574), and later supported by Hendricks and Jefferson (1938, p. 851), is

$$(OH)_2(Mg\ Fe)_3(Si\ Al\ Fe)_4O_{10}\ .\ 4H_2O.$$

The structure according to this formula is essentially that of a neutral lattice, like talc, with neutral water molecules instead of K^+ ions between the layers. Gruner (1934, p. 561) suggested that the change from a negatively charged to a neutral lattice, as necessitated by the substitution of water molecules for K^+ ions between the lattice layers, was accomplished by the replacement of Fe^{++} by Fe^{+++} ions in the octahedral layer. He (Gruner, 1939, pp. 420-433) realized that this formula was not entirely satisfactory during the course of experiments on conversion of vermiculite to NH_4 mica. Since he was able to effect the conversion and since it would not have been possible with a neutral vermiculite structure, the formula was obviously wrong. He then postulated the presence of charged water molecules between the layers, but this was later disproved by Barshad (1948, p. 658) who further investigated the vermiculite structure. The results of his work as they affect structure and composition are summarized as follows:

1. Vermiculite is essentially a mica with Mg^{++} or, Mg^{++} plus Ca^{++} ions instead of K^+ ions, and water molecules, occupying the interlayer positions.
2. Based on experimental and calculated results for interlayered cations, the formula for vermiculite may be written

$$(H_2O)_x(Mg\ Ca)_y(Al\ Fe\ Mg)_z(Si\ Al\ Fe)_4O_{10}(OH)_2$$

where x represents the molecules of H_2O, y the interlayer cations, and z the octahedral ions.

The results of the experimental work upon which Barshad has based the above conclusions permit an entirely new concept of the structure and formation of vermiculite to which the unusual physical properties of the mineral can be better related, and which, in the writer's opinion, supplies additional evidence as to its mode of origin. Therefore a detailed account of the results of these experiments is presented in the following.

Briefly, the investigations deal with the base-exchange property of vermiculite and vermiculite-like minerals, the relationship between the kind of exchangeable bases present and the degree of hydration, between hydration and expansion of the vermiculite lattice, and between exchangeable bases, hydration, and exfoliation of these minerals and combinations of minerals. The experiments also included investigations in the conversion of biotite into vermiculite by means of base exchange.

The experimental materials used were:

Sample No. 1.—Vermiculite from Union of South Africa, pale yellow translucent sheets.
Sample No. 2.—Vermiculite called culsageeite or jeffersite, from Culsagee Mine, Macon county, North Carolina; bronze in colour and in large flakes.
Sample No. 3.—Protovermiculite from Magnet Cove, Arkansas; large golden yellow scales.
Sample No. 4.—Vermiculite from Libby, Montana; dark greenish brown scales. (From the same source as Gruner's vermiculite No. 10).
Sample No. 5.—Vermiculite from Lenni, Delaware county, Pennsylvania; apple green, compact, and in small scales.
Sample No. 6.—Biotite (source unknown).
Sample No. 7.—Prochlorite from Chester, Vermont.

Base Exchange

The concept of base exchange is represented by the equation

$$AX + B^+ \rightleftarrows BX + A^+$$

where A and B represent solution cations of equal charge, and AX and BX represent the exchange material saturated with A^+ and B^+ respectively. When the exchange material has only one kind of exchangeable cation, the material is said to be saturated with respect to that ion. The total amount of exchangeable cations is usually expressed as milliequivalents per 100 grams (1 milliequivalent equals .008 gram) and this quantity is called the base-exchange capacity.

The experimental procedure involved in effecting base exchange included leaching of exchange material in a neutral solution of the desired cation at a temperature of 70°C. for a period of about 10 days, with frequent filtering and renewal of salt solution. Standard methods of analysis were used to determine the bases replaced from the sample, and the bases adsorbed by the material from the solution.

Base-exchange Capacity of Vermiculite

Barshad's experiments (as shown above) determined the actual presence of exchangeable bases in the vermiculite lattice. Walker (1951) later arrived at the same conclusion.

The results of some of Barshad's experiments on base exchange are given in Table VII, which shows the bases present in various samples of natural vermiculite that were exchanged for NH_4 ions.

Table VII

Bases Exchanged for NH_4^+ by Unground and Lightly Ground Vermiculites, when Leached with N Neutral NH_4 Acid Solution

Vermiculite	Exchangeable Bases*					NH_4^+ adsorbed
	Mg^{++}	Ca^{++}	Na^+	K^+	Σ	
Sample No. 1. lightly ground	128.3	13.7	0.0	0.0	142.0	141.3
Sample No. 2. lightly ground	146.0	0	0.0	0.0	146.0	145.5
Sample No. 3. unground	144.5	0	0.0	0.0	144.5	145.9
Sample No. 4. lightly ground	40.0	93.0	0.0	0.0	133.0	134.0
Sample No. 5. lightly ground	65.5	0	0.0	0.0	65.5	64.8

* Milliequivalents per 100 grams air dry material (Barshad, 1948.)

The similarity in the total amounts of bases exchanged (Σ) and of NH_4^+ adsorbed in each case indicates that the bases found in the leachates were actually replaced by NH_4^+. The lack of any marked difference in the exchange capacity between ground and unground samples would appear to indicate that particle size has little effect on the base-exchange capacity of vermiculite.

The results of other experiments conducted by Barshad indicate that the exchange processes between Na^+, Ca^{++}, Mg^{++}, and K^+ ions are completely reversible, whereas those between K^+, NH_4^+, Rb^+, and Cs^+ ions are only partly so. Thus the low exchange capacity of Sample No. 4 (Table VII) is understandable when it is realized that the exchangeable bases in this specimen (Libby, Montana, hydrobiotite) include K^+ ions which could not be exchanged for NH_4^+ ions. It will be noted that Sample No. 5 had an even lower exchange capacity than No. 4. This, however, is not due to the presence of K^+ ions but to the fact that the specimen is not a true vermiculite but a chlorite-vermiculite, and as such, simply has a lower exchange capacity than vermiculite.

That the exchange capacity is not due to the presence of water is indicated by the fact that heating to 255°C. with consequent dehydration to the extent of losing all free water, only slightly reduced the capacity.

Hydration of Vermiculite

As we have already seen, the alteration of mica to vermiculite is accomplished by a slight rearrangement of the atoms within the lattice layers and by the replacement of the interlayered K^+ ions by other cations, generally

Mg^{++}, or Mg^{++} plus Ca^{++} ions in natural vermiculite, by means of base exchange. This exchange process is accompanied by the introduction of varying amounts of water molecules between the lattice layers, the amounts being determined in any one case by the kind of exchangeable ion present (Barshad, 1948).

Tables VIII and IX give the results of differential thermal analyses of the water content of various samples of vermiculite or vermiculite-like minerals. Table VIII shows the results with one sample (No. 2), portions of which were saturated with different cations; whereas Table IX shows the results of similar experiments with samples of natural vermiculite (Nos. 1 and 3), chlorite-vermiculite (No. 5), and hydrobiotite (No. 4) both in its natural state, and after having been saturated with various cations. The interlayered water present in each case is represented by the amount lost during heating below about 300° C. The effect of the kind of exchangeable ion present on the total of such water is readily seen in Table VIII. Note that the water decreases from a maximum of about 15 per cent or 12 molecules per adsorbed ion in the Mg^{++} and Ca^{++} saturated samples, to about 3 per cent or 1 molecule per adsorbed ion in the K^+, Rb^+, and Cs^+ saturated samples. The results of experiments with natural material, reported in Table IX, are very similar to those in Table VIII except for samples No. 4 (natural) and No. 5. Sample No. 4 (natural) is hydrobiotite, in which the

Table VIII

Loss in Water at Various Temperatures from Vermiculite Sample No. 2 (Table VII) Saturated with Various Cations (Barshad, 1948)

Temp.	20-150°C.		150-250°C.		250-550°C.		150-600°C.		550-800°C.	Total
Exchangeable Ion	Per cent	Molecules H_2O per adsorbed cation	Per cent	Molecules H_2O per adsorbed cation	Per cent	Molecules H_2O per adsorbed cation	Per cent	Molecules H_2O per adsorbed cation	Per cent	Per cent
Mg^+	12.85	10	2.65	2	1.32	1			4.59	21.31
Ca^{++}	12.90	10	2.68	2	1.32	1			4.85	21.75
Ba^{++}	8.50	6					2.72	2	3.31	14.54
Li^+	8.30	3					2.83	1	4.79	15.92
Na^+	8.50	3					2.92	1	4.92	16.34
K^+	1.21	0.3					2.46	0.8	2.73	6.40
Rb^+	1.50	0.5					1.60	0.5	2.62	5.72
Cs^+	1.71	0.5					2.29	0.7	2.26	6.26

Table IX

Loss in Water at Various Temperatures from Natural Vermiculites and from Vermiculites and Biotite Saturated with Various Cations (Barshad, 1948)

Temp.		20-150°C.		150-250°C.		250-400°C.		400-600°C.	600-900°C.	Total
Vermiculite Sample No.	Exchangeable Ion	Per cent	Molecules H_2O per adsorbed cation	Per cent	Molecules H_2O per adsorbed cation	Per cent	Molecules H_2O per adsorbed cation	Per cent	Per cent	Per cent
1. Natural	Ca Mg	13.07	10	2.62	2	1.31	1		4.85	21.75
3. Natural	Ca Mg	11.95	10	2.39	2	1.20	1	0.52	4.28	20.34
5. Natural	Mg	5.79	10	1.32	2	0.65	1	4.09	4.70	16.55
4. Natural	Mg Ca K	3.30	10	0.65	2	0.34	1		1.60	5.89
4.	Mg	12.30	10	2.48	2	1.21	1		4.10	20.09
4.	Ca	12.47	10	2.48	2	1.23	1		4.35	20.53
4.	Na	7.46	3	2.35	1				4.50	14.31
4.	K	1.20		0.25					1.60	3.05
1 micron Biotite	K	0.34							1.24	1.59
1 micron Biotite	Mg	12.77		2.70		1.45				

exchangeable bases consist of about 75 per cent K, 15 per cent Ca, and 10 per cent Mg (Barshad 1948, p. 671). Since the interlayered water content is due almost entirely to the exchangeable Mg and Ca present, which in this case is only about one-quarter of that of natural vermiculite, the water content is thus only one-quarter of that of vermiculite, or Mg-saturated hydrobiotite. Sample No. 5 is Mg-saturated, but as previously shown the exchange capacity is only half of that of natural vermiculite, thus the interlayered water content is reduced accordingly.

It is interesting to note that the interlayered water content of natural biotite is almost negligible, but when the K^+ ions are exchanged for Mg^{++} (the biotite is then virtually altered to vermiculite), the amount of interlayered water is equal to that of natural vermiculite.

From the results of Barshad's work we now know the amount of interlayered water in vermiculites and its relationship to the kind of exchangeable ion present. However, in order to understand the reason why this water content is dependent on the kind of exchangeable ion present, it is necessary to consider the factors involved in what is known as hydration of ions.

Hydration of Ions

When charged ions are present in a solution they tend to surround themselves with water molecules. The molecules that surround the ion form its hydration shell and the phenomenon is termed hydration of an ion. The maximum hydration of any given ion is limited to the number of molecules that can be packed in mutual contact around it. When such a condition occurs, the number of water molecules surrounding the ion will be equal to the coordination number of the ion. However, the degree of hydration of any given ion—that is the number of water molecules actually present in the hydration shell compared to the maximum number that could be present if the ion were completely hydrated—is related to the ionic potential of the ion. The value of this potential is a function of the size and the valence or ionic charge of the ion and is equal to Z/r, where Z = the valence, and r = the radius of the ion (Mason, 1952, p. 138).

A list of ionic potentials of the elements with which the discussion is concerned, together with their ionic radii and coordination numbers, is given in Table X (Mason, 1952, p. 138).

Table X

Ionic Potentials

Element	Z/r	r	Coordination No. (calculated)
Cs	0.61	1.65	12
Rb	0.67	1.49	12
K	0.75	1.33	12
Na	1.0	0.98	8
Li	1.3	0.78	6
Ba	1.4	1.43	12
Sr	1.6	1.27	8
Ca	1.9	1.06	8
Mn	2.2	0.91	6
Fe	2.4	0.83	6
Mg	2.6	0.78	6

While the large monovalent ions such as Cs, Rb, and K, theoretically have the most water molecules in their hydration shells since the coordination number of each is 12, they actually possess the lowest degree of hydration, due to their low ionic potential. Bernal and Fowler (1933, p. 533) state that "for univalent ions of radius greater than 1.6Å no hydration is to be expected". All other monatomic univalent and all polyvalent ions will be hydrated to a greater or lesser degree.

The actual determination of the absolute degree of hydration of any given ion is difficult and it is complicated by various factors. Bernal and

Fowler (1933, p. 532) have done so for most of the elements listed in Table X, but their results are not given in terms of molecules of water, and are difficult to interpret. In any case it is sufficient for this discussion to know that the Mg^{++} ion is most probably hydrated completely, whereas the K^{+} ion is only partly hydrated, and the Rb^{+} and Cs^{+} ions not at all. This of course is in accord with the results of experiments by Barshad, which indicate that there are 13 water molecules per adsorbed Mg^{++} ion (per unit cell of vermiculite). Comparing this with the coordination number (6) of Mg, we see that the former is more than double the latter. No clear explanation of this apparent anomaly appears to have been established but the discrepancy may be due to the fact that hydrated ions moving through a liquid carry with them not only the water molecules that are in their hydration shell, but also an additional mass of water (molecules) bound to them by what is called hydrodynamic effect (Bernal and Fowler, 1933, p. 531). It is thought that the amount of such water may likewise be proportional to the ionic potential of the ion. However this may be, we now know that the ratio of water in the hydration shell of Mg^{++} or Ca^{++} ions to total interlayer water is 6/13 or about 46 per cent.

It thus appears that when an hydrated ion, such as Mg^{++} enters the interlayer space in vermiculite, it carries with it 13 water molecules. The disposition of these water molecules within the interlayered space is difficult to ascertain, with the result that there is considerable disagreement among the various workers. From Barshad's work on lattice expansion, it is known that in Mg^{++} saturated vermiculite they occupy a space equal to 4.17Å (the basal spacing of Mg^{++} vermiculite, 14.33, less 10.16Å, the thickness of one single sheet of biotite). It seems reasonable to suppose that the 6 molecules in the hydration shell would tend to remain grouped around the Mg^{++} ion if at all possible. Walker (1952, p. 206) suggested such an arrangement, but appeared to be of the opinion that the space available is greater than that determined by Barshad (4.97Å as opposed to 4.17Å), and he considered that the molecules form an octahedral group around the Mg^{++} ion. Since this entails a minimum space of 5.52Å (twice the diameter of a water molecule) and only 4.17Å is available, this method of packing does not seem entirely feasible. It seems more likely that the 6 molecules form a close-packed group around the Mg^{++} ion, thus making it possible for them to be accommodated in the space available. The remaining water molecules, i.e. those attached by hydrodynamic forces, would be forced into two staggered layers in the space between the groups previously described. Barshad however, did not differentiate between molecules of the hydration shell and the less firmly attached hydrodynamic molecules. He considered that they are all arranged in the form of two monomolecular layers consisting of hexagonal rings similar to the hexagonal rings of oxygen molecules at the bases of the tetrahedra in the lattice layers. The evidence obtained by Barshad's differential thermal analyses of the water content appears to indicate a difference in bond strength for part of the interlayer water, since about 12 per cent is given off below 150°C. with the remaining 4 per cent given off between 150 and 300°C. This would seem to lend support to Walker's theory.

Lattice Expansion

The alteration of mica to vermiculite, involving the exchange of the interlayer K^+ cation for Mg^{++} cations plus the addition of adsorbed water, causes an expansion of the mica lattice. It is this expansion which is responsible for the puffy or bloated nature of vermiculite as compared to the flat, plate-like mica structure. The amount of expansion that takes place is almost directly proportional to the interlayer water content of the specimen concerned, and as we have already seen, this in turn is related to the kind of exchangeable ion present.

The results of Barshad's experiments on lattice expansion, reported in Tables XI and XII, clearly show the difference in the amount of expansion with different saturating cations. The relationship between hydration, lattice expansion, and the kind of saturating cation is indicated in Table XIII.

Table XI

Basal Reflections (d002) for Vermiculites and Biotite Saturated with Various Cations and Dried at Various Temperatures (Barshad, 1948)

Saturating Cation		Mg^{++}	Ca^{++}	Ba^{++}	Li^+	Na^+	K^+	NH_4^+	Rb^+	Cs^+	K^+ 75%, Ca^{++} and Mg^{++} 25%
Specimen											
Verm. #2	Air dry	14.33	15.07	12.56	12.56	12.56	10.42	11.24	11.24	11.97	
Verm. #1	Air dry	14.33	15.07			12.56	10.42	11.14			
Verm. #3	Air dry	14.92	14.92								
Verm. #4	Air dry	14.33	15.07			12.48	10.34				11.77
Biotite	Air dry	14.47					10.29				
Verm. #2	750°C.	9.40	9.55	10.27	9.55	9.55	10.27	9.25	10.46	11.22	
Verm. #1	750°C.	9.50	9.50			9.60	10.27	9.25			
Verm. #3	750°C.	9.60	9.60								

Table XII

Basal Reflections (d002) for Vermiculite Samples Which Have Undergone the following Base-exchange Reactions: Natural X ⇄ KX ⇄ NaX ⇄ MgX (Barshad, 1948)

Sample Air Dry	Natural (MgX)	KX	NaX	MgX
Vermiculite #1	14.33	10.42	12.56	14.33
Vermiculite #2	14.33	10.42	12.56	14.33

Table XIII

Relation Between Hydration, Lattice Expansion and Saturating Cation in Vermiculite #2 (after Barshad)

Saturating Cation	Mg^{++}		Ca^{++}		Na^{++}	
	H_2O on ignition basis %	(d002) basal spacing Å	H_2O on ignition basis %	(d002) basal spacing A	H_2O on ignition basis %	(d002) basal spacing Å
Air dried	27.10	14.33	27.80	15.07	19.51	12.56
Heated to 150°C	10.75	11.77	11.31	11.77	9.36	10.27
Heated to 250°C	7.38	10.34	7.89	10.20	6.77	10.13
Heated to 550°C	5.83	10.00	6.20	10.00	5.87	10.00
Heated to 750°C	0.00	9.50	0.00	9.65	0.00	9.60
Immersed in Water	100.	14.47	100.	15.41	100.	14.76

The data in Tables XI, XII and XIII suggest the following conclusions:

1. Mg^{++} and Ca^{++} saturated samples contain the most water, and have the widest basal spacing (greatest lattice expansion).
2. Rb^{+}, Cs^{+} and K^{+} saturated samples exhibit the smallest basal spacing (the least expansion), and Ba^{++}, Li^{+}, and Na^{+} expand by an amount that is intermediate between that of Mg and that of K.
3. Expansion in conclusion 1 is approximately equal to the thickness of two monomolecular layers of water. Expansion in conclusion 2, when Ba^{++}, Li^{+}, or Na^{+} saturated, is about equal to one monomolecular layer of water; the lattices in Rb^{+}, Cs^{+}, and K^{+} saturated samples remain contracted.
4. Only the Na^{+} sample showed an appreciable increase in expansion of lattice as the result of immersion in water after being saturated with the desired ion as compared to expansion observed in normal

air-dried material. The increased expansion in this case, from 12.56Å to 14.76Å, is equivalent to one monomolecular layer of water.

5. The contraction observed during heating to temperatures below ignition represents loss of water from between the lattice layers, whereas contraction from heating at or above ignition appears to be caused by loss of OH ions from within the layers of linked silica tetrahedra.

Interleaved Structures

So far consideration has been largely confined to specimens of true vermiculite whereas many deposits do not necessarily contain true vermiculite but material in various stages of vermiculitization. Therefore, an understanding of the various types of interleaved structures that occur is important to the economics of vermiculite in general.

Hydrobiotite

The material that is mined from the large and economically important deposits at Libby, Montana is not true vermiculite, but a combination of vermiculite and biotite. Gruner (1934, p. 572) named this material hydrobiotite, and established that it was composed of interleaved layers of vermiculite and biotite in the ratio of 3 biotite to 1 vermiculite. Hendricks and Jefferson (1938), and later Barshad (1949, p. 682), have confirmed Gruner's work.

Barshad investigated the exchange capacity, hydration, and lattice expansion of Libby hydrobiotite, and was able to convert it to true vermiculite by means of base exchange. He reports that the exchangeable bases in the natural hydrobiotite consist of 75 per cent K^+, 15 per cent Ca^{++} and 10 per cent Mg^{++}. Table IX shows that the adsorbed water content of Mg^{++} saturated hydrobiotite was 14.78 per cent, whereas that of natural hydrobiotite was only 4.95 per cent. Therefore, since the interlayered water content of Mg^{++} saturated hydrobiotite is almost identical to that in natural vermiculite samples No. 1 and No. 3, there seems to be little doubt that Barshad's conclusion is correct—the hydrobiotite was actually converted to vermiculite by simple base exchange.

Conversion of Biotite to Vermiculite

The studies conducted by Barshad (1948, p. 670) in conversion of biotite into vermiculite are significant and highly important. He reports that finely ground (1M) biotite when leached for three months in $MgCl_2$ solution at 70°C. was found to be entirely converted to true vermiculite. X-ray diffraction patterns of the leached material showed basal spacings of 14.47Å (*see* Table XI) compared to 10.29Å when K+ saturated (i.e. natural biotite). As shown in Table XI, the converted material contained 15.40 per cent water between the layers, while the unconverted had only 0.34 per cent in the same position. The basal spacing and water content of the Mg+ saturated biotite correspond very closely to those of natural true vermiculite, indicating that the biotite was in effect, actually converted by base exchange into vermiculite. However, it is important to note that the exchange capacity of the biotite decreased rapidly with increase in grain size, and that only the very finely ground material was completely converted to vermiculite in the three months under the conditions prevailing during the experiment.

Occurrence of Vermiculite

Classification of Deposits

Vermiculite always occurs associated with bodies of ultrabasic to basic rocks, and while it is possible to make a broad twofold subdivision of the mode of occurrence, this division is largely based on origin and type of basic rock with which the vermiculite is associated rather than on the actual difference in mode of occurrence of the vermiculite itself.

The divisions that can be recognized are:

1. Vermiculite that occurs as an alteration product of biotite and occasionally phlogopite, that themselves result from alteration of or from reaction between previously emplaced basic or ultrabasic rocks, and subsequently intruded syenitic rocks.

2. Vermiculite that occurs as an alteration product of phlogopite, and occasionally biotite, that occur associated with bodies of diopside apatite-carbonate rock which have been formed by the action of solution emanating from syenitic intrusive bodies upon nearby bodies of dolomitic carbonate.

In both cases the rocks involved are commonly highly serpentinized.

The main difference between the two types of deposits stems from a difference in origin of the associated basic rocks. In the first case the origin of the basic host rocks does not appear to be related to the syenitic solutions that were responsible for the development of the mica, which was subsequently transformed into vermiculite. In the second case the mica, from which the vermiculite was derived, constituted an original constituent mineral of the associated ultrabasic rock; the whole, including the mica, being formed more or less contemporaneously.

Each of these classes can be further divided into two or more subdivisions, on the basis of the structure and mineral association. These classes are:

1(a) Those deposits in which the vermiculite occurs as a contact phase between corundum-bearing albitite (aplite) dykes and basic host rocks; usually accompanied by bands of amphibole and talc.

(b) Where pyroxenite or other ultrabasic bodies have been intruded by syenite pegmatite dykes, or by solutions derived from such dykes causing widespread formation of biotite, which was subsequently altered to vermiculite. The dykes in this case do not appear to be corundum-bearing, nor is the vermiculite associated with amphibole and talc as in 1(a).

(c) Vermiculite associated with deposits of crysotile and amphibole asbestos.

2(a) As more or less evenly disseminated grains, or as clumps of grains, irregular vein-like bodies, and masses of vermiculite replacing carbonate rocks. Generally associated with varying amounts of apatite, diopside, and in some instances magnetite.

(b) As veins, dykes, or irregular lenses of vermiculite or vermiculitized phlogopite associated with apatite, diopside, and calcite, occurring as fracture filling in rocks adjacent to the carbonate bodies in 2(a).

(c) Masses of rock composed almost entirely of vermiculite and serpentine which are found associated with class 2(b) deposits.

Examples of Various Types of Deposits

The deposits belonging to class 1(a) are well exemplified in the corundum-albitite bodies of North Carolina, Georgia and Maryland; the corundum deposits of Northern and Eastern Transvaal, and of the U.S.S.R.

In describing the corundum deposits of Southeastern United States, Larsen (1928, p. 398) noted that "in all the occurrences the albitite and albitite corundum rocks (plumastite) cuts serpentine, peridotite, pyroxenite, hornblendite, or other ultrabasic rocks, and in all the ultrabasic rock next the albitite or plumastite is altered in a similar manner with a layer of biotite-phlogopite or their alteration product vermiculite next the albitite". Referring to the deposits at Wiant's Quarry, Maryland, Larsen (1928, p. 407) noted that "on both sides of the albitite bodies and separating them from the serpentine, there are three distinct layers. In passing from the albitite to the serpentine their order is (1) vermiculite layer; (2) amphibole layer; (3) talc layer. . . . The vermiculite layer is made up very largely of a vermiculite derived from biotite or phlogopite but contains more or less fluorapatite and locally talc and anthophyllite". At Sparvetta Quarry, 1 mile northwest of Sylmar, Maryland, Larsen (1928, p. 409) observed that "about many of the albitite bodies . . . are veinlets of biotite, amphibole, and talc which penetrate for many feet into the serpentine. Some of the veinlets are a foot wide and have centers of vermiculite, flanked first by bands of amphibole, then by talc . . . usually narrower veinlets lack the central vermiculite band, and some narrower ones contain only talc". Larsen (1928, p. 411) and Hunter and Mattocks (1936, p. 3) noted the occasional presence of feldspar crystals within the vermiculite zones of these corundum-albitite bodies.

According to Hall (1920b) the corundum deposits of Northern and Eastern Transvaal exhibit a relationship between aplite dykes, ultrabasic intrusive bodies, and vermiculite that is similar to that of the United States deposits. In particular he noted that "a casing (vermiculite zone) of the reef is almost invariably present".

These occurrences of vermiculite associated with corundum-bearing aplite dykes are only a few of the many examples described in geological literature, but they are sufficient to indicate that the mode of occurrence and mineralogy of all such deposits is similar and that they belong to a distinctly separate class which has world-wide affinities.

The best-known and largest deposits belonging to class 1(b) are those occurring at Libby, Montana. In his summary of these deposits, Heinrich (1949, p. 333) points out that the intrusion of syenite pegmatite into pyroxenite first produced biotite (an alteration product of pyroxene and amphibole) which was altered subsequently to vermiculite by later pegmatitic solutions. It is noted that the vermiculite deposits show no relationship to present water table.

Numerous examples of class 2 vermiculite deposits occur in many parts of the world. In almost all cases they exhibit a marked similarity in mineralogy and in mode of occurrence. For example, the vermiculite deposits that occur in the carbonatite ring structures of Eastern Uganda belong to this class. These structures, of which there are five or more, consist of a carbonate core, surrounded by successive rings of (a) magnetite, (b) apatite and phlogopite in varying proportions, (c) syenitic rocks, and (d) granite. Davies (1947, p. 142) states that in these deposits "phlogopite is never seen within at least 60 feet of the surface and is represented entirely by vermiculite". The vermiculite occurrence at Loolekop in the Palabora district, North East Transvaal is another excellent example of this class of deposit. The general geology of the Loolekop region is similar to that of the carbonatite-apatite ring structure of Uganda, but it has received much more detailed investigation. It appears questionable whether a similar origin can be ascribed to both the Uganda and the Palabora deposits. The essential features of the general geology of the latter region are: a central core of relatively pure dolomitic crystalline limestone containing scattered crystals and blebs of magnetite, small disseminated euhedral crystals of apatite, and small grains of serpentinized olivene surrounded by a zone of highly altered limestone, largely composed of serpentine, apatite, and magnetite. The magnetite-rich parts commonly contain yellow vermiculite; the change from the relatively pure limestone of the central core to the highly silicated zone at the periphery of the core appears to be transitional. Surrounding the central core and its rim of serpentine-apatite-magnetite rock is a wide zone of pyroxenite, composed essentially of diopside, containing stringers, nests, and pockets of dark brown hydrobiotite, and disseminated grains of apatite. Within this pyroxenite body, and forming a more or less central core of it, is a body of almost completely serpentinized rock, some 2,000 feet in diameter. This body of rock is largely composed of vermiculite and serpentine, within which, according to Gevers (1948, pp. 161-2) "the distribution of the two minerals conforms in a general way to the rude E-W banding, i.e. bands of pure or almost pure vermiculite, up to many dozen feet wide, and associated bands, up to more than a hundred feet wide, in which vermiculite predominates over serpentine, alternate with bands of equal width, in which vermiculite is subordinate to serpentine but still represents workable ore, and bands on which vermiculite is comparatively sparingly developed". Surrounding this central vermiculite-serpentine core and between it and the main pyroxenite mass is a marginal zone consisting largely of vermiculite and serpentine, but containing numerous large crystals of diopside. Between this marginal core zone and the normal pyroxenite, which is composed of small prismatic grains of medium green to greenish grey opaque diopside plus more or less vermiculite, is a border zone containing pale greenish to yellowish green, semi-translucent diopside. This zone appears to be transitional between the one containing the coarse pegmatitic diopside and the main pyroxenite mass.

Origin of Vermiculite

The origin of vermiculite has been, and still is a controversial subject among geologists. Some maintain that it is the result of hydrothermal processes whereas others are equally convinced that it is formed by the action of meteoric waters; still others consider that it is formed by a combination of both these processes. In some deposits such as those at Libby, Montana, there seems to be little doubt that the hydrothermal theory of origin is correct, but in many others the evidence is not so decisive.

It has long been recognized by most geologists that vermiculite is an alteration product of one or other of the mica minerals, but until recently there has been no clear understanding of just what change takes place during the alteration, and what factor or factors control this change. The works of Barshad (1948, 1949), summarized in the foregoing, have provided information that was lacking, and this, combined with a critical review of the mode of occurrence should provide a firmer base upon which to draw conclusions as to origin.

The more important factors relating to the structure, formation, and occurrence of vermiculite, which any theory of origin must be capable of explaining, are contained in the following.

Significant Features of Vermiculite and Vermiculite Deposits

1. Vermiculite is an alteration product of mica (disregarding for the time being, vermiculite-chlorite mixtures).

2. It is formed from mica by the processes of base exchange whereby the interlayered K^+ ions are replaced by Mg^{++} ions with an accompanying marked increase in hydration of the structure. Additional structural changes involve oxidation of Fe^{++} to Fe^{+++} ions, with some of the latter replacing Si^{++++} in the silicon-oxygen tetrahedron.

3. The degree of hydration varies with the kind of exchangeable ion present from a maximum of about 15 per cent with Mg^{++} or Ca^{++}, 8 to 10 per cent with Ba^{++} or Li^+, and about 3 per cent with either K^+, Rb^+, or Cs^+.

4. Hydration of the structure is accompanied by lattice expansion which attains a maximum of about 8Å (about 40 per cent) per unit cell when the exchangeable ion is Mg^{++} or Ca^{++}. When the exchangeable ion is K^+, no expansion occurs and the structure is virtually that of mica.

5. In naturally occurring vermiculite, Mg^{++} is almost always the exchangeable ion present.

6. The alteration of biotite to vermiculite by means of base exchange has been performed experimentally, but only after prolonged leaching in $MgCl_2$ solution at 70°C. and then only with extremely fine-grained material.

7. Vermiculitization is not confined to any particular type of mica nor to any particular mode of occurrence of the mica. Any mica, no matter what its origin and mode of occurrence will alter to vermiculite if subjected to the correct conditions.

8. Vermiculite deposits the world over are invariably associated with syenitic intrusives.

9. In some deposits, notably those in Africa and Madagascar, the vermiculitization of the mica appears to be related to the present surface with vermiculite gradually giving place to unaltered mica at varying depths down to 100 feet.

10. Even in those deposits which exhibit such an apparent relationship to the present land surface, detailed examination indicates little or no evidence that the alteration was due to the action of meteoric waters. In describing the Loolekop deposits Gevers (1948) states that "fresh unaltered mica extends to below the surface cover of soil, calcrete, and magnesite, and is found side by side with fully hydrated, high-grade vermiculite. Transition into vermiculite is lateral and in some cases even downward . . . where phlogopite and vermiculite occur associated near the surface both minerals are frequently traversed by veins of magnesite indicating free and abundant circulation of meteoric waters. Nowhere is there the slightest suggestion that vermiculitization progressed along such veins or other fractures filled with downward percolating waters".

Somewhat similar conditions exist in parts of the Stanleyville vermiculite area of southeastern Ontario. In one small pit, an 8- to 10-inch 'vein' of completely vermiculitized phlogopite occurs not more than 5 feet from a similar but wider 'vein' of completely unaltered phlogopite. In both cases the 'veins' extend to within a few feet of the surface. The area between the two is occupied by a pronounced shear zone indicating the possibility of post-mineralization movement.

Gevers also states that at Loolekop "vermiculite has been found completely enclosed in crystals of pegmatitic diopside showing no alteration by weathering whatever . . . similar flakes also occur enclosed in completely fresh, crystalline limestone showing no trace of weathering".

11. In some cases it appears that vermiculitization is related to the presence of abundant apatite and to the presence of felspathic stringers.

Gevers noted "that around particularly abundant apatite or veins and stringers of feldspar in bodies of only slightly hydrated varieties of vermiculite, the latter are transformed into more highly or even fully hydrated types of vermiculite".

At Stanleyville, Ontario, vermiculitization of phlogopite was observed in one pit to be associated with a felspathic stringer which cut diagonally across the phlogopite body some 10 feet below the surface. Alteration of the phlogopite to vermiculite was very pronounced immediately adjacent to the stringer, but two feet away on either side, the mica was not altered at all. Completely unaltered phlogopite was present immediately below the soil cover.

12. While it is true that vermiculite is commonly associated with pegmatites, and minor syenitic intrusive bodies, the great majority of such bodies which themselves contain much mica and have biotitic border phases or which cut mica-rich rocks, do not contain or have vermiculite associated with them.

13. The largest and most productive vermiculite deposits are associated with bodies of diopside-apatite-phlogopite-biotite rock. However, most of these bodies do not contain vermiculite.

Conclusions

(*a*) Vermiculite is formed by hydrothermal alteration of mica.

(*b*) The solutions effecting the alteration probably had their source in associated syenitic intrusive bodies and are considered to have been rich in magnesium. The source of the magnesium is debatable. The solutions may have been inheritantly Mg-rich, or the Mg may have been derived by reaction of the solutions with Mg-rich wall-rocks through which they traversed.

(*c*) Solutions that are not Mg-rich, or which do not penetrate Mg-rich rocks from which they can obtain Mg, will not produce vermiculitization. This is evidenced by the abundance of unaltered mica (biotite and muscovite) associated with many pegmatite dykes.

(*d*) The apparent relationship between vermiculitization and present land surface in some deposits is considered to be fortuitous and to have no genetic significance.

Chapter V

OCCURRENCES OF MICA IN CANADA

Muscovite

Muscovite is one of the commonest accessory minerals occurring in bodies of granite pegmatite; dykes containing small concentrations of book muscovite are common in all the pegmatite districts throughout the country. Despite this, the occurrence of pegmatite bodies containing book muscovite in sufficient quantity and of sufficient quality to permit economic extraction is very rare. Canada has no known mica-rich pegmatite districts comparable to any of the above, but several areas contain numerous mica-rich pegmatite bodies which constitute potential sources of sheet muscovite.

The following briefly describes each district as a whole, with more detailed information about the more important properties. The prospects are listed in Table XIV.

North Bay District, Ontario

The area which the writer has termed the North Bay pegmatite district encompasses a large part of southern central Ontario, north of latitude 45 degrees between the Ottawa River on the east and Georgian Bay on the west. The northern limit appears to be about the Sudbury-North Bay latitude. Within this area are hundreds of pegmatite bodies which contain book muscovite in varying amounts, but in general, greater than the average. Numerous bodies have been surficially prospected for mica and a few have been mined, mostly with indifferent success.

The most promising part of the district is an area of probably less than 50 square miles, immediately north of the Trans-Canada Highway, at the village of Eau Claire, 13 miles west of Mattawa. At Eau Claire, the frequency of occurrence of mica-rich pegmatites appears to be higher than elsewhere in the district. It is here that the Purdy mica mine, the only mica mine in Canada that has ever been operated successfully for any considerable length of time, is situated.

Most of the muscovite occurring in the pegmatites of the North Bay district is light to medium green, or olive green to greenish brown. A few deposits contain pink or ruby muscovite. In most of the deposits the books are small and the quality is generally poor. The deposits of the Eau Claire area, especially those of the Purdy mine, are therefore unusual in that they commonly contain large size, excellent books of light green muscovite.

Purdy Mica Deposit

References: Lang, 1943b; Spence, 1947.

The Purdy mica mine is at present owned by the North Bay Mica Company, Limited.

The mine is located in Mattawan township, 13 miles west of Mattawa, Ontario, about 2 miles north of the Trans-Canada Highway. It is reached from the highway by a rough, hilly truck road.

The main workings are on patented claims 35974, 35975, and 36095.

The topography of the country in the vicinity of the mine is quite hilly. The Mattawa River is incised to an elevation of about 500 feet above sea-level. Immediately to the north is an abrupt rise to a terrace with an elevation of about 700 feet. From this terrace northward the land rises to a rolling upland surface covered with glacial drift, with an average elevation of about 850 feet. In places, large rocky ridges and smaller rocky knolls rise to about 1,000 to 1,250 feet above sea-level. Although a few outcrops project through the drift in low-lying regions, rock exposures and areas of shallow drift are almost entirely confined to the hills and ridges. The main Purdy workings are on the crest and southwestern slope of a low rocky knoll, which rises about 300 feet above the surrounding land.

The history of the property prior to 1943 is outlined by Lang who writes, "Ever since the construction of the Canadian Pacific Railway attempts have been made from time to time to mine the pegmatite dykes of the Eau Claire area, but, although some feldspar was mined, no appreciable muscovite was produced.

"Late in 1941, J. Purdy and H. MacDonald discovered a dyke containing large crystals of high-grade muscovite from which they are reported to have sold $700 worth of mica. They recorded claims 35974 and 35975 in December, 1941, and claim 36095 in May 1942.

"Soon after the original discovery they found a larger dyke in the same general zone, containing muscovite crystals of unusual size and grade, and they are reported to have shipped about $12,000 worth during the winter. Mr. Purdy was killed shortly afterwards and his parents engaged R. Basher to operate the mine with a small hand-steel crew. Production was not hurried pending negotiations for the sale of the property, but roughly 20 tons of run-of-mine mica was obtained from mining of about 350 tons of rock, up to October 1942.

"In the spring of 1942 a large block of claims adjoining the three Purdy claims were staked by N. Vincent and associates. Nine of these, including those immediately adjoining the Purdy claims, were optioned to Inspiration Mining and Development Company, Limited, shortly afterwards, and that company produced a relatively small amount of mica from what are known as 'east showings' on these claims. Paul and Wilfred Croteau, who prospected in the area for the Inspiration Company, discovered and staked what are known as the Croteau showings, from which mica was mined during the summer and autumn of 1942. The Inspiration Company established a grading and trimming plant in Mattawa, treating the product from the Croteau and East workings and also some mica sold by Purdy. About November 1 the Inspiration bought the Purdy claims and formed Purdy Mica Mines, Limited, to amalgamate these claims with the nine claims optioned and the 25 claims staked by Inspiration prospectors." The property was operated by Purdy Mica Mines Limited until October 1945 when it was closed because the deposit was considered to be exhausted.

In 1949 J. J. Kenmey and associates formed the North Bay Mica Company, Limited, and optioned the property from Purdy Mica Mines, Limited. Under Mr. Kenmey's able direction the mine was reopened and development work commenced. It soon became evident that the deposit was by no means exhausted and North Bay Mica Company purchased the property outright. Mining commenced in June 1949 and continued until September 1953. In 1952, Mr. Kenmey became ill, and ownership and management were reorganized. During the summer of 1952 and the earlier part of 1953 the production of mica decreased and the operators were unable to find additional ore. Faced with rapidly dwindling ore reserves and decreasing prices for muscovite the company was forced to suspend operations in September 1953.

Production by Purdy Mica Mines, Limited, during the period November 1943 to October 1945 was 1,968,804 pounds of raw mica valued at $936,002.12. During the period June 1949 to the end of August 1951 North Bay Mica Company, Limited produced 324,933 pounds of raw mica valued at $203,651.24. Production figures from August 1951 to September 1953 are not available.

General Geology

A geological diagram of the Eau Claire area (Figure 11) shows the distribution and relative abundance of the various rock types present. The oldest rocks are early Precambrian paragneisses which occur as roof-pendant bodies in foliated pink granites and injection gneisses of Precambrian age, with which much pegmatite is associated.

The rocks comprising the roof-pendant bodies consist of dark to light, fine-grained, thinly banded gneisses of probable sedimentary origin, which range in composition from dark grey to black hornblende quartz feldspar and biotite quartz feldspar gneiss to light grey to pink quartz feldspar gneiss. All are more or less garnetiferous. Banding is commonly very persistent and is considered to be a reflection of original compositional differences within a single sedimentary series. All the meta-sediments in the area are highly metamorphosed and commonly strongly folded. In places they are highly granitized as the result of the intrusion of nearby pink granite. Where the mafic-free bands have been thus granitized it is extremely difficult to distinguish them from the intrusive granite, especially in areas of limited outcrop.

The rocks outcropping in the areas mapped as granite consist of medium- to coarse-grained pink granite of the alaskite variety, composed chiefly of microcline and quartz. They are commonly foliated and contain numerous injections or segregations of pegmatite both parallel to the foliation, and as crosscutting dykes and lenses.

Geology of the Deposit

Muscovite-bearing pegmatite dykes are known to outcrop in at least twelve different places on the property. Where seen they all strike northeast and dip steeply to the northwest. They pinch and swell both horizontally and vertically with widths varying from 2 to 20 feet. In places they branch and split into two or more parallel to sub-parallel dykes. In other places they contain horses of barren wall-rock, which are commonly completely enclosed within pegmatite. The walls are generally clean and sharply defined.

The structural control that appears to have governed the emplacement of the pegmatite dykes is a strong set of parallel, northeasterly striking fractures. Differential movement of the walls of these uneven fractures prior to mineralization probably resulted in the formation of dilatant zones into which the pegmatite solutions were injected, and the minerals crystallized.

The dykes are composed essentially of microcline, sodic plagioclase, and quartz. In addition, some dykes, or parts of dykes contain muscovite and biotite, and small amounts of garnet, tourmaline, epidote, chlorite, and in one instance, uraninite.

The muscovite occurs as isolated, well-formed books or crystals, and as aggregate masses of small, poorly formed crystals intergrown with the various other minerals present. In book form, the mica ranges from dark olive green to light yellowish green with the former being the more common. Thin plates or blocks are light olive green or rum-coloured. Films are colourless.

The isolated books commonly range in diameter from 2-3 inches to 8-10 inches. Crystals from 2 to 3 feet in diameter are not uncommon, and one giant crystal approximately 7 feet in diameter was found during the early stages of mining. These isolated, euhedral crystals contain a very high percentage of excellent quality sheet muscovite. It is almost invariably flat, and usually free from mineral staining. Much of it is free from inclusions of other minerals and is therefore free-splitting. The only structural imperfection present to any appreciable degree is ruling, but even this is rare in the well-formed euhedral crystals. Where the mica occurs in masses of poorly formed crystals, it is usually of poor quality. Most of the books are small, commonly intergrown at random orientations, and crowded with inclusions of quartz, feldspar, and in some cases, garnet and tourmaline. Structural imperfections such as ruling and reeving are common. The percentage of usable sheet muscovite obtainable from this type of mica is very low.

Almost all the pegmatite bodies examined at the Purdy mine exhibit some degree of zoning, and the degree of complexity of this zoning appears to be directly proportional to the width of the body. Narrow, linear bodies generally contain only a narrow border zone and a medium-grained centre zone similar in composition to wall zones in the wider bodies. In some cases the centre zone, composed of well-crystallized muscovite, medium- to coarse-grained plagioclase, perthitic microcline, and interstitial quartz, is flanked by wall zones containing finer grained material, generally high in muscovite, and containing more plagioclase than the centre zone. Where seen, the size and shape of the centre zones, which are equivalent to intermediate zones in more complex bodies, reflect the size and shape of the entire dyke. Cores, or core zones, as defined by Cameron *et al.* (1949, p. 20) are present in a number of the wider parts of some of the bodies. In most cases they have been mined out and little or no record is available of the type of zoning that was originally present. The fact that these highly productive parts of the old workings were well zoned is inferred from descriptions of the early workings. Lang (1943a, p. 310) states that large books of muscovite were encountered "under a large quartz capping". This description refers to the occurrence of the giant crystal found in No. 1 pit. The dyke at this point was 20 to 25 feet wide and from the description, contained a large quartz core under which was found the giant crystal. The same quartz core was encountered 60 feet to the northeast where large muscovite crystals 2 to 2½ feet in diameter were adjacent to the core on both the hanging- and foot-wall sides. The fact that the giant crystal was found immediately underneath the quartz core suggests that it occurred in an enlarged intermediate zone, or at the contact of the intermediate zone with the core. A similar, large, central quartz core is present in what is known as No. 7 'vein'. The dyke has been benched out for a distance of 10 to 15 feet along strike, leaving a vertical face 8 to 10 feet high. At this point the 'vein' is about 10 to 12 feet wide and consists of a centre core zone 7 to 9 feet wide, flanked on either side by a wall zone 2 to 3 feet wide. The core is largely composed of pure white quartz, with a scattering of large poorly formed biotite crystals, and one or two well-formed books of clear muscovite about 8 to 10 inches in diameter. All the biotite crystals examined in this dyke contained thick, wedge-shaped, interlaminations of perfectly clear to slightly smoky quartz, markedly different from the white quartz of the core.

The wall zones flanking the core are largely composed of coarsely crystalline perthitic microcline, and where seen in the pit face, the only mica present was biotite.

Mine Workings

Purdy Mica Mines, Limited mined the property by means of a number of shallow open-pits. Major production was derived from No. 1 and No. 3 'veins', with smaller amounts produced from other 'veins'. The surface plan (Figure 12) shows the location of the various 'veins' and a number of waste dumps. North Bay Mica Company at first concentrated its efforts on No. 3 'vein', which the previous owners had considered to be mined out. Mining by inclined shaft was successful to a depth of 120 feet below the collar, and much excellent mica was obtained. Work was then discontinued on this orebody because working conditions were becoming dangerous and mining methods employed were highly wasteful. The Company then decided on a program of underground mining and development. The plan was to explore the dykes at depth by means of a low-level adit, driven to intersect No. 2 'vein' and drift northeast on it until No. 3 'vein' was reached. Further exploration of parallel veins could then be carried out by crosscut and drift from the main adit. Work on this phase of the operation commenced in the summer of 1951. By the summer of 1952, No. 2 'vein' had been reached and drifted on for 317 feet, a ventilation shaft put through to the surface, and a large orebody on No. 2 'vein' stoped out. Underground exploration was then discontinued. Subsequently the management reopened No. 1 pit and drifted southwest on No. 1 'vein' from a point about 40 feet directly below the main adit. In June 1952 this drift had been advanced about 40 feet and was entirely within pegmatite. Considerable good mica had been found and a small amount of stoping done at the time of the writer's visit. Results of further work on this 'vein', as well as as the outcome of operations of No. 3 pit which was reopened during 1953, are not known.

Significant Features Relating to Concentration and Distribution of Muscovite Within the Dykes

The mining of the Purdy dykes has provided considerable information on the concentration and distribution of muscovite within the pegmatite dykes which may be summarized as follows:

1. The most profitable orebodies appear to occur where the dykes are enlarged into lens-shaped bodies.
2. The pegmatite within these bodies is commonly well zoned; barren quartz cores are common.
3. The greatest concentration of mica in these lenses occurs in the wall zones along the keel and lower sides of the body.
4. The greatest concentration of large book mica occurs in the coarse-grained intermediate zone, at or near the contact with the keel of the quartz core.
5. Where the walls of a dyke are straight and the dyke has an appreciable dip, the greatest concentration of mica occurs on the hanging-wall side.
6. The distribution and frequency of occurrence of these lens-shaped enlargements within any given pegmatite does not appear to fall into any regular pattern, or at least none has as yet been recognized. However, it might be fairly safe to say that it is a repetitive feature, probably both vertically and horizontally. It should be understood that the width of a dyke between lenses is commonly reduced to almost nothing, or that a dyke may split into two or more parts. Such occurrences do not necessarily indicate the end of a dyke, but merely the end of the lens or shoot.
7. All evidence obtained by previous workers and by the writer indicates that economic concentrations of muscovite, in this district at least, only occur in dykes in meta-sedimentary or meta-volcanic rocks. Intensive prospecting has not revealed any within the granitic rocks.
8. The areal extent of the meta-sedimentary body of rocks at the Purdy mine is well known; the vertical or downward extent is unknown.

It has been stated that the contact between these rocks and the intrusive granite probably occurs at the elevation of the bottom of the hill, or in other words that it is a hill of meta-sediments sitting on intrusive granite. The fact that the bottom sections of two out of nine short vertical drill-holes from the floor of No. 1 pit were in granite is not too significant considering the nearness of the granite-meta-sediment contact to the south, and the similarity between much of the more highly granitized meta-sediments and the intrusive granite. Certainly no sign of intrusive granite was seen in any of the underground workings. The basal contact may be only a short distance below these workings or it may be at a considerable depth. In any event it is probably highly irregular.

Cariboo Lake—Memesagamesing Lake Mica Deposits

Numerous zoned, muscovite-bearing pegmatite dykes occur in fractures in the noritic rocks comprising the Cariboo Lake and Memesagamesing Lake complexes. The writer examined the Cariboo Lake pegmatite bodies during the summer of 1952, when Inspiration Mining and Development Company, Limited had just commenced preliminary development work on one of the dykes with a view to mining it for its muscovite content. At the time, the occurrence of similar muscovite-bearing pegmatite dykes in another norite body at Memesagamesing Lake, some 7 miles northeast of Cariboo Lake was known, but the dykes had not been examined. The complex was later mapped by Friedman (1955, pp. 590-608) who reported that "mica is not normally abundant".

Cariboo Lake Deposits

Cariboo Lake is in McKonkey township, Parry Sound county, Ontario, about 45 miles west of Trout Creek, a small town on highway No. 11, 24 miles south of North Bay. The site of the deposits is reached by car over a good gravel road from Trout Creek to the village of Port Loring, then about 2 miles over a somewhat less-traveled road to a landing at the eastern end of Cariboo Lake, and then by boat some 3½ miles to the camp on the shore of the Lake.

Cariboo Lake is surrounded by low, rolling, completely timberclad hills. Average elevation of the summits above the lake level is probably less than 200 feet. The lakeshore, for the most part, is rocky and in places quite precipitous, providing excellent well-washed exposures of the various bedrock types. Inland, outcrop is surprisingly poor, probably not more than 5 to 10 per cent. Fortunately the pegmatite dykes of the district commonly occur as ridges protruding above the softer host rocks, and are easily recognized. Timber is mostly hardwood and underbrush is light.

Geology

Cariboo Lake and part of the area immediately surrounding it are underlain by norite which forms a pear-shaped plug within the surrounding gneissic rocks of the Grenville series. The long axis of the body trends slightly north of west across the lake, with the narrow part of the 'pear' just east of the east end of the lake, and the wider part just north of the west end of the lake. The noritic rocks are cut by many zoned pegmatite dykes.

All the known pegmatite dykes that contain muscovite in appreciable quantity occur within the norite body. With few exceptions they all strike northeast and dip steeply northwest or southeast. They are markedly regular in width and linear in habit. Contacts are commonly sharp and clean but in a few instances are gradational. Widths vary from 2 to 200 or more feet, with the average about 20 feet. It seems probable that emplacement of the dykes was controlled by a set of strong northeast-striking fractures in the norite body that were formed prior to the intrusion of the pegmatite fluids.

All the dykes examined exhibit some degree of zoning. In most instances the zoning was simple, consisting of narrow fine-grained border zones of feldspar, quartz and muscovite with or without biotite, separated by a single zone similar in composition to wall zones of polyzoned pegmatites. The essential minerals are usually coarser grained than those in the border zones and consist of alkali feldspar, sodic plagioclase, quartz and muscovite. As usual the greatest concentration of mica occurs close to the contact with the border zone on the hanging-wall side. Foot-wall concentrations similarly disposed with respect to the border zone are commonly present but the percentage and size of the individual books is invariably smaller. A few of the dykes examined were polyzoned, consisting of border zones similar to those described above, pronounced wall zones containing muscovite, and in one instance possibly two intermediate zones surrounding a central core zone. In these well-zoned pegmatites, grain size of the mineral constituents was observed to increase towards the centre.

Description of Showings

No. 1 showing consists of a large pegmatite dyke in P.S. 1658 that is exposed in natural outcrops and in pits for a length of about 300 feet. Width of exposure varies from 50 to 100 feet. No actual wall-rock contacts are visible but total width is estimated to be about 150 feet. Strike of the outcrop varies from N80°W at the west end, to S70°W at the east end. This change in strike of the outcrop does not necessarily reflect a similar change in strike of the dyke as a whole. The dyke was worked in a small way early in the century and a few hundred pounds of sheet muscovite was recovered. Present workings consist of a pit, now partly filled with water, 50 feet long, 15 feet wide, and about 10 feet deep in the south central part of the exposure.

The dyke is apparently well zoned but insufficient work has been done to permit structural mapping of the zones. The main mass of the outcrop consists of fine- to medium-grained, more or less equigranular sodic plagioclase, quartz, muscovite, biotite and minor microcline. Towards the centre of the dyke, where it is exposed in the central and southern parts of the pit, what appears to be an intermediate zone is exposed. It consists of very coarsely crystalline albite, quartz, microcline and reputedly coarsely crystalline clear ruby muscovite. The zone is about 12 feet wide and occupies the central part of the dyke at this point. No core zone was observed. However, at another place in the outcrop there are indications of a core zone of barren quartz.

No. 2 showing is a 20-foot-thick pegmatite dyke that strikes N15°E, dips 75°SE and outcrops on the top of a small knoll rising 15 to 20 feet above the surrounding land surface. The dyke has been exposed by an opencut at the southwest end for some 12 feet, ending in a face 10 feet wide by 8 feet high. Northeast of the cut the dyke has been stripped for about 50 feet and several pits have been opened up. Walls are clean, straight and well defined. Zoning is very pronounced. From the walls inward, zones consist of a thin border zone 1 inch to 2 inches thick, followed on the hanging-wall side by a 3- to 4-foot-thick wall zone composed of medium to coarsely crystalline feldspar, quartz, muscovite and biotite. The crystals of mica, both muscovite and biotite, range from 2 to 3 inches to 3 to 4 feet in diameter. The percentage of muscovite in the zone is high, but the quality is poor. In general it is strongly warped, reeved and heavily stained. A similar but thinner wall zone occurs on the foot-wall side of the dyke. The centre zone is mainly composed of quartz with some feldspar.

No. 3 showing was being actively explored by open-pit at the time of the writer's visit to the property. General strike of the dyke appears to be about N30°E, and in the open-pit in which mining operations were being conducted, appears to have a moderate dip of about 30°NW. Wall-rock contacts are not exposed on the surface and only the hanging-wall side was visible in the pit, thus no accurate estimation of thickness could be made. From what could be seen in the pit there appears to be a hanging-wall zone 3 to 6 feet thick composed of coarsely crystalline alkali feldspar, sodic plagioclase, quartz and muscovite. Below this there are indications of a core zone of barren quartz. Total thickness is probably about 10 to 12 feet. The muscovite in the wall zone occurs in well-formed books about 3 to 10 inches in diameter. However, nearly every book examined exhibited the comparatively rare phenomenum of multiple crystallization. The books have undoubtedly crystallized in two stages: the initial stage is represented by a well-formed inner crystal or core of clear, flat, free-splitting rum-coloured muscovite; this is surrounded by heavily stained muscovite of much the same colour, representing the second stage. Most of the books examined were moderately reeved in one direction. Many are large enough, No. 5½, No. 5 and some No. 4, fully trimmed, clear quality block mica from the inner part. The outer stained parts would yield No. 6 and possibly some No. 5½ black stained block mica.

The small dyke that strikes N70°W and joins No. 3 dyke 50 feet northeast of the open-pit contains clear quality ruby muscovite in narrow wall-zone concentrations, but the books are generally less than 2 to 3 inches in diameter. The dyke that strikes N30°W and intersects No. 3 dyke at a point 367 feet northeast of No. 3 pit also contains clear quality ruby muscovite. The largest book observed in the outcrop exhibited an exposed edge 10 inches long. Insufficient stripping had been done to permit determination of the size or internal structure of this dyke.

Several other pegmatite dykes in the same general area were examined but none appeared to contain economic concentrations of muscovite.

Conclusions

Although several of the dykes examined in the Cariboo Lake area contain relatively high concentrations of muscovite it is unlikely that any could be mined at a profit. In most cases the mica is of poor quality and only suitable for scrap purposes. The outcrops occur in flat, low-lying ground, which would make mining operations difficult and expensive. Judging from reports of early work and from the type of zoning present, it is possible that No. 1 dyke may contain economic concentrations of large, good-quality muscovite.

Saguenay and North Shore of St. Lawrence District, Quebec

The region bordering the north shore of the St. Lawrence River is underlain by rocks of the Grenville series, including meta-sedimentary gneisses and schists, that have been intruded by many bodies of granitic rocks. These meta-sedimentary rocks contain many large and small, usually conformable, lens-shaped bodies of granite pegmatite. The majority are simple pegmatites composed of quartz, feldspar, and the usual minor accessory minerals, but a few have higher-than-average muscovite content.

The most notable feature of the mica-rich pegmatites of the general Saguenay River area—and the feature that has attracted attention to the district for more than half a century—is the quality and type of ruby mica which characterizes the district, and which closely resembles India ruby mica. Unfortunately, as yet no large-sized economic concentrations have been found.

A number of more promising deposits in the Pontgrave-Bergeronne area have been worked intermittently in a minor way since late in the last century. In a few cases small amounts of good-quality ruby muscovite have been produced. Activity in the district increased during World War II but little success was achieved. The McGie mine produced 500 to 600 pounds and the nearby Simard property some 22,000 pounds by the end of 1941. In 1952 the old Beaver Lake property was re-staked by Strategic Metals Ltd. and minor development work was done shortly thereafter. It is understood that this company intended to mine the deposit for feldspar and mica. The histories, records, and general descriptions of the various properties in this area are reported by Greig (1952).

During the summer of 1952 the writer spent two weeks examining what were considered to be the most promising properties in the Bergeronne district. So far as could be seen, none contained anything approaching economic concentrations of sheet muscovite. Pertinent details of the various prospects visited are contained in Table XIV.

None of the known deposits of sheet muscovite on the north shore of the St. Lawrence River appear to be economical under present conditions. They do, however, constitute a potential source of supply which could be utilized in times of stress.

Beaver Lake or Hall Mine

References: Greig, 1952; Ross, 1950.

The Beaver Lake or Hall mine was examined in some detail because of its unusually high 'bull' muscovite content, which might constitute a good source of supply of high quality scrap for grinding purposes. A brief general summary of the deposit follows.

The pegmatite body on the Beaver Lake property is exposed at intervals in several open-cuts and in natural outcrops on a northerly trending ridge, for a distance of about a mile. The body varies in width, averaging about 40 to 50 feet. Dip is unknown. At the northern end, for about 300 feet, the body widens to about 150 feet, then ends abruptly with a 40-foot drop-off to a swamp. The crest of the ridge at the cliff face is 60 to 70 feet above the level of the surrounding country.

Despite the large size of the dyke, surface exposures show little or no zoning, except for a few small more or less centrally located quartz pods near the south end. In general the composition is quite regular and fairly fine grained, consisting of quartz, acid plagioclase, and abundant small, well-formed books of ruby muscovite. Size of the books is rarely greater than 2 inches and generally less than an inch. Percentage of mica varies considerably but is noticeably greater in the wide part at the north end, where it probably averages 10 to 15 per cent.

Judging from the outcrops along the ridge the natural assumption is that the body is not zoned, and is composed entirely of the fine-grained mixture of minerals mentioned above. The only evidence that this may not be the case is on the northern cliff face, where four fairly well defined zones are exposed. The lowest, which disappears downward into the talus, consists almost entirely of crystalline, white microcline plus minor muscovite and biotite. Above this is a muscovite-rich zone 1½ to 2 feet thick composed of 20 to 30 per cent muscovite in small books, quartz and acid plagioclase. Above this again is a 5- to 6-foot-thick zone of almost pure, coarsely crystalline feldspar, which in turn is overlain by the fine-grained surface zone containing much 'bull' mica. Good clean exposures are confined to the central part of the cliff face so that it is not possible to trace the zones for any distance across the face, but they seem to conform in shape to the general cross-sectional outline of the ridge. It would therefore seem possible that the fine-grained bull mica pegmatite exposed on the top of the ridge is in reality a mica-rich wall zone, occurring in the form of a hood, under which other, more coarsely crystalline zones may occur. However the longitudinal extension of the zones may not, and probably does not, conform in any way with the shape of the surface of the dyke. It may be horizontal or it may plunge north or south at any angle, or the zoned part of the body may not have any appreciable longitudinal extension at all, in which case it would probably be a small, isolated pod of little significance. Details of the internal structure will be an important factor in determining the possible tonnage of fine-grained mica-rich pegmatite from which scrap mica for grinding purposes could be produced.

British Columbia Mica Deposits

In British Columbia known deposits of sheet muscovite are almost entirely confined to a belt of meta-sedimentary rocks which occur along or near the western side of the Rocky Mountain Trench from Fort Grahame in the northwest to and beyond the 'Big Bend' of the Columbia River in the southeast.

Within this belt of metamorphic rocks, mica-rich pegmatite dykes are known to occur in three widely separated localities. In the Fort Grahame district several muscovite-bearing pegmatite bodies occurring in the rocks of the Wolverine complex (Roots, 1954, p. 101) have been explored by open-cut and adit (Dolmage, 1927, p. 31A). Similar occurrences of mica-rich pegmatites have been reported in the southeastward extensions of rocks of this complex in the Manson Creek map-area (Armstrong, 1946) and in the northeastern part of the Carp Lake map-area. Continuing southeastward along the Trench the next known occurrence is in the vicinity of Tête Jaune Cache (de Schmid, 1913, pp. 42-49), where meta-sedimentary schists and gneisses similar to those of the Wolverine complex again contain muscovite-bearing pegmatites. Still farther southeastward, muscovite occurs in pegmatites in the Mica Creek area of the 'Big Bend' of the Columbia River, and in the Beavermouth area 50 miles to the southeast. In both these cases the host rocks are meta-sedimentary mica schist and gneisses.

The muscovite in the pegmatites of all these districts is reported to be of good quality, light brown to greenish in colour, and to occur in well-formed books up to a foot in diameter. However, according to the reports, the percentage of mica in any one of the dykes is not unusually high, nor do the dykes appear to be well zoned. In all cases the deposits occur at or near the summits of rugged mountains which are snow covered for eight months of the year.

Although there seems to be little doubt that this whole region constitutes a mica-rich pegmatite province, and that other mica-rich pegmatites probably occur in the more unexplored parts of the region, the possibility of any being mined at a profit, under normal conditions, appears to be remote. Nevertheless they do represent a potential source of supply of high quality muscovite that could be utilized if necessary.

Phlogopite

The distribution and occurrence of phlogopite deposits in Canada are almost entirely restricted to a belt of northeasterly trending rocks of the Grenville series, extending northeastward from about the vicinity of Kingston to the Ottawa River at Ottawa, and thence northerly between the Gatineau and Lièvre Rivers to about the vicinity of Maniwaki. The total length of the belt is about 150 miles; its width is from 60 to 70 miles.

For about 15 miles north from Kingston, and from the Rideau Lakes on the southwest to the Ottawa River on the northeast, the Grenville rocks of the belt are overlain by a cover of early palæozoic sedimentary rocks. The latter divide the belt into two entirely separate parts, with the northern being termed the Quebec district, and the southern, the Ontario district. Each of these districts contains scores of deposits of known commercial importance, and innumerable minor occurrences.

Table XIV

Tabular Summary of Canadian Muscovite Deposits

ONTARIO

Name	Location	Size, colour, and quality of mica	Workings	Production, date, and comments	References
Purdy Mica	Mattawan tp.	See report, p. 72			
Anderson claims	Olrig tp., 2 miles northwest of Purdy claim 36299	Green, up to 8 inches in diameter, 10% of pegmatite	Small, 6 by 10 feet	Nil, 1943	Lang (1943b)
Anderson claim	Mattawan tp., adjoins Johnson claim.	Green, up to 5 inches diameter	Stripping shows extensions of dykes on Johnson claim	Nil, 1943	Lang (1943b)
Johnson claim	Mattawan tp., near Mica Consolidated claims northwest of Purdy	Green, average 4 inches, largest 10 inches	Stripping — 8 dykes, 1 to 5 ft. wide; in area — 550 ft. wide, 450 ft. long	Nil, 1943	Lang (1943b)
Mica Consolidated Mines, Ltd.	Mattawan and Olrig tps., west of Purdy	See report on Purdy Mica, p. 72			
Graff showing	Calvin tp., lot 9, con. 1	Clear, green, up to 10 inches	Two old pits, 60 by 30 ft. and 8 by 50 ft., and 50-ft. trench on 3-ft. dyke	Old feldspar and mica (?) working, minor work in 1943	Lang (1943b)
	Calvin tp., lot 15, con. 8	Fair to good quality, green, up to 7 inches, scattered crystals	Two dykes — old workings	Nil, 1943	Lang (1943b)
J. Cataford showing	On boundary between Crerar and Gibbons tps.; farm of A. Dupras	Concentrations of small and some large, clear quality green muscovite	Small area of pegmatite visible on south showing; size unknown	Nil	Lang (1943b)

Tabular Summary of Canadian Muscovite Deposits—Continued

ONTARIO—*Continued*

Name	Location	Size, colour, and quality of mica	Workings	Production, date, and comments	References
Campbell showing	Chisholm tp., Nipissing district, con. 3, lot 24	Large pegmatite containing much small clear, but smoky muscovite up to 6 inches in diameter	No work done	Exposed in low swampy ground difficult to mine	
Brent property, North Bay Mica	Deacon tp., S½ lot 10, con. Xi; N½ lot 12, con. x11	Two separate pegmatite bodies both containing much green mica, exceptionally well-formed books, requiring little trimming; mostly stained	Extensive work and considerable production by North Bay Mica Co. during 1950 and 1951; only property other than Purdy considered by this company to be economic at that time.		
Foy showing	Canncy tp., Nipissing district, con. 14, lot 10	Narrow, irregular pegmatite containing small books of good, clear quality ruby muscovite	Not reported	Not reported, probably nil; inaccessible	
Finlan property	Davis tp., con. 1, lot 7	Unknown, but considerable quantity good quality, almost stain-free greenish brown muscovite averaging 4 by 5 inches produced during 1919 and 1920	Open-cut. Further work would require sinking		
Cariboo Lake showings	McKonkey tp., lots 7 and 8, Parry Sound district	See report, p. 78			

Jeffry property	North shore of Cecebe Lake, Chapman tp., con. 13, lots 17 and 18, Parry Sound district	According to North Bay Mica — excellent quality light green purchased from this deposit; that seen was much twisted and reeved; large dyke exposed, 50 ft. wide, 200 ft. long	Small amount of benching and stripping	Small amount sold to North Bay Mica; very little mica visible in dyke at present	
Armstrong property	Parry Sound district, Christie tp., con. 14, lots 13 and 14	Stated to contain books 5 by 6 inches, by 6 inches thick; quality of specimens submitted poor; heavily stained with magnetite films	Open-pit	Old property revived during World War II	Spence, H. S. (1929)
Mazinaw Lake property (Orser mine)	Lennox and Addington county, Effingham tp., con. 6, lot 8N½	Pegmatite dyke plus 15 ft. wide, containing concentration of muscovite in 6-ft. hanging-wall zone; books up to 12 inches; quality good, especially in large books; clear and free from mineral staining; colour unknown	Open-pit 100 ft. long, 15 ft. wide, 15 to 20 ft. deep	Developed and worked by F. Orser 1938 to 1942; production unknown. Immediately adjoins old mica mine of General Electric Co., apparently on extension of same dyke; two main pits on G.E. property said to be 80 to 90 ft. deep; combined length of dyke over 1500 ft.; probable large reserves	Spence, H. S. (1942, unpublished report)

Tabular Summary of Canadian Muscovite Deposits—Continued

QUEBEC

Name	Location	Size, colour, and quality of mica	Workings	Production, date, and comments	References
Simard mine	Saguenay county, Bergeronne tp., claim Q-29658, 1500 ft. south of east end of Charlotte Lake	Clear, good quality ruby muscovite in 5- by 6-inch books; little good mica visible at the present time; much of that seen was spoiled by reeving and biotite intergrowth	Two open-pits 400 ft. apart on same dyke	83,000 pounds up to end of 1943. Known concentration of good quality mica appears to have been mined out; lack of obvious zoning makes it difficult to predict possible locations of additional concentrations	Greig, E. W. (1952, p. 11)
McGie property	Block G, Saguenay county, Bergeronne tp., north shore of Lake Charlotte	Ruby and green mica, variable quality	Very old property, little work done in recent years; main open-pit in hillside of north shore of Lake Charlotte, originally mined by inclined shaft, now caved. Dyke appears to pinch out at north end of pit; considerable ruby mica in small books visible in pegmatite remaining on walls of pit, but mostly of poor quality	Reputedly several thousand pounds about the year 1900, and 500 to 600 pounds in 1941; does not appear to be of economic importance	Greig, E. W. (1952, p. 12)
Beaver Lake or Hall mine	Saguenay county, Bergeronne tp., northwest of Beaver Lake	Large pegmatite dyke containing much 'chigger' muscovite; colour —ruby; (See report, p. 82, for details)			Greig, E. W. (1952, p. 20)

Lac Pieds des Monts	Charlevoix county, Desales tp., 15 miles northwest of Murray Bay	Mined in 1893 producing 15 to 20 tons mine-run mica from horizontal pegmatite dyke 20 to 30 ft. thick; mica slightly spotted ruby, in crystals up to 2 ft. in diameter			Obalski, J. (1894, pp. 98-99)
Lac Pieds des Monts	Charlevoix county, Sagard tp., about ½ mile east of David Lake	Unknown	Several large pegmatite dykes containing about 5% muscovite		Ross, S. H. (1950) Pitts, P. D. (personal communication)
Pittsco Exploration Co. property	Chicoutimi county, Dumas tp., 1½ miles northeast of east end of David Lake		One of many pegmatite dykes, including the ones noted above in Sagard tp., occurring in a narrow sinuous band of mica schists and paragneisses, and hornblende schists and gneisses, which form a crescent-shaped band extending north and easterly from Lake Druillettes to about Lake Lyonne; some of these dykes are known to contain more than the usual amount of muscovite and the area would seem to be worthy of more intensive prospecting		Ross, S. H. (1950) Miller, M. L. (1952) Pitts, P. D. (personal communication)
Villeneuve mine	Papineau county, Villeneuve tp., rge. 1, lot 31	Spotted 'white' muscovite from small and a few large books	Extensive workings on pegmatite dyke 150 ft. wide	Mined for mica and feldspar around 1890; reported to have produced 35,000 pounds of trimmed mica during the period 1884-1888	Obalski, J. (1888) Spence, H. S. (1929)

Tabular Summary of Canadian Muscovite Deposits—Concluded

BRITISH COLUMBIA

Name	Location	Size, colour, and quality of mica	Workings	Production, date, and comments	References
Mica Mountain deposits	Tête Jaune Cache, at elevation 7000 ft.	Clear greenish or brown muscovite of excellent quality; sheet 16" by 10" is reported	Known and worked in a small way, intermittently since 1898; difficult of access and snow covered for most of the year		Geol. Surv., Canada, Ann. Rept. 1898, vol. XI, pp. 80A, 38D. de Schmid, H. S. (1913)
Mica Creek Property deposits	'Big Bend' district, Columbia River, on divide between Mica, End, and Yellow Creeks	Similar to Mica Mountain deposits (above)	Occurrences known for many years are remote and difficult of access		Same as for Mica Mountain above
Fort Grahame district	Butler rge., 5 to 10 miles southwest of Fort Grahame	Clear brownish green, up to 10 inches in diameter	Several dykes explored by open-cut and trenching; one by adit and shaft in 1924-1927; small shipment made		Dolmage, V. (1927)

The only other known Canadian occurrence of phlogopite is that near Petit Pré, a few miles east of Quebec City. It likewise occurs in rocks of the Grenville series, and according to reports, is similar in all respects to deposits in the areas mentioned.

The Canadian phlogopite mining industry flourished during the period 1890 to 1928, but since then, few if any important new discoveries have been made and gradually all the major producing mines of that time have ceased to operate and have long ago fallen into disrepair.

For details of all known properties the reader is referred to the works of de Schmid (1912) and Spence (1929) which are far more complete and accurate than any the writer could obtain by personal examination of the old workings. Property description in this report is restricted to a tabular summary of the most recently operated major producing mines. (*See* Table XV).

Vermiculite

No vermiculite is mined in Canada at the time of this writing, but the mineral is known to occur in a number of places, chiefly in the areas of Grenville rocks in southeastern Ontario and near Blue River in British Columbia. Elsewhere it has been reported in a few localities as a contact phase between pegmatite dykes and basic intrusive rocks.

Stanleyville District, Ontario

Reference: Spence, 1929.

Vermiculite in the Stanleyville area, some 15 miles southwest of Perth, Ontario, was first discovered in 1950. Subsequently, exploration by open-pit and diamond-drilling by three companies, Siscoe Vermiculites Mines Ltd., North Bay Mica Co., and Pittsco Exploration Co., has indicated the occurrence in varying amounts over a large area, but apparently not in sufficient concentration to warrant further exploration.

The distribution of the various rock types of the Stanleyville area is shown in Figure 13. They consist of a series of northeasterly striking, steeply dipping, highly metamorphosed Precambrian sedimentary rocks that have been intruded by bodies of syenite, and quartz syenite, and associated pegmatites. Remnants of flat-lying Ordovician sandstone of the Nepean formation, unconformably overlying the Precambrian rocks, occur at one or two places.

The meta-sedimentary rocks comprise a series of massive quartzite containing small intercalated lenses of limestone, garnetiferous biotite and hornblende feldspar gneiss, and limestone. The limestone varies from a pure, coarsely crystalline limestone to a highly silicated rock composed of varying

Table XV

Tabular Summary of the Most Recently Operated Major Producing Canadian Phlogopite Mines

Name	Location	Description of Deposit	Production and History	References
Nellis or Vavasour mine	Hull county, East Hull tp., rge. 12, lot 10, Quebec	Numerous 'parallel mica leads' containing much excellent quality mica	Large production mined at intervals over a long period, including during World War II, and a short time after	Spence, H. S. (1929, p. 58)
Wallingford mine	Papineau county, Templeton tp., rge. 8, lot 16 west ½, Quebec	High quality, light amber mica; some exceptionally large crystals; associated with much apatite	Large production from a number of large-sized open-pits	Spence, H. S. (1929, p. 62)
Blackburn mine	Papineau county, Templeton tp., rge. 11, lot 9, Quebec	High quality light silver-amber phlogopite associated with much apatite in unusually large-sized deposits	Mined over a long period by open-pit and underground workings; very large total production, second only to that of the Lacey mine; production ceased shortly after World War II	Spence, H. S. (1929, pp. 62-63)
North Hill mine	Papineau county, Templeton tp., rge. 11, lot 10, Quebec	Very well defined vein averaging 5 feet wide, containing much medium-sized, light silver-amber mica, associated with much calcite	Worked entirely by underground mining from a shaft 325 feet deep; production commenced in 1908 and continued at intervals until about 1930	Spence, H. S. (1929, pp. 63-64)

Lacey mine	Frontenac county, Loughborough tp., con. 7, lot 11, Ontario	Large, vertical, vein-type deposit, mainly a mass of phlogopite crystals associated with a small amount of calcite and apatite; two types of mica — clear wine and opaque milky amber	Largest Canadian producer; mined almost continuously from 1880 until about 1930; reopened for a short time during World War II	Spence, H. S. (1929, pp. 69-71) Leitch, H. C. (1946) Mott, D. P. F. and Allen, J. M. (1948)
Bobs Lake mine	Frontenac county, Bedford tp., con. 6, lot 30, Ontario	Large number of parallel veins containing much large-sized dark amber mica; worked by open-pit; last reported work done in 1925		Spence, H. S. (1929, p. 71)

amounts of tremolite, diopside, phlogopite, biotite, and recrystallized carbonate. Isoclinal folding of these rocks has apparently resulted in repetition of the paragneiss and limestone members, but whether the quartzite member is the oldest or youngest of the series is unknown.

The granitic rocks that outcrop in the area are chiefly biotite- and hornblende-rich, quartz-feldspar gneisses, but include areas of massive syenite and small areas of remnants of clearly recognizable meta-sedimentary rocks. Injection gneisses are common, especially near the borders of the massive granitic rocks. Both massive and gneissic rocks are cut by many small pegmatite and aplite dykes. The assemblage has been mapped under the general term migmatites.

Three types of vermiculite occur in the Stanleyville area. The most important type, both economically and quantitatively consists of disseminated grains of vermiculitized phlogopite associated with diopside, apatite, and other contact metamorphic silicates, in parts of the various bands of crystalline limestone. (*See* Figure 13.) The second type comprises more or less vermiculitized phlogopite occurring in dykes or veins at various places within the crystalline limestone, and in the adjacent paragneisses; this type is only important from a mineralogical point of view. The third type is really a variation of the first, the difference being in colour which varies from almost black to light green; like the vein type, it is quantitatively unimportant in most instances.

The disseminated vermiculite associated with tremolite diopside, minor apatite, and other silicates in contact metamorphosed limestone, was derived by hydration of phlogopite. The distribution of the phlogopite within the limestone is exceedingly erratic, with all variations between pure limestone and almost-pure phlogopite occurring more or less at random. The distribution of the vermiculite is even more erratic in that only a part of the phlogopite has been vermiculitized. Likewise, the degree of hydration or vermiculitization varies greatly, and in no obviously predictable manner. Thus it is difficult to forecast the quantity and quality of the vermiculite in any given deposit.

The physical appearance of the vermiculite is influenced by the colour of the original phlogopite, by the degree of hydration, and by the type and amount of mineral inclusions introduced between the layers of the structure apparently during hydration. Thus the vermiculitized product varies in colour from a light silver tan through several shades of brown and reddish brown to almost black. Generally the lighter-coloured varieties appear to be more highly hydrated.

The rocks in certain parts of the area have been greatly altered to, and replaced by talc, which occurs as distinct light to dark green dykes and veins, and as pseudomorphs after phlogopite and other minerals. Serpentinization is also present throughout the area, but to a much lesser degree than talcification. Where talc is abundant the amount of vermiculite is low, since the phlogopite is converted to talc rather than to vermiculite.

The presence of phlogopite deposits in the Stanleyville area has been known for many years. According to Spence (1929, p. 73) the Pike Lake mine, con. 9, lots 16 and 17, "is said to be one of the earliest mica mines to be worked in the province. Records show that large mica sheets were shipped from it to France as far back as 1860". However, the descriptions of the mica contained in the deposits (de Schmid, 1912), do not indicate any possibility of vermiculite, and since the workings have long since been filled with water, it is impossible to examine the deposits to see whether or not vermiculite is present. Nevertheless, examination of three separate vein-type phlogopite deposits in this vicinity showed that a part of the phlogopite had been vermiculitized in two cases, and all of it in the other case. In each case it was observed that, where present, vermiculitization had proceeded from the edges of the books of phlogopite inward towards the centre. The process is accompanied by a progressive decrease in the elasticity of the mica, an increase in volume with consequent distortion of the sheets, a change in colour from an even dark amber to a somewhat mottled reddish brown, and a change in lustre from pearly to earthy. In general, the vermiculitized mica is leathery both in appearance and to the touch. The change in colour from brown to reddish is apparently due to the introduction of finely divided hematite between the double layers of the mica structure. The amount of change in any one of these physical properties in a given specimen depends on the degree to which vermiculitization has progressed.

The presence of crystals exhibiting all possible gradations of vermiculitization from almost completely unaltered to entirely vermiculitized phlogopite, plus the evidence that vermiculitization proceeds from the edges of the crystals inward, is clear proof that the process is secondary. No evidence was found that would indicate that vermiculitization was related to, or controlled by the action of ground water.

Green vermiculite occurs at a number of localities within the Stanleyville area. It is also present in the H. G. Green deposit, rges. 2 to 4, Cavendish tp., Ontario, some 10 miles north of Lakefield.

Examination of hand specimens and thin sections indicates that this green type of vermiculite is also derived from phlogopite. The green colour appears to have developed after hydration of the phlogopite. Proof of this is seen in samples which show progressive changes from brown to green vermiculite within one specimen. Again the alteration appears to have proceeded from the edges inward and outward from cracks. In some cases where alteration is incomplete the result is a mottled green and brown effect.

The reason for the green colouration is unknown.

Siscoe Vermiculite Showing

The vermiculite occurrence which first attracted attention to the Stanleyville district in 1950, and which was later explored by Siscoe Vermiculite Mines Ltd., is located on the north half of lot 17, con. 8, North Burgess tp., Leeds county, Ontario.

The vermiculite is found in a band of highly metamorphosed and silicated limestone which underlies an open field approximately 2,400 feet long by 700 feet wide. Within this area bedrock is only exposed in a few scattered outcrops. However, the thick mantle of residual soil which covers the field contains a variable percentage of light tan to silvery-white vermiculite, which presumably led to the original discovery. In 1950 the Siscoe Company sampled the surface and near-surface material by pits and trenches, and the underlying bedrock by three widely spared diamond-drill holes. Later, some trenching was done to explore the extent of vermiculite occurrences in small limestone lenses in the massive quartzite to the northwest of the main showings. Results obtained during exploration were not encouraging and active work by the Company was discontinued in 1951. The locations of the larger trenches and the diamond-drill holes, southwest of Stanleyville, are shown in Figure 13.

At the time of the writer's visit in 1952, little information on subsurface geology could be obtained by examination of exposures in the trenches because of the highly weathered character of the bedrock. But later examination of drill cores showed that the property is underlain by a fairly uniform, medium-grained, light greenish to white, mottled rock. This is largely composed of fibrous, light green to white tremolite, light to dark green diopside, brownish carbonate and varying amounts of serpentine, unaltered phlogopite, vermiculitized phlogopite, and phlogopite altered to and replaced by talc. Percentages of the different constituents vary considerably, but in general the most abundant mineral is tremolite, followed by diopside, serpentine, carbonate, phlogopite and talc in decreasing order of abundance.

Vermiculitization of the phlogopite appears to have been related to the intrusion of the aplitic dykes and veinlets which cut the body in many places. A later phase of hydrothermal activity produced widespread serpentinization and talcification.

Exfoliation tests conducted by the Mines Branch on representative samples throughout the total length of core from No. 1 diamond-drill hole indicated an average of about 10.5 per cent of expandable mica. After expansion the average bulk density was 17.6 pounds per cubic foot. The lowest was 14.6 pounds per cubic foot. Average bulk density of commercial vermiculite ranges from 6 to 10 pounds per cubic foot depending on the grain size. It seems quite probable that the late-stage introduction of talc may have materially reduced the percentage of expandable mica.

The degree of vermiculitization of the material obtained from No. 1 diamond-drill hole is quite uniform throughout the entire length of the hole, and does not appear to be related in any way to the present land surface. In fact the highest bulk density of 33.8 pounds per cubic foot was obtained from material occurring at a vertical depth of about 60 feet, whereas expanded material from a depth of about 215 feet had a bulk density of 15.9 pounds per cubic foot, or less than half that of the relatively near-surface material.

Farrel Vermiculite Showings

The Farrel vermiculite showings occur on the farm of Peter Farrel, lot 14, con. 9, North Burgess tp., Leeds county, Ontario, about two-thirds of a mile north of the village of Stanleyville.

The distribution of the various rock types in the vicinity of the farm, together with the sites of prospect pits, trenches, and diamond-drill holes, is shown in Figure 13. Exploration work by open-pit and short diamond-drill hole was carried out on various parts of the property by North Bay Mica Company and Pittsco Exploration Company during the summer of 1951. No further work has been done since.

The bedrock geology of the Farrel property is much more complex than it has been possible to indicate on the geological map of the area. Much of the area shown on the map as metamorphosed limestone is in fact a complex of relatively unaltered limestone, highly silicated, hydrothermally altered and serpentinized limestone, and hydrothermally altered and unaltered micaceous paragneiss, all of which are cut by many fine-grained granitic or aplitic dykes and stringers, and by a lesser number of fine-grained, dark-coloured gabbroic dykes. Owing to the lack of adequate surface exposures it was virtually impossible to satisfactorily establish the geological relationships between the various rock types.

The vermiculitization of the mica occurring in the rocks on the Farrel property is similar to that observed on the Siscoe property, in that it appears to have been related to hydrothermal solutions associated with the intrusion of the aplitic dykes. In this case, however, the solutions not only produced vermiculitization of the phlogopite occurring in parts of the silicated limestone, but also produced vermiculitization of some of the biotite occurring in parts of the associated paragneiss. The process in this area was commonly accompanied by the development of hematite or some red hydrous iron oxide between the mica plates, thus imparting a characteristic dull red colour to much of the vermiculite. In some places however, the vermiculite is dark green, and in others, both green and red varieties occur intimately intermixed. No satisfactory explanation of the origin of the green colour has been found.

Owing to the erratic distribution of the vermiculite, and to the wide variation in the degree of vermiculitization it was not possible to form any accurate opinion on the grade or tonnage of vermiculite present in the deposit.

Other Showings in the Stanleyville Area

Similar occurrences of vermiculitized phlogopite in altered limestone were encountered at numerous other places during mapping of the area. These are shown in Figure 13.

Mississagua Lake Deposit

The Mississagua Lake vermiculite deposit is on lots 13 and 14, con. 2, Cavendish tp., Peterborough county, Ontario, about 25 miles north of the town of Lakefield.

The vermiculite occurs in a band of crystalline limestone that is exposed for about 100 yards on both sides of the road at the point where the road crosses the boundary between lots 13 and 14, con. 2. The limestone band, which is approximately 250 feet wide, strikes northwest and dips steeply southwest. It is flanked on either side by granitic gneisses.

At the point where the road cuts across the limestone, both red and green vermiculite similar to that found on parts of the Farrel Stanleyville property, are exposed in three small open-pits some 25 feet west of the road. The vermiculite occurs as concentrations of small flakes in lenses and seams, and as disseminated small flakes in the white crystalline limestone. The concentrated masses of vermiculite appear to be confined to a narrow part of the limestone band not more than 10 feet wide. Further stripping may indicate the presence of other similar concentrations since minor amounts of both the red and green types are visible in scattered outcrops of the limestone for 100 or more feet north along the west side of the road, and also on the top of a small hill immediately west of the road. The more highly vermiculitized parts of the limestone are cut by dykes and stringers of serpentine.

In general the area underlain by the limestone is lightly but effectively covered with overburden. Insufficient work has been done to permit the formation of any accurate conclusions as to the extent of the deposit.

Holleford Deposit

Light tan to silvery vermiculite is present on lot 1, con. 11, Loughborough county, Ontario. The showing is on the open slope of a southerly facing hillside, some 200 feet east of the road, and 1⅓ miles north of the village of Holleford.

The hillside is completely covered by a mantle of residual soil. Although no actual bedrock is visible even in the shallow trenches, it is evident that the surface material grades downward into a deeply weathered, soft serpentinized rock, which contains vermiculite. The type of residual soil, the deeply weathered bedrock, and the light silvery colour of the vermiculite indicate that the deposit is similar to the Siscoe deposit at Stanleyville. It is not known how the percentage of vermiculite compares with that of the Siscoe deposit.

Verity Deposit, British Columbia

Reference: McCammon, 1950.

The Verity vermiculite deposit is situated on the steep easterly slope of the North Thompson River valley about 170 miles north of the city of Kamloops, near Blue River.

The mountainside, on which the showings occur, is heavily timbered and underbrush is thick. Outcrops are small, scarce, and scattered; overburden generally is thick.

The predominant rock type in the vicinity of the showings is a well-banded augite-hornblende gneiss. Conformably interbanded with the gneiss is a layer of coarsely crystalline limestone. The average regional strike of the foliation is approximately N70°E. The dip is about 20°SE.

A vermiculite-bearing zone along the upper limestone-gneiss contact has been explored by two main open-cuts, and by four smaller ones spaced irregularly over a strike length of about a mile.

The occurrence of the vermiculite, as exposed in the various open-cuts, is apparently confined to a relatively narrow part of the limestone band immediately underlying the upper limestone-gneiss contact, and to a narrow, irregular zone at or near the actual contact. The mode of occurrence and type of vermiculite present in the limestone are quite different from those at the contact. The material within the limestone occurs disseminated throughout, as books averaging about one-half inch, but in some cases 4 inches in diameter. It is associated with apatite, the percentage apparently increasing more or less regularly as the contact is approached. The irregular vermiculite-rich zone at the contact is composed of a mass of small, rectangular flakes, and is commonly associated with much biotite. It varies from 2 to 5 feet in width.

The disseminated vermiculite, from its typical association, would appear to be the alteration product of phlogopite similar to that found in many of the deposits in Ontario and Quebec, whereas that occurring at the contact appears to be pseudomorphic after hornblende. McCammon (1950, p. A230) states that it appears to be derived from hornblende "in some cases directly but in others through an intermediate stage." The formation of vermiculite from hornblende without an intermediate biotite stage is not compatible with what is known of the origin and structure of the mineral. In this case it is suggested that a biotitic stage, although not always visible, was probably present in all cases. If it is assumed that the mineral was derived by direct replacement of hornblende, and that the replacement was complete, the resulting mineral should be true vermiculite. Examination of the results of the expansion tests conducted by McCammon (1950, p. A230) do not indicate this. Water losses on expansion of the samples are reported to have been 5.5 per cent for that derived through an intermediate biotite stage, and 7.5 per cent for that derived directly from hornblende; whereas the water loss on expansion of true vermiculite is about 21 per cent. Obviously then, neither of the Verity samples was true vermiculite. In view of this evidence it seems probable that they were both hydrobiotite similar to that found at Libby, Montana, which also is derived from hornblende through an intermediate biotite stage, and which has a water loss on expansion of 5.89 per cent.

It would seem that the thermal metamorphism and metasomatism that resulted in the formation of phlogopite and apatite in the limestone were also responsible for the formation of biotite from hornblende in the overlying gneiss. Subsequent hydrothermal solutions probably introduced along the limestone-gneiss contact produced partial vermiculitization of the previously formed phlogopite in the limestone, and of the biotite in the gneiss near the contact.

Chapter VI

OCCURRENCE AND PRODUCTION OF SHEET MICA AND VERMICULITE IN FOREIGN COUNTRIES

Sheet Mica

More than 80 per cent of the world's output of sheet mica is produced in countries that use relatively little mica themselves, India, Brazil, Madagascar, and Argentina being the chief suppliers. Of the countries which consume the bulk of the sheet mica, only the United States and Canada supply some of their sheet mica requirements from home deposits. Information on sheet mica supplies in the principal foreign countries is summarized in the following.

India

References: Crookshank, 1945; Dunn, 1947; Krishnan, 1952 and 1953; Rajgarhia, 1951.

India accounts for about three quarters of all sheet mica entering world trade. All Indian mica is muscovite, and the country's reserves of high-grade mica are large. Most of the mica produced is mined in the Bihar district of Bengal, the Nellore district of Madras, and in the Ragasthan district. Each of these districts has hundreds of mines, most of them small and worked by primitive methods. The few large, modern mines use up-to-date machinery.

Wage rates in the Indian mica industry are very low, and since labour costs constitute a large part of the total production cost, sheet mica production in India has a competitive advantage over that in most other mica-producing countries. India is virtually the sole world source of muscovite splittings and is also a leading supplier of high-grade block and film mica.

India sheet mica exports consist predominantly of splittings. Before World War II splittings accounted for 80 to 85 per cent of total exports, but in recent years exports of splittings have been higher than 90 per cent of the total; they accounted for 94 per cent in 1950. The decline in exports of block mica is probably due in part to the increasing importance of Brazil as a source of high-grade block mica. However, it is doubtful whether any other country can become an important source of muscovite splittings, or surpass India as a supplier of high-grade block mica.

The United States is by far the greatest market for Indian splittings, having accepted an average of about 60 per cent of India's total exports of that material in recent years. The United Kingdom has ranked second, with other western European countries and Japan also being fairly important markets. India block mica has been shipped chiefly to the United Kingdom and the United States, the two countries often taking three quarters or more of the total exports.

Bihar has been the most important mica-mining centre in India for many years. The mica belt here is about 90 miles long and up to 16 miles wide. Of the 4,857 tons produced in the province in 1952, about three quarters came from the Hazaribagh area, and most of the remainder from the Gaya and Monghyr areas. The notable part of the belt is along the edge of the Chota Nagur plateau, where deep stream dissection has exposed numerous mica-rich pegmatites that range in thickness from a fraction of an inch to over 100 feet. In some cases mining has been carried on to a depth of about 500 feet, and there is no evidence that the deposits will not continue to greater depths. No estimate of reserves of mica is available, but when the size of the belt is considered, the reserves are governed only by the depth to which economic working is possible. Of the mica mined, roughly 25 per cent is block or sheet and 75 per cent splittings.

The mica belt of the Nellore district of Madras extends about 60 miles along the coast and is 8 to 10 miles wide. Production is confined mainly to spotted mica and although output has been fairly steady it has fallen behind that of the Bihar State in recent years. Madras mica is flatter than that from Bihar or Ragasthan.

In Ragasthan, pegmatites are distributed over a 60-mile-wide belt extending over 200 miles from Gaipur in the north to Udaipur in the southwest. The average size and quality of the Ragasthan mica are undoubtedly superior to the average bulk of Bihar mica, but lack of flatness has seriously affected its commercial value. Practically the entire production from Ragasthan is bought by Bihar manufacturers and processed in Bihar.

The most prolific mica area in Ragasthan is in Udaipur State, where the trade centres around Bhilwara. At the beginning of World War II much low-grade mica from this area was exported to Japan and Germany, but lack of demand for this type of product after the outbreak of hostilities with Japan made it necessary for the producers to concentrate on better-quality mica. At the time of this writing, sickle-dressed block ruby mica and a small amount of black spotted mica are being mined, but it is hard to assess the exact quality of these products as they are sent direct to Bihar and there mixed with Bihar mica.

Brazil

Brazil has become the second largest source of sheet muscovite entering world trade. During World War II the Brazilian mica industry received considerable assistance from the United States in funds and personnel, and also in equipment to modernize the mines and to help expand the mica-mining industry. Block is the chief form of mica produced and exports compare favourably with the Indian product. Before the war most Brazilian mica went to western European countries, but during and since the war the United States has been by far the principal foreign market. Formerly, Brazilian producers regularly shipped considerable quantities of mica to India for fabrication (splitting) and re-export. This practice was discontinued in 1948 by action of the Indian government.

Muscovite mica occurs in a number of widely separated localities in Brazil, but production has come largely from deposits in the southeastern and eastern parts of the State of Minas Gerais. In the ten-year period 1936-45, the pegmatite mines of Minas Gerais produced some 7,200 metric tons of sheet mica. More than 85 per cent of the few hundred commercially significant mica-bearing pegmatites in Brazil are in the belt of eastern Minas Gerais, where about 95 per cent of Brazil's output of muscovite has originated.

From the year 1900 to 1945, about 8,500 metric tons of processed muscovite were exported from Brazil, about 60 per cent of this amount after 1940. The total mine production since 1900 is estimated to have been about 100,000 metric tons of crude mica. Before 1943 almost all the mica was mined by hand. In the period 1943-45, some 30 mines employed earth-moving equipment in open-pit operations, and about 20 used air compressors for underground rock drilling. As a result of the high rate of production during the war, a number of mines have seriously depleted their indicated reserves, but others have developed even greater reserves. According to Pecora *et al.* (1950, p. 206) "In September 1945, the seven largest mines had a total measured reserve of about 2,000 metric tons of mine-crude mica and a total indicated reserve of about 5,000 metric tons. Geological relations in many other mines are favourable for an orderly exploration in depth. The indicated reserve of mine-crude mica in Minas Gerais is about 100,000 metric tons, and the inferred reserve is several times this amount. The mica industry as a whole and many mica mines in particular are more firmly established in the postwar period than they were in prewar years."

In 1952 the United States imported 1,312,925 pounds of sheet muscovite (ruby), valued at $1,883,178, from Brazil, whereas imports of India sheet mica in that year amounted to 524,174 pounds, valued at $1,275,860. From these figures it can be seen that although the unit value of Brazilian mica is still considerably less than that of the Indian product, the total dollar value of United States imports of sheet mica from Brazil now exceeds that of the Indian imports.

The geologic features of the mica-bearing pegmatites of the Minas Gerais area are described by Pecora *et al.* (1950, pp. 205-305).

United States

Sheet muscovite has been produced in the United States for many years, but generally in relatively minor amounts and never in sufficient quantity to meet the total domestic demand.

During the 1943-47 period, production increased sharply over prewar output, averaging about 1½ million pounds per year, but declined again in 1947 to a low of about 200,000 pounds. A slight increase in price in the 1948-51 period resulted in increased production which, during this period averaged about 500,000 pounds per year.

In 1950 the government commenced a support program designed to encourage the exploration, development and mining of critical and strategic metals and minerals including mica. Under this program, the government contributed 90 per cent of the approved costs of mica exploration, repayable from net returns within 10 years. As a further inducement a long-range purchasing program for domestic mica was started in 1952. This plan was to continue until June 20, 1955 or until the stockpile had reached the equivalent of 25,000 tons of hand-cobbed mica. (Ninety pounds of full-trimmed mica is considered equal to 1 ton of hand-cobbed mica.) The support price paid for mica under this program was between four and five times the current market price. As a result, U.S. domestic production of crude sheet mica in 1952 increased 17 per cent in quantity and 466 per cent in value over 1951 production.

The main mica-producing areas in the United States are the southeastern states, North Carolina, Virginia, and Georgia, and the New England states, New Hampshire and Maine.

Southeastern States

The general mica-producing area of the southeastern states is divided into two main mica belts: the Blue Ridge belt of North Carolina and Georgia on the northwest; and the longer and broader Piedmont belt on the southeast. Each of these major belts embraces numerous mica-producing districts, of which the Spruce Pine district of North Carolina is by far the most important, both in annual and total production of mica, and in the number of mines.

Geologic features of mica-bearing pegmatites in the southeastern states are described by Sterrett (1923); Griffitts, Jahns and Lemke (1953); Pegau (1932); Kesler and Olson (1942); Olson (1944); Galpin (1915); Furcron and Teague (1943); and Clark (1921).

New England States

Major production of sheet mica in the New England states has been derived from a belt of mica-rich pegmatites extending northeasterly from

Surrey in Cheshire county, to Easton in Grafton county, New Hampshire. During 1943 and 1944, mines in this area supplied approximately 20 per cent of the United States domestic production.

Geologic features of the various deposits are described by Cameron, *et al.* (1945); Bannerman and Cameron (1943); Sterrett (1923); and Olson (1942).

Australia

References: Mineral Resources of Australia; *Australia, Bur. Mineral Resources, Geol. and Geophysics,* Sum. Rept. No. 4, Mica, 1948.
The Australian Mineral Industry; *Australia, Bur. Mineral Resources, Geol. and Geophysics,* 1951 Review.

Virtually all Australian production of sheet mica is from muscovite-bearing pegmatites in the Northern Territory, but a little has been produced from Queensland, Western New South Wales, South Australia, and Western Australia. About the only place where mica has been mined by underground methods is at Harts range, in the Northern Territory, where irregular workings have followed mica-rich sections of some pegmatites down to depths of about 100 feet.

In Harts range, commercial muscovite occurs in numerous pegmatite bodies distributed over an area of more than 400 square miles. The pegmatites are intrusive into gneisses and schists and have a wide range of composition and texture. Very large books have been recovered from time to time. Production includes some hard sheets of high quality.

The Plenty River mica field lies about 50 miles east of the centre of the Harts range area. Production is much less than that from the Harts range, but the average quality of the mica has been high.

During 1952, 36 tons of block mica were obtained from the Harts range-Plenty River area, with more than 6 tons of this coming from the Spotted Tiger mine.

New Zealand

References: Wellman, 1947; Willett, 1946.

At present New Zealand does not produce any mica, although small amounts of sheet muscovite were obtained from several pegmatite deposits in South Westland during 1944, when overseas supplies were cut off. Inaccessibility and high labour costs are the main deterrents to production in normal times.

Northern Rhodesia

Reference: Deans, 1942.

Large books of muscovite occur in pegmatite bodies in several localities in Northern Rhodesia, but the only commercial production is from the Mazabuka district.

The Sachenga mine, 56 miles east of Mazabuka and 45 miles from Kafue, has been worked since 1925 and has been the only producer for many years. The mica produced is reported to be good quality ruby muscovite. In 1951 Northern Rhodesia produced 18 tons of sheet mica.

Tanganyika

Mica is very widely distributed throughout Tanganyika, produced in seven of the eight provinces. Owing to the abundance of easily worked surface exposures of mica-rich pegmatite bodies, the majority of the workings consist of shallow, inexpensive open-pits.

Excellent quality muscovite is obtained north of Masasi in the Southern Province, and also in the Bundali Hills region of the Southern Highlands Province. Mica from deposits in the Uluguru region is reported to be heavily stained.

In 1952 the Netherlands firm of Van Eeghen and MacLaine Ltd. built a mica-sorting plant in Marogoro with a working force of about 100 employees. This company was Tanganyika's fourth largest exporter of sheet mica.

In 1952, 132 tons of block and sheet mica were produced in Tanganyika.

Southern Rhodesia

The mica production of Southern Rhodesia during 1952 was 104 tons of block and sheet, and 732 tons of scrap.

The chief centre of production is in the Limagundi district, some 80 miles north of Sonia, where the mineral occurs in pegmatite dykes cutting mica schists.

A company was formed in 1950 to open up some potential mica and beryl areas at Miami. The Last Hope mine currently produces 1½ tons of very good quality ruby muscovite monthly.

South Africa

In 1952 South Africa produced 5½ tons of sheet mica and 2,936 tons of scrap mica, mainly derived from mica-bearing pegmatites occurring in a well-defined belt in the Letaba area of northeastern Transvaal. The belt is 2 to 4 miles wide and extends for about 50 miles from the neighbourhood of Mica Siding eastward through the Game Reserve towards the border of Portuguese East Africa. The most important deposits in the area lie between the Oliphants River and Mashishimala hills.

Angola

Reference: Cardoso, A. J. F.: Angola, Your Neighbour (private publication, 1950).

Angola produced 29 metric tons of sheet mica and 200 tons of scrap in 1952. According to Cardoso (1950) mica-rich pegmatites occur in the Councils of Dande and Ambriz. In 1949 two mines were operating in the Dande area.

French Morocco

Pegmatite bodies of the Tazenakht region are reported to contain abundant muscovite and beryl. The total production in 1951 was 12 metric tons of block and 25 tons of scrap.

Argentina

Deposits of muscovite apparently occur in many parts of Argentina, but detailed information concerning them is generally lacking. Mica-bearing pegmatites are known to occur in the States of Cordoba, San Juan, San Luis, La Rioja, and Catamarca. The best-known productive mines are near La Toma, on a branch railroad in San Luis province, about 400 miles west of Buenos Aires, and at Calamuchita in nearby Cordoba. Other deposits are in the extreme northern province of Salta on the Bolivian border, and in the extreme southern state of Santa Cruz, Patagonia.

Annual production of sheet mica is estimated to be about 300 tons, and although a large part of this output is reported to be of the electric (stained) class, there have been some imports into the United States of very fine clear sheet. Some of the mica exported from Argentina is trimmed nearly as perfectly as that from India.

Madagascar

Madagascar is generally in the same commanding position as a supplier of phlogopite mica as that held by India as a supplier of muscovite; although production in Madagascar is low compared with that of India. Madagascar has extensive deposits of both phlogopite and muscovite, but current production is confined almost exclusively to phlogopite. The principal deposits are in the southern and south-central parts of the island, and mode of occurrence is very similar to that of Canadian phlogopite deposits. Modern mining equipment is being installed and used in several Madagascar mines, but primitive methods are still used in most.

The availability of low-cost labour has enabled Madagascar to become the world's chief source of phlogopite splittings. Exports of block phlogopite are small. Total annual production of sheet mica during the period 1941 to 1948 was about 1 million pounds, but since that time it has just about doubled.

Vermiculite

A summary of foreign vermiculite deposits is given in Table XVI.

Table XVI

Tabular Summary of Foreign Vermiculite Deposits

UNITED STATES

Location	Occurrence of Vermiculite	Host Rock	Associated Minerals	Associated Intrusives	Relationship to Present Land Surface	References
LIBBY, Montana (Zonolite Company)	Vermiculite consists of hydrobiotite and occurs more or less disseminated throughout the whole pyroxenite body in small amounts. But within the body, an area 2000 feet wide by 2 miles long, contains several large dyke-like and irregular lens-shaped concentrations - of nearly pure vermiculite. The margins of concentrations generally grade into pyroxenite, the amount of pyroxene increasing until the amount of vermiculite may be less than 10% or even 5%. Concentrations have a nearly vertical trend, and may be as much as 100 feet wide and 100 feet long, although their width is more commonly 20 to 40 feet. Very large reserves.	Pyroxenite; composition variable, from almost pure diopside to almost pure biotite. Intruded into argillites, quartzites, and limestone of Precambrian Belt series.	Diopside; biotite; apatite (fluor) up to 10%; sphene, magnetite, and ilmenite, in places up to 10%; feldspar generally less than 15%.	Syenite in form of large stock in contact with pyroxenite, and as syenite dykes and syenite pegmatite dykes cutting the pyroxenite body.	Vermiculitization shows no relationship to present water table or land surface. Origin generally considered to be result of hydrothermal alteration of biotite.	Pardee and Larsen (1929, pp. 17-29) Perry (1948, pp. 24-28)
Deposits near HAMILTON, Montana.	Almost similar to Libby deposits. Vermiculite (hydrobiotite) occurs as disseminations and as local concentrations 6 inches to 3 feet in width, in body of pyroxenite (diopside) which intrudes impure limestones and argillites of the Belt series. Vermiculite concentrations said to occur over an area 3 miles long by 1 mile wide.	Pyroxenite as at Libby.	Diopside, apatite, biotite; magnetite up to 15% in places, sphene up to 4%; tourmaline and titaniferous garnet.	Syenite as intrusive masses and as pegmatite dykes. Extensive areas of Idaho Batholith quartz monzonite nearby.	Same as Libby deposit.	Perry (1948, pp. 28-30)

Deposit near PONY, Madison county, Montana	Vermiculitized biotite as layers or bands up to 3 feet thick in biotite gneiss. Successive bands separated by parallel bands of quartz and feldspar 1 inch to 1 foot thick. Very large reserves. Percentage of vermiculite in any one layer varies from about 50 to almost 100. Degree of vermiculitization is likewise variable.	Biotite, quartz, feldspar gneiss.	Biotite, quartz, feldspar, and minor garnet.	Pegmatite dykes.	None apparent.	Perry (1948, pp. 32-34)
WYOMING deposits	Deposits in Encampment, Wheatland, and Sweetwater Uplift districts all exhibit similar geological relationships with vermiculite occurring, with one or two exceptions, at the contacts of pegmatite dykes with biotite and/or hornblende schists. Where hornblende is the mafic mineral, alteration appears to have first produced biotite, which was subsequently altered to vermiculite by hydrothermal or pegmatitic solutions. In the Glenrock district deposits, vermiculite occurs at the contacts of granitic pegmatites with hornblendic rocks, and at serpentinite-pegmatite contacts. In the latter case there is usually a narrow zone of chlorite, amphibole, and talc present between the serpentinite and vermiculite. Reserves do not appear to be large.				None apparent.	Hagner (1944, pp. 18-32)
COLORADO deposits	Available information suggests relationships between pegmatite dykes and hornblende and biotite schists and gneisses, similar to those of Wyoming deposits.					Goldstein (1946, pp. 12-17)
NORTH CAROLINA, NORTHERN GEORGIA, and MARYLAND	Vermiculite occurs at contacts between albitite dykes and ultrabasic rocks. May be either hydrobiotite or hydrophlogopite. Vermiculite (or unaltered mica) always occurs next to the albitite, and is separated from the host rock by successive layers of amphibole and talc.	Serpentinite; peridotite, pyroxenite, hornblendite commonly highly serpentinized.	Corundum in the dykes, biotite, phlogopite, amphibole, talc, apatite.	Albitite dykes.	None.	Larsen (1928, pp. 398-443) Hunter and Mattocks, (1936)

Tabular Summary of Foreign Vermiculite Deposits—Continued

AFRICA

Location	Occurrence of Vermiculite	Host Rock	Associated Minerals	Associated Intrusives	Relationship to Present Land Surface	References
Kenya, South Kitui deposits	Vermiculite occurs as numerous small and irregular lenses between pegmatite dykes and dunite.	Dunite.	None.	Pegmatite.	Not known.	Varley (1952, p. 30)
Kenya, Kinyiki deposits	Along contacts of pegmatite dykes cutting dunite and hornblende schists.	Dunite and hornblende schists.	Not reported.	Pegmatite.	Not known.	Varley (1952, p. 31)
	As vermiculitized mica within pegmatite dykes. Vermiculitization apparently not complete; type of mica not reported.	Pegmatite.	Not reported.	Pegmatite.	Not known.	Varley (1952, p. 31)
Uganda, Bukusu Hill and other carbonate ring structures	Vermiculite (vermiculitized phlogopite) associated with magnetite, apatite, and phlogopite which occur as a ring or band surrounding a central carbonate core. Details on mode of occurrence not available.	Carbonate wholly or partly replaced by apatite, magnetite, and phlogopite. Diopside not reported.	See Occurrence.	Ring of syenitic rocks surrounds structure and separates it from main granite mass.	Said to occur only within 60 feet of the surface.	Varley (1952, p. 32)
Nanekara deposit	Thought to be a somewhat similar ring structure to those in the Bukusu District except that vermiculite occurs associated with dunite.	Carbonate? dunite.	Not reported.	Not reported.	Not known.	Varley (1952, p. 32)

Tanganyika, Kwekivu deposit	Vermiculite occurs as clusters of large bent plates in a small irregular intrusion of pegmatite penetrating an ultrabasic remnant within a granitic biotite orthogneiss. Vermiculite on the walls of the pegmatite body is commonly fine-grained or sandy in character; whereas that occurring within the body is commonly in the form of books and plates.	Pegmatite.	Quartz, oligoclase, amphibole asbestos, scapolite, serpentine talc calcite, albite. Relationship of these minerals to vermiculite or ultrabasic rock not reported. Apatite not present.	Pegmatite.	Considered to be of probable hydrothermal origin.	Varley (1952, p. 33)
Union of South Africa, Cape Province Kimberlite Pipes	More or less disseminated throughout the near-surface parts of the pipes.	Kimberlite (serpentinized peridotite).	Olivine, apatite, perovskite, ilmenite, chromite, enstatite, garnet, diopside. Secondary minerals: calcite, iddingsite, serpentine, apophyllite, chlorite.	None.	Vermiculite usually passes in depth into unaltered phlogopite.	Varley (1952, p. 36)
Transvaal, Loolekop deposits	*General Description of the Regional Geology*: The general geology of the Loolekop deposits appears to be similar to that of the Uganda deposits, in that the body consists of a somewhat similar circular ring structure. However, due to much more extensive exploitation, more detailed information regarding mode of occurrence is available in this case. The centre of the body consists of an eliptical mass of magnetite and apatite bearing dolomitic marble which grades on the periphery into a zone of serpentine-magnetite-apatite rock containing vermiculite (after phlogopite), and minor unreplaced carbonate. Surrounding this is a large mass of pyroxenite, containing a large body of serpentine-vermiculite rock from which most of the vermiculite produced is obtained. The whole ring complex is surrounded by intricately intermingled syenite and granite which are everywhere intrusive into the pyroxenite. Small- to medium-sized syenite plugs commonly occur at or near the granite-pyroxenite contact. Pyroxenite in contact with syenite exhibits a wide felspathized zone, whereas felspathization of pyroxenite at granite contacts is much less pronounced.					

Tabular Summary of Foreign Vermiculite Deposits—Continued

AFRICA—*Continued*

Location	Occurrence of Vermiculite	Host Rock	Associated Minerals	Associated Intrusives	Relationship to Present Land Surface	References
Transvaal, Loolekop deposits (Cont.)	*Description of Zone:*					
Central Carbonate Core	Sparsely disseminated flakes of yellow vermiculite (after phlogopite)	Coarse white to yellowish white crystalline limestone.	Magnetite in grains, blebs, and masses up to 2 feet in diameter scattered throughout; Apatite — small grains sparsely disseminated throughout; Serpentinized olivine — as small isolated grains becoming more abundant towards the periphery.	None reported.		
Peripheral Zone of Carbonate Core	As masses of yellow vermiculite up to 1 foot in diameter. Most abundant in magnetite-rich parts.	Serpentine-magnetite-apatite rock containing little or no residual carbonate: a little residual olivine. Transition from central carbonate	See "Host Rock"	None reported.		

		core appears to be gradational.			
Pyroxenite Zone (*a*) *Inner Zone of 'normal' Pyroxenite*	Black to brown vermiculite (after biotite) occurring in nests, pockets, and bands; particularly abundant near pyroxenite-limestone core contact. Yellow vermiculite (see below).	Pyroxenite; massive medium green to dark green rock composed almost wholly of diopside prisms 4-5 mm. in length, containing phlogopite and biotite disseminated throughout and also in local concentrations.	Apatite; small grains scattered throughout; coarser grains fairly limited and associated with concentrations of vermiculite and phlogopite.		
	Towards the centre of the pyroxenite mass there is a noticeable coarsening of grain size of the pyroxene crystals, with an accompanying development of masses of almost pure yellow vermiculite and apatite. In such masses the percentage and grain size of vermiculite is greatest at the centre and gradually decreases as the pyroxene is approached. Apatite is likewise coarsest in the central parts of such masses. In particularly rich or coarse zones, recrystallized diopside appears as idiomorphic crystals of varying size. Feldspar may also be present as isolated crystals or as stringers.				
(*b*) *Pegmatitic Pyroxenite Zone surrounding the Serpentine Vermiculite Body*	In nests, bands, pockets, and irregularly shaped bodies of yellow vermiculite, a few to more than a dozen feet wide, usually associated with idiomorphic crystals of pegmatitic diopside, small crystals of which occur as vug filling with terminal ends of crystals enveloped in vermiculite or phlogopite.	Semi-translucent diopside, pale greenish to yellowish green in colour, of coarser and distinctly granular texture. Zone varies in width from a few dozen feet to hundreds of yards.	Diopside; phlogopite; no apatite.		

Tabular Summary of Foreign Vermiculite Deposits—Concluded

AFRICA—*Continued*

Location	Occurrence of Vermiculite	Host Rock	Associated Minerals	Associated Intrusives	Relationship to Present Land Surface	References
(*c*) *Serpentine-Vermiculite Body*						
1. Central Core	Bands of pure or almost pure yellow vermiculite, up to many dozens of feet wide, and bands up to more than 100 feet wide in which vermiculite predominates over serpentine, alternate with bands of equal width in which vermiculite is subordinate to serpentine but still represents workable ore, and bands in which vermiculite is comparatively sparsely developed. Bands dip steeply, are generally lenticular in character, and have irregular contacts. Vermiculite and phlogopite in this zone is generally finer grained than that occurring in the surrounding outer marginal zone.	Phlogopite and serpentine.	Phlogopite and serpentine; minor amounts of residual olivine, similar in composition to that occurring in limestone; no apatite.		Evidence obtained thus far indicates that at Loolekop both yellow and black vermiculite pass into less highly hydrated types and finally to phlogopite and biotite respectively at depths to 100 feet. However, detailed examination of the occurrence of phlogopite does not indicate any relationship between the alteration of phlogopite with resultant formation of vermiculite and the action of downward percolating waters. In fact these waters do not seem to produce any effect on phlogopite.	Gevers (1948, pp. 133-173) Schwellnus (1935) Laschinger (1944) Varley (1952, pp. 38-39)
2. Outer Margi-	Vermiculite and serpentine, accom-	Pegmatitic diop-	Diopside, ser-			

2. Outer Marginal Core	Vermiculite and serpentine, accompanied by, but predominating over, diopside. Towards the outer margin of the zone pegmatitic diopside becomes progressively more abundant; near the outer margin it occurs in bands more than 12 feet wide, as well as in clusters. Within these bands vermiculite occurs in stringers and nests. Zones of vermiculite and serpentine become progressively narrower as the margin is approached. The amount of serpentine decreases more rapidly than vermiculite, which is generally abundant right up to the outer margin.	Pegmatitic diopside, phlogopite.	Diopside, serpentine, and phlogopite; no apatite; phlogopite and vermiculite commonly replace diopside along cleavage planes.			
AUSTRALIA						
South Australia, LYNDOCH occurrence	Vermiculite is associated with a deposit of asbestos, occurring as veins ½ inch to 3 inches thick and as isolated patches in metamorphosed country rock on the foot-wall side of the asbestos.					Varley (1952, p. 43)
Western Australia, YOUNG RIVER deposit	Details of geology of area not available, but it is reported that the vermiculite zone lies towards the western margin of a complex of sheared basic rocks intruded into interbedded hornblende granulite and biotite gneiss. Both the basic intrusives and the gneisses have been invaded by granite and pegmatites.	Not reported.	Not reported.		Evidence favours hydrothermal origin.	Varley (1952, pp. 44-45)

Chapter VII

STATUS OF THE CANADIAN MICA INDUSTRY

Historical Review

The history of the Canadian mica industry is almost synonymous with that of Canadian phlogopite mining. From 1886 to about 1920, Canada was the world's chief source of supply of sheet phlogopite or amber mica. During the early part of this period, production in the form of thumb-trimmed sheets, was derived from many mines in Quebec and Ontario. Due to the erratic nature of most of the deposits, several mines had very short lives, and by 1910 the number of producing mines had decreased sharply. From then on the major part of the production was from a few large mines. Production and exports increased until about 1917, and continued at a fairly constant high level from then until 1924. Thereafter the increasing competition of phlogopite from Madagascar, combined with a decreasing demand for sheet phlogopite and changing economic conditions, brought about a reduction in available markets and consequent decrease in production. Organized mining in Ontario ended with the closing of the Lacey mine in the early thirties, and in Quebec all but two or three mines in Hull and Templeton townships had closed by 1939. Production of high-quality phlogopite for use in aircraft engines and condenser films increased sharply during the early stages of World War II, but the resurgence of activity was short-lived and soon after virtually all organized mining ceased. However, intermittent small-scale mining of scattered deposits has continued to date, and production has been sufficient to satisfy local Canadian demands. During recent years small amounts of sheet and scrap have been exported to Japan.

For a brief interval during World War II, and for a few years after, Canada assumed the role of a major sheet muscovite producer. Almost the entire production during this period was derived from the Purdy mica mine; the latter prospered because it was discovered during a period of record prices, and because the deposit contained a number of relatively rich concentrations of large-sized book muscovite from which an unusually high proportion of sound, high-quality sheet was produced at minimum cost.

Future Possibilities

Future possibilities of a resurgence of the Canadian phlogopite industry are not great, not because of a lack of worthwhile deposits, but because it is virtually impossible to produce phlogopite in Canada at a price which will compete successfully with prices of that produced in countries where labour costs are much lower.

Past experience has shown that sheet muscovite mining in Canada is unlikely to be profitable except in times of stress, when prices are high, and even then only when the deposits are exceptionally good.

Production Statistics

The annual Canadian production and export of mica from 1886 to 1954 are shown in Tables XVII-XX which follow. Records of the various classes of mica produced prior to 1921 are not available. Up to 1941 the figures relate almost wholly to phlogopite since until that time production of muscovite in Canada seldom exceeded a few hundred pounds in any one year. The sharp increase in production, and more particularly in gross annual value from 1942 to 1945 and from 1950 to 1953, is due almost entirely to production from the Purdy mica mine.

Table XVII

Annual Production of Mica in Canada
1886-1920

Year	Tons	Value	Year	Tons	Value
		$			$
1886	—	29,008	1904	—	160,777
1887	—	29,816	1905	—	178,235
1888	—	30,207	1906	—	303,913
1889	—	28,718	1907	—	312,599
1890	—	68,074	1908	—	139,871
1891	—	71,510	1909	369	147,782
1892	—	104,745	1910	758	190,385
1893	—	75,719	1911	590	128,677
1894	—	45,581	1912	580	143,976
1895	—	65,000	1913	1,104	194,304
1896	—	60,000	1914	595	109,061
1897	—	76,000	1915	417	91,905
1898	—	118,375	1916	1,208	255,239
1899	—	163,000	1917	1,166	385,851
1900	—	166,000	1918	747	271,550
1901	—	160,000	1919	2,754	273,788
1902	—	135,904	1920	2,203	376,022
1903	—	177,857			

Table XVIII

Canadian Mica Production (Primary Sales) by Classes
1921-1954

Class	1921		1922		1923		1924	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$
Rough, mine-run or rifted	329,010	31,920	186,470	22,305	280,767	26,926	535,295	33,337
Thumb-trimmed	48,517	17,481	95,702	25,837	419,130	87,769	662,709	142,405
Splittings	20,350	15,365	112,778	72,303	210,056	176,785	164,734	137,248
Total Sheet Mica	397,877	64,766	394,950	120,445	909,953	291,480	1,362,738	312,990
Scrap	986,230	5,282	6,302,157	31,818	6,139,076	35,494	6,819,636	44,282
Ground	20,000	15	...	...	...	...	...	...
Total	1,404,107	70,063	6,697,107	152,263	7,049,029	326,974	8,182,374	357,272

Class	1925		1926		1927		1928	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$
Rough, mine-run or rifted	413,500	23,471	109,880	11,724	255,925	16,943	...	...
Thumb-trimmed	357,943	73,443	322,639	64,958	443,090	72,513	91,064	16,698
Splittings	188,265	129,454	180,603	120,503	81,919	54,048	25,367	14,974
Total Sheet Mica	959,708	226,368	613,122	197,185	780,934	143,504	116,431	31,672
Scrap	7,080,331	35,095	4,476,405	32,109	4,696,058	30,873	7,043,795	50,507
Total	8,040,039	261,463	5,089,527	229,204	5,476,992	174,377	7,160,226	82,179

Class	1929		1930		1931		1932	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$
Rough-cobbed	...	...	44,330	1,142	...	...	...	...
Thumb-trimmed	97,331	17,131	8,096	8,281	49,835	5,717	2,019	1,254
Splittings	22,750	13,732	77,530	35,601	37,475	14,398	3,350	2,014
Scrap	7,986,878	87,686	2,211,022	50,980	2,589,918	33,951	612,980	3,560
Total	8,106,959	118,549	2,340,978	96,004	2,677,228	54,066	618,349	6,828

Class	1933		1934		1935		1936		1937	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$		$
Rough-cobbed	...	...	2,459	514	30,605	2,448	10,940	2,615	106,917	12,090
Knife-trimmed	8,591	3,923	61,003	25,628	111,459	52,959	113,169	48,086	203,961	66,852
Thumb-trimmed	51,881	8,397	90,726	27,360	12,013	3,616	35,289	3,233	173,519	11,826
Splittings	74,550	27,446	75,050	33,120	32,921	15,506	24,376	97,780	72,500	32,495
Scrap	1,753,375	9,518	1,766,031	10,449	1,068,618	7,509	1,417,783	10,842	1,333,479	10,468
Total	1,888,397	49,284	1,995,269	97,071	1,255,616	82,038	1,601,557	74,556	1,890,376	133,731

Table XVIII—Concluded

Class	1938		1939		1940		1941		1942	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$		$
Rough-cobbed	12,000	360	6,700	67	142,916	22,801	169,315	25,977	362,600	40,055
Knife-trimmed	81,127	45,419	92,333	38,370	158,200	80,836	264,409	144,356	264,858	177,628
Thumb-trimmed	17,050	4,366	68,181	6,832	144,232	17,383	139,577	19,738	67,292	19,334
Splittings	51,434	22,456	176,051	83,633	170,375	103,624	184,830	121,879	165,610	102,666
Scrap	875,415	8,388	1,792,091	18,419	1,334,496	12,501	2,729,760	23,338	5,159,311	43,884
Total	1,037,026	80,989	2,135,356	147,321	1,950,219	237,145	3,487,891	335,288	6,019,671	383,567

Class	1943		1944		1945		1946	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$
Rough, mine-run or rifted	1,429,365	54,450	314,878	22,733	11,910	886	692,339	35,381
Sold for mechanical splitting	190,209	26,048	427,426	62,842	329,476	57,816	254,363	42,523
Splittings	73,691	53,820	44,350	32,123	4,050	3,865	13,050	10,725
Scrap and ground	6,065,551	63,210	5,381,779	66,167	1,753,030* 4,877,866†	36,799* 30,074†	2,657,230* 5,073,092†	51,146* 38,216†
Trimmed	291,876	356,328	516,413	657,161	67,869	103,830	30,595	21,048
Total	8,050,692	553,856	6,684,846	841,026	7,044,221	233,270	8,720,669	199,039
Varieties								
Phlogopite	7,498,578	309,803	6,408,900	261,892	5,694,504	142,535	7,104,739	175,579
Muscovite	552,114	244,053	275,946	579,134	1,349,717	90,735	1,615,930	23,460

* Ground mica

† Scrap mica

	Class	1947		1948		1949		1950		1951	
		Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
			$		$		$		$		$
	Rough, mine-run or rifted	246,947	30,504	21,918	2,693	10,091	1,214	20	4	274,980	48,646
	Sold for mechanical splitting	291,549	54,357	317,005	67,635	8,019	1,762	104,400	17,062	108,831	17,350
	Splittings	10	3	17,514	14,028	8,550	7,470	2,100	1,785	6,302	5,421
	Ground	4,177,251	66,596	3,748,268	84,224	1,854,844	49,907	2,215,919	68,253	2,062,854	75,140
	Scrap-shop and mine	3,578,898	30,781	3,716,840	33,813	1,518,101	13,202	1,376,040	11,651	2,278,009	12,784
	Ungraded	....	....	5,734	345	43,069	3,172	....	....	....	....
	Trimmed	24,100	18,662	75,024	17,210	47,882	31,731	180,730	153,856	230,532	288,309
	Total	8,318,755	200,903	7,902,303	219,948	3,490,556	108,458	3,879,209	252,611	4,961,508	447,650
Varieties	Phlogopite	6,510,755	176,663	7,400,503	211,418	2,869,143	92,878	3,236,430	118,594	3,559,426	129,658
	Muscovite	1,808,000	24,240	501,800	8,530	621,413	15,580	642,779	134,017	1,402,082	317,992

	Class	1952		1953		1954	
		Pounds	Value	Pounds	Total Value f.o.b., Shipping Point	Pounds	Total Value f.o.b., Shipping Point
			$		$		$
	Rough, mine-run or rifted	14,350	850	62,744	5,310	11,416	1,495
	Sold for mechanical splitting	105,794	19,756	168,537	30,521	40,150	8,841
	Splittings	6,900	10,849	8,289	16,568	1,901	3,551
	Ground	988,052	41,545	664,741	25,236	937,076	44,057
	Scrap, mine or shop waste, and mica mined and sold for grinding	838,220	9,276	1,284,334	16,597	687,205	8,571
	Trimmed	61,625	111,830	50,933	65,949	18,939	17,811
	Unclassified	....	....	25,550	947	10,083	813
	Total	2,014,941	194,106	2,265,128	161,128	1,706,770	85,139
Varieties	Phlogopite mica (amber) and biotite	1,499,381	84,162	1,863,130	106,767	1,440,770	82,546
	Muscovite mica (white) and schist	515,560	109,944	401,998	54,361	266,000	2,593

Table XIX

Exports of Canadian Mica 1906-1920

Year	Tons	Value	Year	Tons	Value
		$			$
1906	912	581,919	1914	335	410,000
1907	558	422,172	1915	440	641,962
1908	290	198,839	1916	654	824,107
1909	359	256,834	1917	636	224,683
1910	469	330,903	1918	433	464,512
1911	347	242,548	1919	2,740	757,276
1912	448	334,054	1920	3,303	824,107
1913	409	451,345			

Table XX

Exports of Mica from Canada by Classes
1921-1954

Class	1921		1922		1923		1924	
	Tons	Value	Tons	Value	Tons	Value	Tons	Value
		$		$		$		$
Rough-cobbed and thumb-trimmed	12	12,942	74	45,151	85	40,286	88	52,527
Splittings	185	195,479	286	366,974	502	624,110	285	424,503
Scrap	967	12,061	3,473	41,949	4,855	70,866	4,519	63,610
Mica manufactures	....	4,201	....	10,438	....	22,014	....	3,326
Total	....	224,683	....	464,512	....	757,276	....	543,966

Class	1925		1926		1927		1928	
	Tons	Value	Tons	Value	Tons	Value	Tons	Value
		$		$		$		$
Rough-cobbed and thumb-trimmed	28	21,366	44	20,516	165	54,937	32	15,951
Splittings	230	324,967	315	432,345	159	213,651	84	80,902
Scrap	4,991	63,931	3,799	45,297	4,536	57,499	4,346	78,262
Mica manufactures	....	1,046	....	1,084	....	759	....	646
Total	....	411,310	....	499,242	....	326,846	....	175,761

Table XX—Concluded

Class	1929		1930		1931		1932		1933		1934	
	Tons	Value	Tons	Value	Tons	Value	Tons	Value	Pounds	Value	Pounds	Value
		$		$		$		$		$		$
Rough-cobbed and thumb-trimmed	2	1,342	2	1,461	24	3,428	1	177	52,800	6,425	190,000	69,574
Splittings	91	96,726	39	35,351	19	14,672	50	26,833	65,700	29,479	88,600	38,602
Scrap	4,789	112,905	1,039	48,436	1,232	32,600	300	2,843	2,152,400	9,560	1,680,400	7,736
Micanite	....	2,086	....	1,289	....	797	....	1,260	....	729	....	1,890
Total	....	213,059	....	86,537	....	51,497	....	31,113	....	42,213	....	117,802

Class	1935		1936		1937		1938		1939		1940		1941	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$		$		$		$
Rough-cobbed, thumb-trimmed and knife-trimmed	149,600	52,196	168,300	61,474	254,400	98,804	118,200	57,960	169,700	42,924	413,200	141,087	508,200	190,300
Splittings	34,600	16,615	26,900	10,331	132,600	57,414	49,100	12,143	228,500	108,823	196,800	120,815	243,800	151,336
Scrap	1,340,000	6,189	2,473,000	14,152	2,443,300	13,042	1,288,600	7,649	1,971,100	12,525	1,164,000	6,073	2,536,800	13,803
Mica plate and manufactures	....	950	....	1,343	....	2,410	....	1,507	....	980	....	5,829	....	5,907
Total	....	75,950	....	87,300	....	171,770	....	89,259	....	165,252	....	273,804	....	361,346

Class	1942		1943		1944		1945		1946		1947		1948	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$		$		$		$
Scrap and waste	4,323,800	27,167	4,279,500	34,660	4,879,200	36,072	4,853,600	33,200	3,899,400	33,601	2,560,600	21,724	1,998,900	16,002
Splittings	148,300	112,756	65,900	47,108	75,800	56,211	5,200	4,088	8,400	6,913	3,400	2,186	11,300	8,272
Manufactures	....	18,091	....	16,540	....	994	....	2,614	....	2,193	....	185	....	1,862
Rough untrimmed	484,700	224,481	863,100	422,710	955,000	133,149	801,400	107,740	675,900	99,059	430,200	71,002	354,300	75,205
Trimmed					282,100	572,541	67,600	146,026	25,800	47,494	46,100	25,492	8,500	3,835
Ground	....	....	....	....	600,900	18,340	352,000	11,055	451,000	17,808	180,000	6,940	2,121,200	45,185
Total	....	382,495	....	521,018	....	817,307	....	....	....	....	....	127,529	....	150,361

Class	1949		1950		1951		1952		1953		1954	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
		$		$		$		$		$		$
Scrap and waste	678,300	3,526	1,183,000	12,585	980,400	10,555	889,000	8,434	1,354,700	19,583	453,600	6,241
Splittings	30,000	1,220	....	....	....	....	3,500	5,089	....	....	....	....
Manufactures	....	3,426	....	1,475	....	2,217	....	363	....	123	....	2,847
Rough untrimmed	78,000	12,983	164,800	27,983	246,700	49,060	178,800	31,319	240,500	43,704	60,700	12,647
Trimmed	97,900	26,571	67,300	96,481	430,700	378,846	50,600	85,634	79,400	93,560	17,400	21,583
Ground	430,000	15,866	560,000	28,117	775,000	44,090	440,400	26,020	320,000	19,158	240,000	13,319
Total	....	63,592	....	166,661	....	484,768	....	156,859	....	176,128	....	56,637

Chapter VIII

GROUND MICA

Powdered mica has been used to a much greater extent in recent years, chiefly by roofing-paper and paint industries. Production is very largely confined to the United States, although both Canada and Norway produce minor amounts.

Muscovite, the commonest raw material, is obtained in the form of mine or shop scrap, or small flake material recovered from mica and sericite schists, and as a by-product of feldspar and kaolin beneficiation. Minor amounts of phlogopite and biotite are also used. United States domestic production of scrap and flake muscovite is sufficient to supply 80 to 90 per cent of the raw material requirements of the industry. The remainder is imported, chiefly from India. In 1952 the price of North Carolina scrap varied from $32 to $35 per ton, depending on quality. The average cost at the time of this writing, of high-quality imported scrap delivered at grinding plants was $45 per ton.

Depending on the use to which the product is to be put, the mica is either dry or wet ground, or more recently, pulverized or micronized by the steam-jet principle. Approximately 84 per cent of the total 1952 production was dry ground.

Processes

Dry Grinding

Dry grinding produces a relatively coarse-grained product that is widely employed by roofing-paper manufacturers to coat the underside of asphalt roofing paper and shingles to prevent sticking. The process is also used to a lesser extent by paint and plastics manufacturers. It is considerably cheaper and quicker than either wet grinding or micronizing. The roofing-grade product, ranging from 20 to 80 mesh, averaged $72.50 per ton in 1952; paint and plastics grade (100 mesh) was $82.50 per ton in the same year.

Wet Grinding

Wet grinding produces a high-quality, very fine-grained, uniform product of low bulk density. In a number of grades varying from 200 to minus 325 mesh, it is made by batch process in plants employing steel- or wooden-shod chaser mills. The process is essentially one of re-lamination rather than actual grinding, and the individual grains, although very small, retain their platy habit—or as the industry terms it, the product has a low sphericity factor, which is defined as a ratio of thickness to area of the flake. The product thus has a low bulk density and a high relative covering capacity.

Raw material is carefully selected to ensure a grit content of less than 5 per cent and is commonly made up of a mixture of both ruby and green mica which has been found to produce the whitest product.

The wallpaper industry was formerly the largest consumer of wet-ground mica, but in recent years by far the greatest part of production has been used in the manufacture of paint, chiefly the relatively new types of emulsion paints. More detailed information on this topic is contained in bulletins of the Wet Ground Mica Association which has conducted numerous experiments in the uses of wet-ground mica in the paint and other industries (Technical Bulletins 1-21, 1949 and later).

The following are prices of high-quality, paint-grade, wet-ground mica for 99.98 per cent pure and 99 per cent minus 325 mesh, as reported by Concord Mica Corporation Inc., together with a list of wet-grinding mills.

Prices—December 1955

Carloads (30,000 pounds minimum) freight allowed	$155 per ton 7¾¢ per lb.
L.C.L., freight allowed	$170 per ton 8½¢ per lb.

Wet-grinding Mills

North Carolina—four plants, a micronizer mill and one wet-grinding biotite plant.
Virginia—one plant and a jet-pulverizer plant.
Massachusetts—one plant.
New Hampshire—one plant.

'Micronizing' or Jet Pulverizing

The steam-jet principle used by 'micronizing' and jet-pulverizing plants is not new, but was not successfully applied within the industry until quite recently. Details of techniques employed are not known.

The product ranges in size from 1 micron to 5 microns and is thus somewhat finer grained than wet-ground mica. However, it is not entirely comparable to wet-ground mica since the process destroys the micaceous lustre and the sphericity factor is higher—1 to 5 as opposed to 1 to 10 for wet-ground mica. The product therefore has a higher bulk density and a lower relative covering capacity.

Production

Statistics on the production and consumption of ground mica in the United States are given in Tables XXI and XXII.

Table XXI

Ground Mica Sold by Producers in the United States, 1943-47 (average) and 1948-52, by Methods of Grinding

(U.S. Bureau of Mines, Minerals Yearbook 1952)

Year	Dry-ground		Wet-ground		Total	
	Short tons	Value	Short tons	Value	Short tons	Value
		$		$		$
1943-47 (average)	48,121	1,417,749	8,430	859,162	56,551	2,276,911
1948	55,494	2,035,618	9,148	1,197,014	64,642	3,232,632
1949	49,133	1,850,400	7,260	1,010,556	56,393	2,860,956
1950	61,139	2,374,089	11,111	1,561,608	72,250	3,935,697
1951	59,200	2,294,620	10,922	1,548,008	70,122	3,842,628
1952	62,465	2,526,407	12,341	1,751,696	74,804	4,278,103

Table XXII

Ground Mica Sold by Producers in the United States, 1951-52, by Use

(U.S. Bureau of Mines, Minerals Yearbook 1952)

Use	1951			1952		
	Short tons	Per cent of total	Value	Short tons	Per cent of total	Value
			$			$
Roofing	27,919	40	846,801	30,922	41	887,700
Wallpaper	865	1	121,065	583	1	79,673
Rubber	6,551	9	507,602	5,126	7	457,194
Paint	11,760	17	1,028,490	16,566	22	1,549,671
Plastics	1,186	2	138,778	1,959	3	181,889
Pipeline enamel	6,378	9	202,741	2,668	4	85,537
Welding rods	1,203	2	78,916	1,749	2	102,934
Well drilling	*	*	*	4,847	6	245,504
Miscellaneous†	14,260	20	918,235	10,386	14	688,001
Total	70,122	100	3,842,628	74,806	100	4,278,103

*Included with "Miscellaneous" to avoid disclosure of individual company operations.

†Includes mica used for molded electric insulation, house insulation, Christmas-tree snow, manufacture of axle greases and oil, annealing, well drilling (1951 only), and other purposes.

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