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THE PETROLOGY AND SULFIDE MINERALIZATION OF THE PARTRIDGE RIVER TROCTOLITE, DULUTH COMPLEX, MINNESOTA

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ABSTRACT

The Partridge River troctolite, a basal intrusive body of the Duluth Complex, is located in the Ely–Hoyt Lakes region of northeastern Minnesota. The upper part of this body is a sequence of troctolites and augite troctolites. The basal zone is 100–150 m thick, contains numerous xenoliths and is quite variable in composition; it contains most of the sulfides (pyrrhotite, cubanite, chalcopyrite and pentlandite). Rock types present are augite troctolite, olivine gabbro, gabbro and gabbro-norite. In the basal zone, the iron content of olivine, the sodium content of plagioclase and the silica and potassium contents of the bulk rock increase with depth as do the sulfur content and the copper–nickel and iron–nickel ratios of the rocks. The chemical trends in the rocks of the base are a result of contamination from the underlying Virginia Formation. Minor contamination was caused by the mixing (near xenoliths and within 30 m of the base) of a partial melt derived from the Virginia Formation. The dominant contaminant from this melt was silica. Most of the contaminants were added to the magma by a hydrous S-bearing fluid derived from the Virginia Formation by the heat of the intrusion. This fluid transported copper, iron and alkalis. It mixed with the magma at a fairly early stage in the crystallization of the troctolite to cause the changes seen in plagioclase and olivine. Values of the copper–nickel ratio of the sulfides in the region suggest that localization of copper-rich sulfides was due to the availability of Virginia Formation in the footwall rocks.

Keywords: Duluth Complex, copper–nickel sulfides, contamination, Partridge River troctolite, Minnesota.

SOMMAIRE

La troctolite de Partridge River, massif intrusif à la base du complexe de Duluth, est située dans la région des lacs Ely - Hoyt, dans le Nord-Est du Minnesota. La partie supérieure de ce massif est une séquence de troctolites et de troctolites à augite. La zone inférieure, d'une épaisseur de 100 à 150 m, a une composition assez variable et contient un grand nombre de xénolites. Cette zone porte également la plupart des sulfures (pyrrhotine, cubanite, chalcopyrite et pentlandite). Troctolite à augite, gabbro à olivine, gabbro et gabbro noritique constituent les roches observées. Dans cette zone, les teneurs en fer de l'olivine, en sodium du plagioclase et en silice et potassium de la roche globale augmentent avec la profondeur, à l'instar de la teneur en soufre et des rapports cuivre–nickel et fer–nickel des roches. La zonation chimique de ces roches s'expliquerait par leur contamination au contact de la formation Virginia sous-jacente. Autour des xénolites et à moins de 30 m de la base, le produit d'une fusion partielle de la formation Virginia s'est mêlé au magma, le contaminant légèrement. Le contaminant principal fut la silice. La plupart des éléments mobilisés furent ajoutés au magma par un fluide aqueux sulfuré, libéré de la formation Virginia par la chaleur de l'intrusion. Ce fluide a transporté le cuivre, le fer et les alcalins. Il réagit avec le magma à un stade de la cristallisation de la troctolite assez précoce pour causer les modifications relevées dans le plagioclase et l'olivine. D'après le rapport cuivre–nickel des sulfures de la région, on dirait que la localisation des sulfures riches en cuivre n'a pu se produire que grâce à la présence de la formation Virginia à la paroi inférieure du massif intrusif.

(Traduit par la Rédaction)

Mots-clés: complexe de Duluth, sulfures de cuivre et nickel, contamination, troctolite de Partridge River, Minnesota.

INTRODUCTION

The 1100 million-year-old Duluth Complex (Faure *et al.* 1969), located in northeastern Minnesota, crops out as an arcuate belt extending from Duluth northward to Hovland on the north shore of Lake Superior near the Canadian border. It was not intruded in one pulse but rather as a succession of intrusions of mafic magma, leading to rocks ranging from troctolite to anorthosite in composition (Weiblen & Morey 1980). Copper-nickel sulfides were emplaced along the base of the Duluth Complex in the Ely–Hoyt Lakes region (Fig. 1).

This study was undertaken to investigate one of the basal intrusive bodies in the Ely–Hoyt Lakes region, the Partridge River troctolite. The silicate and sulfide mineralogy and petrology are described, and

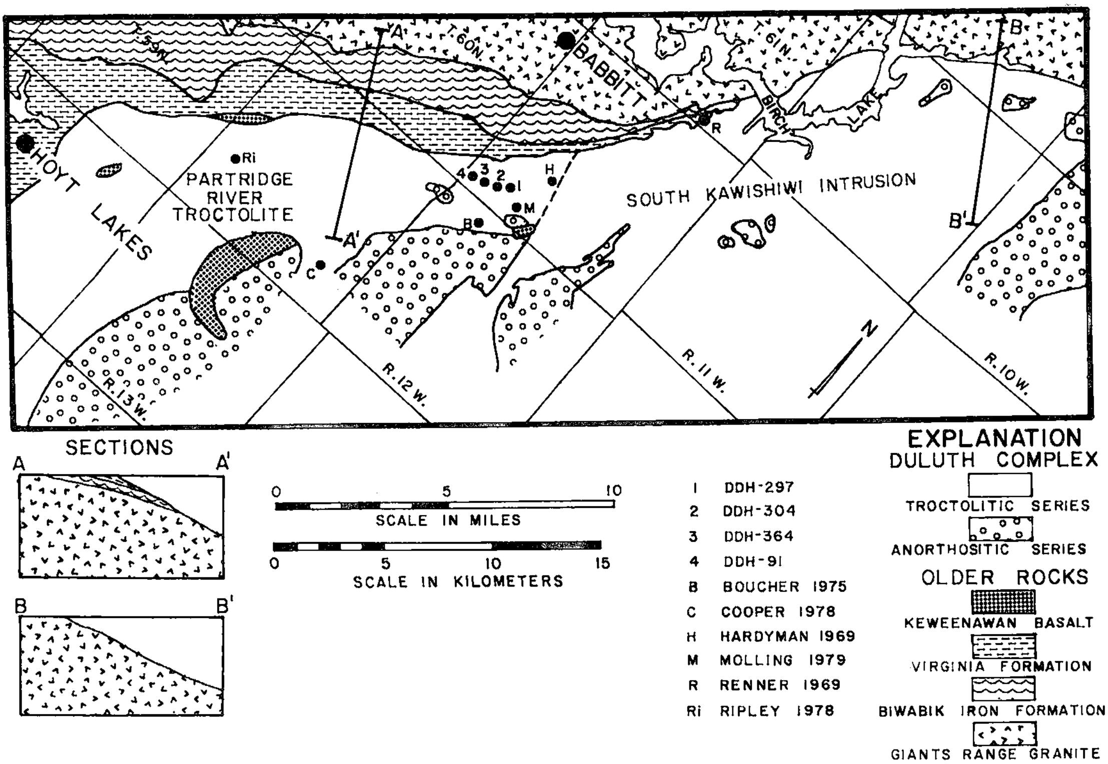

FIG. 1. Geologic map of the Ely–Hoyt Lakes region, northeastern Minnesota, showing the location of the different intrusive complexes, of previous study-areas and of the present study-area. The cross sections are hypothetical but were derived from relationships observed in drill core. This diagram was adapted from Bonnichsen (1974).

a stratigraphic subdivision of the Partridge River troctolite and the mode of sulfide emplacement are proposed. Together, these may allow for the identification of additional copper–nickel deposits along the base of the Duluth Complex in other areas.

Cores from four nearly vertical drill-holes (provided by AMAX Exploration, Inc., Babbitt, Minnesota), located in St. Louis County in the southwestern corner of T.60N, R.12W (Fig. 1), were selected for detailed study of the Partridge River troctolite. They were chosen from nearly 400 available cores; the four cores provide closely spaced penetrations of the intrusive body, with a trend nearly parallel to the strike of the base of the complex in this area. Each core was described megascopically, and preliminary stratigraphic units were determined (Tyson 1979). Representative samples from each stratigraphic unit in each core were chosen for detailed study. The spacing of samples ranges from 0.3 m to 6 m and averages 3 m. Forty-five thin sections from samples representative of the stratigraphic units in each drill core were studied. Modal compositions of 75 samples from two of the holes have been determined; the tabulated data are available, at nominal cost, from the Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, Ontario K1A 0S2. The composition of olivine in most samples collected was determined using X-ray diffraction by measuring the 131 peak (Agterberg 1964). Plagioclase was analyzed optically for anorthite content using the dispersion in the index of refraction (Morse 1968) and the Michel-Lévy method. Whole-rock analyses for iron, strontium and rubidium were carried out using X-ray fluorescence.

GEOLOGY OF THE ELY – HOYT LAKES REGION

The Duluth Complex lies in the Superior Province of the Canadian Shield. The oldest rocks present in the Ely – Hoyt Lakes region are an Archean granite–greenstone terrane. Unconformably overlying the granite is the Animikie Group (1.7 Ga). The uppermost unit in the Animikie Group is the Virginia Formation, which forms the footwall of the basal contact of the Duluth Complex in much of the Ely –

Hoyt Lakes region (Fig. 1). The Virginia Formation is characterized by argillite, although argillaceous siltstone and fine-grained greywacke are also present. Small amounts of limestone, dolomite, chert and sideritic iron-formation are present locally (Morey 1972a). The argillite is black to dark grey and commonly contains carbonaceous material. Quartz and plagioclase are the dominant minerals. Muscovite, chlorite and pyrite are commonly present (Morey 1972a).

The intrusive bodies in the Ely - Hoyt Lakes region are made up of the lower stratigraphic portion of the Duluth Complex. These include the basal Troctolitic Series and the lowermost part of the Anorthositic Series, as defined by Weiblen & Morey (1980). Two major troctolitic intrusive bodies, South Kawishiwi and Partridge River, are present along the base.

The South Kawishiwi body is the basal troctolite in the northeastern part of the Ely - Hoyt Lakes region (Fig. 1). Green *et al.* (1966), Phinney (1969), Bonnichsen (1972), Bonnichsen & Tyson (1975) and Bonnichsen *et al.* (1980) recognized a series of stratigraphic units. A Basal Zone, 60 to 400 m thick, is composed of fine- to medium-grained troctolites, gabbros and norites and medium- to coarse-grained troctolites, melatroctolites and dunites. An Augite Troctolite unit, approximately a thousand metres thick, overlies the Basal Zone. A sharp contact, locally complicated by xenoliths of anorthosite or hornfelsed basalt, separates the two units. Overlying this is a Troctolite unit. A gradational contact exists between these two units. The top of the Troctolite unit is not exposed in the region.

Exposures of the Partridge River troctolite, to the southwest (Fig. 1), are extremely limited owing to extensive glacial deposits covering the pluton. As a result, it has not been studied in as much detail as the South Kawishiwi pluton. Previous studies, mostly from single drill-cores, have shown that the Partridge River troctolite does not have the same stratigraphy as that exhibited by the South Kawishiwi pluton, nor does its plagioclase exhibit as strong a foliation (Hardyman 1969, Bonnichsen & Tyson 1975, Boucher 1975, Molling 1979, Tyson 1979).

PETROGRAPHY OF THE PARTRIDGE RIVER TROCTOLITE

The basal 550 m of the Partridge River troctolite, as revealed by the four drill-cores, consist dominantly of a mixture of troctolite, anorthositic troctolite, augite troctolite and melatroctolite. The most abundant minerals are plagioclase, olivine and augite. Biotite, hypersthene, ilmenite and sulfides occur in accessory amounts.

FIG. 2. Textures typical of unit M. Plagioclase is tabular (T) and irregular (I). Augite, at extinction, is poikilitic. Cross-polarized light. Scale bar is 1 mm.

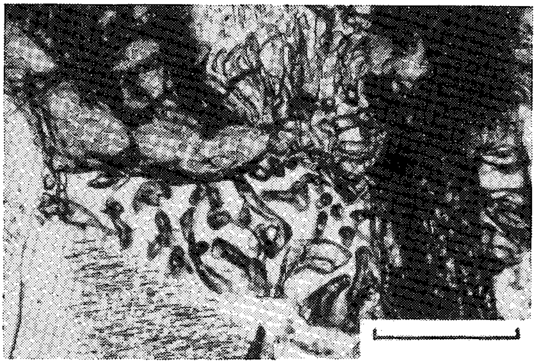

FIG. 3. Symplectitic intergrowth of hypersthene and plagioclase on the edge of an olivine grain. A selvage of pyroxene separates the intergrowth from the olivine. Note the ilmenite rods in the plagioclase. Plane-polarized light. Scale bar is 0.3 mm.

Plagioclase

Plagioclase exhibits two habits in the Partridge River troctolite: the earlier plagioclase is tabular, and the later generation has an irregular (or interstitial) habit (Fig. 2). Both types of plagioclase are labradoritic. The tabular plagioclase occurs as subhedral to euhedral crystals 0.5 to 10 mm in length, with size decreasing as the basal contact is approached. These crystals exhibit normal zoning; however, the transition from core to mantle is not gradational. If, as suggested by Bonnichsen (1972), the magma was intruded as a crystal mush, the cores could represent the plagioclase crystals developed prior to intrusion and the mantles would represent that portion solidified *in situ.*

The irregular plagioclase embays the tabular plagioclase and locally exhibits an amoeboid shape as if it had partly assimilated the earlier-formed plagioclase. The zoning in the irregular plagioclase is patchy and exhibits no regular pattern.

The tabular and, less commonly, the irregular crystals of plagioclase contain exsolved rods of ilmenite (Fig. 3) and plates of nearly opaque, reddish brown rutile. Both minerals were identified optically, the ilmenite in reflected light and the rutile in transmitted light. These two oxide minerals, where present in the irregular plagioclase, are uniformly distributed throughout the grain. In the tabular plagioclase, ilmenite and rutile tend to be concentrated in the core, leaving the mantle relatively free of the Ti-rich species. If, as has been postulated above, the core and mantle of the tabular plagioclase represent two periods of crystallization, then these textural data suggest that the titanium content of the magma fluctuated with time as crystallization of the magma progressed.

Olivine

Olivine occurs in three textural forms in the rocks: irregular, equant and poikilitic to interstitial. The timing of the crystallization of olivine indicated by these textures is one characteristic used to identify the stratigraphic units (Table 1). Olivine in different units formed prior to, at the same time as, and after plagioclase. Petrographic evidence indicates it was always earlier than augite, hypersthene, biotite, ilmenite and the sulfides.

Augite

Augite was the last major silicate phase to form. It exhibits two textural forms, which are mutually exclusive in any particular sample. Poikilitic augite most commonly encloses plagioclase crystals. It may also incompletely to completely enclose olivine, depending upon the unit in which it is observed. Augite may also be interstitial to the other silicates. In most occurrences, augite will exhibit exsolution. The most common products of exsolution are opaque rods of ilmenite. These are accompanied by less common reddish brown anisotropic plates, tentatively identified as rutile. The exsolved minerals can occur as a light dusting in the pyroxene or be so concentrated that the augite appears opaque. Locally, the exsolved phases are arranged *en échelon.* The occurrence of these titanium-rich exsolved phases in the augite suggests that titanium was abundant in the later stages of the differentiating magma.

Hypersthene

Hypersthene is present as interstitial crystals and as symplectitic intergrowths with plagioclase.

TABLE 1. CHARACTERISTICS OF THE STRATIGRAPHIC UNITS

Characteristic	Unit M	Unit P	Unit C	Unit B	Unit A
Plagioclase					
Texture	Tabular & Irregular	Anhedral	Tabular	Tabular	Tabular
Composition	An_{58}-An_{70}		An_{61}-An_{64}	An_{55}-An_{58}	An_{51}-An_{55}
Mode	60-74%	10-78%	50-60%	55-75%	52-58%
Olivine					
Texture	Poikilitic & Irregular	Equant & Euhedral	Poikilitic	Interstitial-Subpoik.	Interstitial-Subpoik.
Composition	Fo_{55}-Fo_{68}	Fo_{54}-Fo_{72}	Fo_{40}-Fo_{60}	Fo_{35}-Fo_{56}	Fo_{35}-Fo_{50}
Mode	15-25%	10-73%	8-19%	10-22%	0.5-8%
Augite					
Texture	Interstitial-Poikilitic	Poikilitic	Poikilitic	Poikilitic	Interstitial-Poikilitic
Mode	2-12%	4-12%	20-30%	2-10%	10-17%
Biotite					
Texture	Interstitial or Epitactic		Epitactic to Augite	Interstitial	Interstitial or Epitactic
Mode	0-5%	Trace	4-7%	2-4%	7-10%
Hypersthene					
Mode	0-2%	0-2%	0-4%	1-3%	7-21%

Hypersthene typically makes up less than 2% of the rocks except at the base, where it exhibits a much higher abundance (up to 20%).

A symplectitic intergrowth of plagioclase and hypersthene (Fig. 3) is more common than the interstitial crystals of hypersthene. It can compose up to 9% of the rock. The symplectite most commonly occurs at the contact between olivine and plagioclase, embaying the latter. It may also be present along the contact between two plagioclase crystals or associated with biotite. The intergrowth is separated from olivine by a selvage of augite or orthopyroxene. Other minerals, such as amphibole and serpentine, may also form the selvage.

Biotite

Biotite is an accessory mineral in nearly all samples studied. It occurs in two ways: as irregularly shaped crystals commonly associated with the sulfides and the oxides, and as epitactic overgrowths on augite and, locally, olivine.

STRATIGRAPHY OF THE PARTRIDGE RIVER TROCTOLITE

Five correlatable units (informally labeled M, P, C, B and A) have been identified in all four cores (Table 1). Furthermore, Molling (1979; pers. comm.) found all but unit B in the core he studied (nearly 1 km to the southeast), suggesting that these units are widespread in the Partridge River troctolite.

Unit M

Unit M forms the upper part of this section. It is quite variable laterally and vertically with respect to mineral textures and rock types present. Neither of these parameters could be correlated between holes. The rock types and their textures may be continuous vertically for hundreds of metres or for less than three metres. Their contacts may be sharp or gradational for over three or more metres. Part of the complexity in this unit may be due to the presence of more than one intrusive pulse, as suggested by Molling *et al.* (1979) and Grant & Molling (1981).

Unit P

Unit P, a group of xenoliths with similar textures, is completely enclosed by unit M. The thickness of these rocks varies from 10 to 150 metres, and their height above the basal contact varies from core to core. The contacts between this unit and unit M are sharp. Dykes of unit M commonly cut unit P. Local-

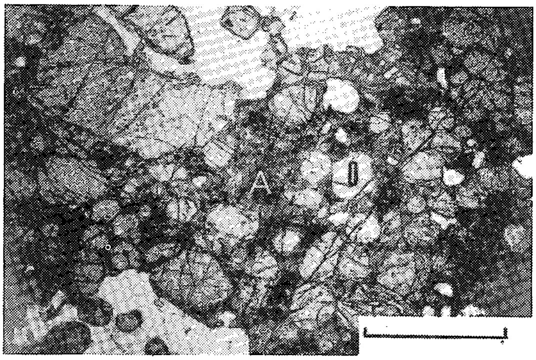

FIG. 4. Texture typical of unit P. Olivine (O) is equant or euhedral. Augite (A) is poikilitic to olivine, forming a glomerophyric mass. This example shows less extensive serpentinization than most samples of unit P. Plane-polarized light. Scale bar is 1 mm.

FIG. 5. A texture characteristic of unit C. Biotite (B) is epitactic to poikilitic augite. The biotite is parallel to the schiller in the augite. The darker patches in the cores of plagioclase crystals are concentrations of ilmenite rods. Plane-polarized light. Scale bar is 1mm.

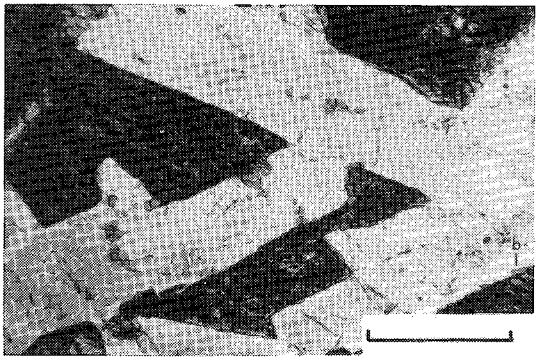

FIG. 6. A texture characteristic of unit B. Biotite (b) occurs along the plagioclase – poikilitic augite boundaries. Note that the biotite is not oriented relative to any crystallographic direction of the augite. The darker patches in the core zone of the plagioclase are concentrations of ilmenite rods. Plane-polarized light. Scale bar is 1 mm.

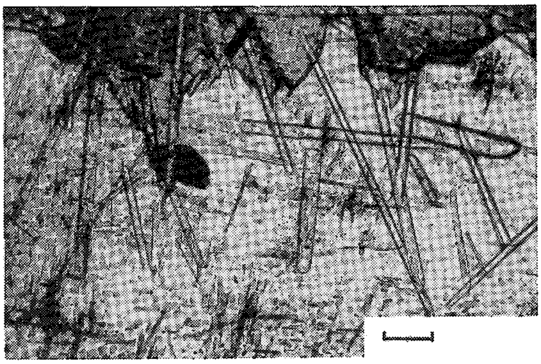

FIG. 7. Apatite inclusions associated with plagioclase and augite. This occurrence is typical of unit C. Plane-polarized light. Scale bar is 0.1 mm.

ly associated with unit P is a short interval of hornfels composed of Virginia Formation or, less commonly, Keweenawan basalt.

Unit P is the only unit in the Partridge River troctolite to exhibit rhythmic layering. A melatroctolite or, locally, a dunite occurs at the base of each rhythmic unit. It grades upward into a troctolite containing sporadic layers of melatroctolite a few centimetres thick. Above this, there is a sharp contact with the overlying melatroctolite or dunite of the next unit, and the sequence is repeated. The thickness of these rhythmic units varies from 2 to 15 metres. The rhythmic layering is approximately parallel to a distinct foliation exhibited by the rocks in this unit. The dip of this foliation varies within a single core and between cores. The dip is commonly at a high angle to the core axis.

The textures seen in unit P (Fig. 4) are quite different from those seen in the other units (Table 1). Furthermore, unlike samples from the rest of the units, olivine and augite in unit P have commonly been serpentinized. Plagioclase, in most places, is fresh, although locally it is saussuritized. As the rocks in unit P become more felsic, the effects of alteration decrease.

Units A, B, and C

Units A, B and C together form a zone of contaminated rocks in the basal 60–90 m of the Partridge River troctolite. Petrographically, these three units are distinguished from each other and from unit M by their modal mineralogy and the textural features exhibited by olivine, augite and the accessory minerals (Table 1). Modal data show that, except for local variation, the abundance of olivine decreases with depth. Over the same interval, augite, biotite, plagioclase - orthopyroxene symplectite and hypersthene increase in abundance.

Unit C, the uppermost of the contaminated units, has gradational contacts with unit M above and unit B below. Short intervals of unit C can be found within unit M, several metres above the contact. Two features are diagnostic of unit C. Olivine is poikilitic throughout and forms oikocrysts up to 15 mm in diameter. Biotite commonly occurs as subhedral epitactic crystals on augite and, locally, olivine (Fig. 5).

Unit B has no distinguishing textural features. It can be recognized by its placement between units A and C, the lack of textures characteristic of the enveloping units and the continuation of the chemical trends exhibited by units A and C. Olivine is interstitial to subpoikilitic. Biotite occurs along the boundary between augite and plagioclase crystals, but it lies parallel to this contact, and its growth is not oriented relative to the augite (Fig. 6).

Unit A, the lowermost of the contaminated units, lies directly above the contact of the Partridge River troctolite with the Virginia Formation and commonly contains xenoliths of the slates. The xenoliths are typically fine grained and composed of plagioclase, pyroxene, biotite and, locally, cordierite. Olivine, where present in unit A, occurs as interstitial to subpoikilitic crystals. With depth, olivine decreases in abundance and disappears. In the same interval, hypersthene increases in abundance. The common occurrence of hypersthene is diagnostic of unit A. A second characteristic of unit A is the occurrence of apatite as inclusions in plagioclase (Fig. 7) or associated with biotite or augite.

Basal contact

The contact between unit A and the Virginia Formation is the basal contact of the Partridge River troctolite. In the four cores studied, the contact may be sharp or gradational over one metre. Elsewhere in the region, the contact zone may be tens of metres thick (Kirstein 1979, Weiblen & Morey 1980). Recognition of the basal contact is hampered by the fine-grained nature of the intrusive and metasedimentary rocks in this zone. It is further complicated in drill core by the presence of xenoliths of the Virginia Formation and Keweenawan basalt and of troctolitic dykes in the footwall rocks.

Chemistry

Several chemical trends are apparent in the contaminated units, as indicated by whole-rock compositions (Fig. 8), modal data and mineral compositions (Fig. 9). Data from DDH-297 (Fig. 8) are typical of the trends present in the four cores. The anorthite content of plagioclase decreases from An_{70} to An_{51}

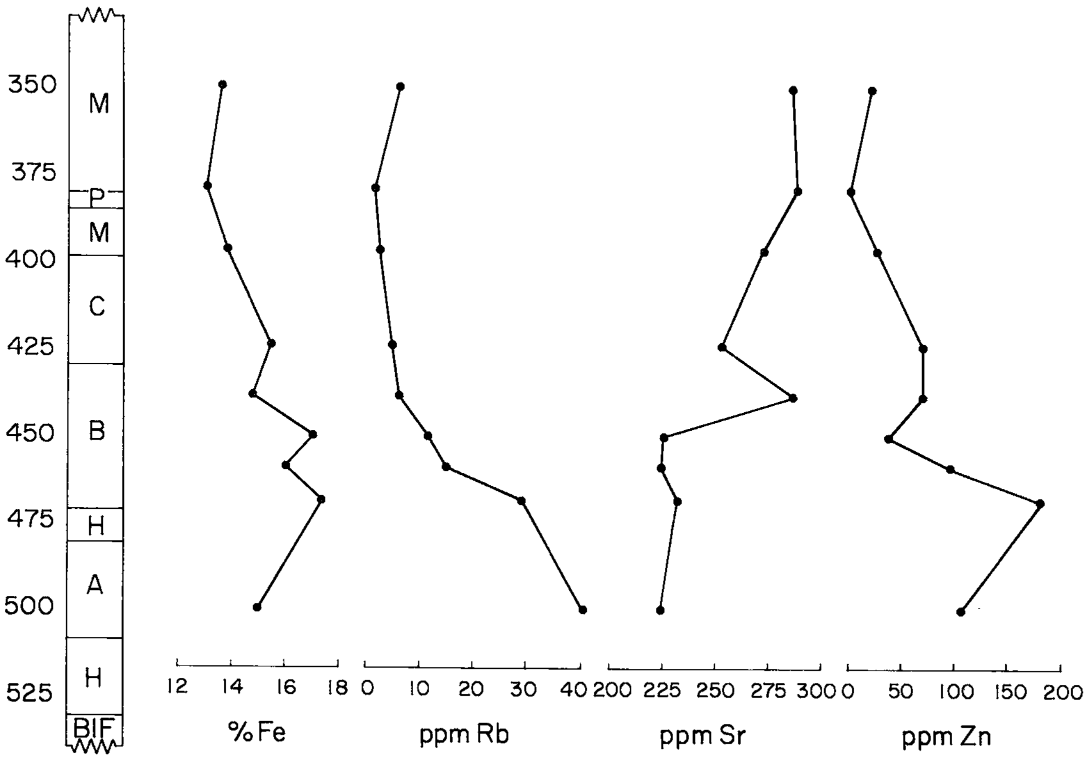

FIG. 8. Whole-rock concentration of strontium, rubidium, iron and zinc in DDH-297 determined by X-ray fluorescence. The petrographic units (M, P, C, B, A, H and BIF) and depth in metres are shown to the left. H hornfels derived from the Virginia Formation; BIF Biwabik iron-formation. The curves are interpreted in the text.

within the bottom 200 m of DDH-297. Over the same interval, the forsterite content of olivine decreases from Fo_{60} to Fo_{35}. This trend is paralleled by an increase in iron in the rock (Fig. 8). The olivine curve does not exhibit a smooth transition, perhaps reflecting inhomogeneities in the magma or incomplete mixing of an iron-bearing component from a source external to the magma. The initiation of sodium enrichment in plagioclase and iron enrichment of olivine coincides approximately with the top of unit C (defined by petrography). In the same interval, whole-rock rubidium increases and strontium decreases.

Unit A shows some definite chemical trends that do not occur higher up in the section. Biotite increases from 2–3% of the rock in unit M to 10% in unit A (Fig. 9), which reflects an increase in potassium content with depth. An increase in the amount of Si in unit A is inferred by the decrease in olivine and the increase in hypersthene. As will be discussed below, these compositional variations at the base of the section are due to contamination from the underlying metasedimentary rocks, especially the Virginia Formation.

OXIDE AND SULFIDE PETROGRAPHY

The opaque oxides occur as grains interstitial to the silicates. They are commonly associated with biotite, which typically mantles them. The predominant opaque oxide is ilmenite, which exhibits no exsolution. Magnetite, the other oxide present, occurs locally. Its presence shows no relationship to the previously described stratigraphy or chemical trends. The magnetite is titaniferous, as evidenced by the presence of ulvöspinel and ilmenite exsolution lamellae.

Sulfides occur sporadically throughout the drill cores examined. The "cloud zones" and the basal zone are two horizons of sulfide concentration. The "cloud zones" are 15- to 30-metre-thick intervals normally containing less than 1 modal % sulfides (*e.g.*, note 355 m depth on Fig. 13). They occur hundreds of metres above the other major area of sulfide concentration, in the basal zone. The "cloud zones" may be sulfides that were original components of the magma and not the result of contamination by the Virginia Formation.

The basal zone has a higher abundance (0.5% to

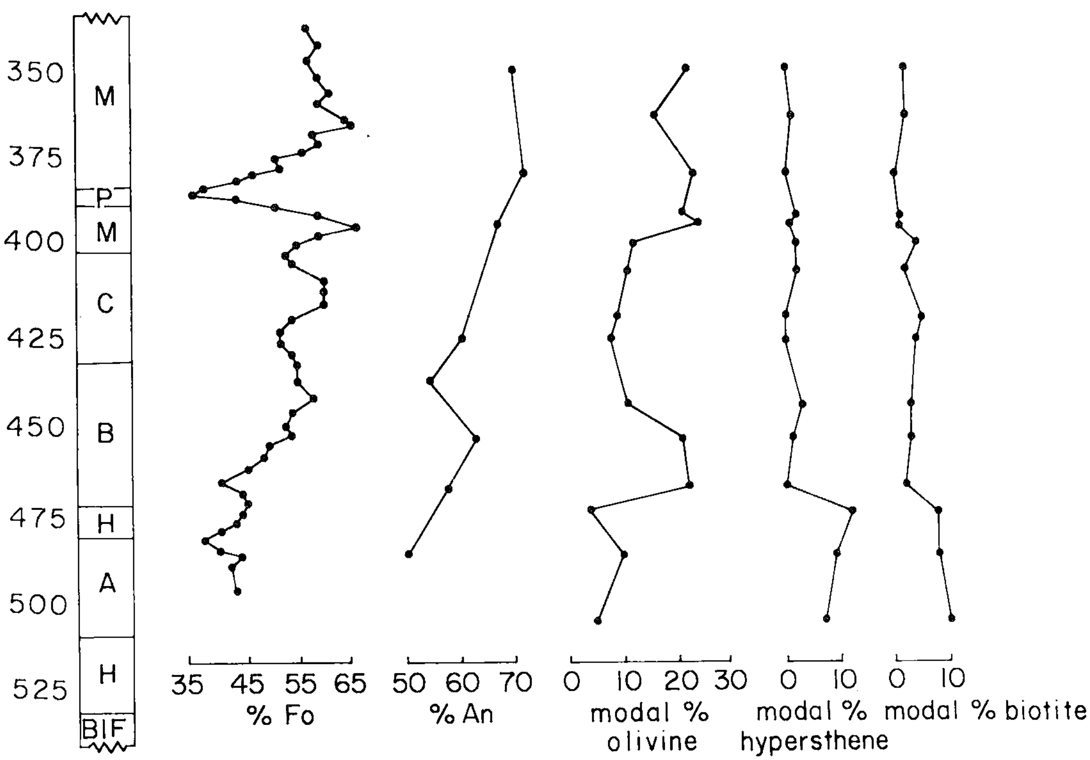

FIG. 9. Proportion of forsterite component in olivine, of anorthite component in plagioclase and modal abundances of olivine, hypersthene and biotite *versus* depth in DDH-297. The petrographic units (defined in Fig. 8) and depth in metres are shown at the left. These curves are interpreted in the text.

>3%) of sulfides and tends to be thicker (100-200 m) than the "cloud zones". The major sulfide minerals in both horizons are pyrrhotite, cubanite, chalcopyrite and pentlandite. Minor amounts of troilite, bornite and valeriite are also present.

FIG. 10. Textures typical of the sulfides in the Partridge River troctolite. The sulfides (opaque) are interstitial to the silicates, locally replace plagioclase, form veinlets within plagioclase cleavages and exhibit eutectoid relationships with pyroxene. All these textures are illustrated in this photograph. Note the biotite (b) mantling the sulfides. Plane-polarized transmitted light. Scale bar is 1 mm.

Chalcopyrite is the predominant sulfide in the "cloud zone" and in the upper part of the basal zone. However, with increasing depth in the basal zone, cubanite and pyrrhotite become more important modally. At the bottom of the basal zone, pyrrhotite and cubanite predominate, and locally chalcopyrite is absent. Pentlandite is present in variable amounts, exhibiting no particular pattern throughout either sulfide zone.

The sulfides exhibit three textural relationships with the silicates. The bulk of the sulfides occurs as grains interstitial to the silicates (Fig. 10). In the basal zone, this texture locally grades into a net texture of sulfide around silicate crystals and, rarely, to massive sulfide.

Sulfides also occur as fine veinlets connecting interstitial grains. These veinlets generally occur within plagioclase crystals, occupying cleavages (Fig. 11) within the silicate. The veinlets are typically enriched in copper relative to the associated interstitial sulfides. A third textural occurrence of the sulfides is

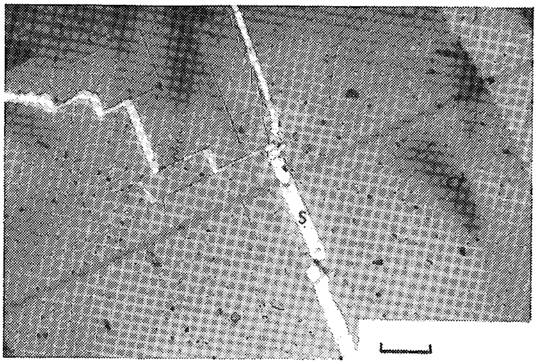

FIG. 11. A sulfide veinlet (S) following cleavages in plagioclase. The sulfide is dominantly chalcopyrite. Plane-polarized reflected light. Scale bar is 0.1 mm.

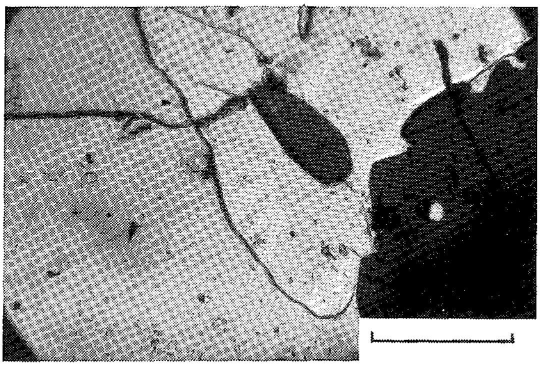

FIG. 12. Typical texture of sulfides in the basal zone of the Partridge River troctolite. Copper–iron sulfide is present as a bleb at the edge of a pyrrhotite grain (medium grey). Note the exsolution relationship between cubanite (light grey) and chalcopyrite (white). Plane-polarized reflected light. Scale bar is 1 mm.

as eutectoid intergrowths with either ortho- or clinopyroxene (Fig. 10). One (rarely, more) of the sulfides chalcopyrite, cubanite and pyrrhotite occur in these intergrowths.

Each of the major sulfides can make up an entire grain, but commonly, two or more sulfides will comprise a grain. In this case, a variety of textures can be seen between the sulfides. Where cubanite and chalcopyrite occur together, they commonly exhibit mutual exsolution textures (Fig. 12).

The textural relationships between pyrrthotite and chalcopyrite are varied. Some chalcopyrite (and cubanite) is present as lamellae within pyrrhotite. More commonly, blebs of the copper–iron sulfides are present on the edges of pyrrhotite grains (Fig. 12). This latter texture may be interpreted in one of three ways. Chalcopyrite and cubanite may have replaced already crystallized pyrrhotite, as has been suggested by Boucher (1975); the sulfides may have been annealed, with the copper–iron phases migrating toward the boundary of the pyrrhotite, or the texture may be explained by fractionation of a sulfide liquid, enriching it in copper. In their discussion of the phase relationships in the system Cu-Fe-S, Kullerud *et al.* (1969) indicated that a sulfide liquid will crystallize *Mss* more iron-rich than the original liquid; the resulting liquid would be progressively enriched in copper.

Pentlandite, the other major sulfide phase, occurs as rounded blebs within pyrrhotite. Pentlandite is commonly cut by fractures that may be filled with chalcopyrite or cubanite. Troilite occurs as exsolution lamellae in pyrrhotite in the copper-poor zones. Conversely, bornite has exsolved from chalcopyrite in the copper-rich zones.

Chemical trends of the sulfides are presented in Figure 13. Sulfur exhibits a sharp increase that coincides with the contact between units B and C. Below the level of this increase, the sulfur content remains high (generally greater than 0.5%). This same trend is exhibited by the other three cores. The copper-nickel ratio of the sulfides shows an increase with depth that starts at the top of unit C. The increase in this ratio suggests an influx of copper relative to nickel into the magma or, conversely, an increasing partition of nickel into olivine with depth. The iron-nickel and iron-copper ratios are quite variable. However, both curves exhibit a marked increase immediately at the base of the intrusive body.

PETROGENESIS OF UNITS M AND P

Of the five silicate units described, unit M represents the main intrusive body of the Partridge River troctolite. It exhibits no foliation, rhythmic layering or chemical trends indicative of accumulation of crystals. Unit M in this part of the Ely–Hoyt Lakes region appears to have crystallized in place. Units A, B and C are a result of contamination of unit M as described below.

Unit P, as described above, is composed of olivine orthocumulates and, in its more felsic portions, olivine–plagioclase orthocumulates. It is quite different texturally and compositionally from the other stratigraphic units in the Partridge River troctolite. It is enveloped by rocks of the Main Unit and exhibits rhythmic layering typical of that seen in other large mafic intrusive complexes (Wager & Brown 1967). Unit P was not intruded into unit M as indicated by its characteristics:

1. Unit P is mafic to ultramafic. The magma from which such rocks crystallized would have been very hot (*ca.* 1300°C) and would have metamorphosed

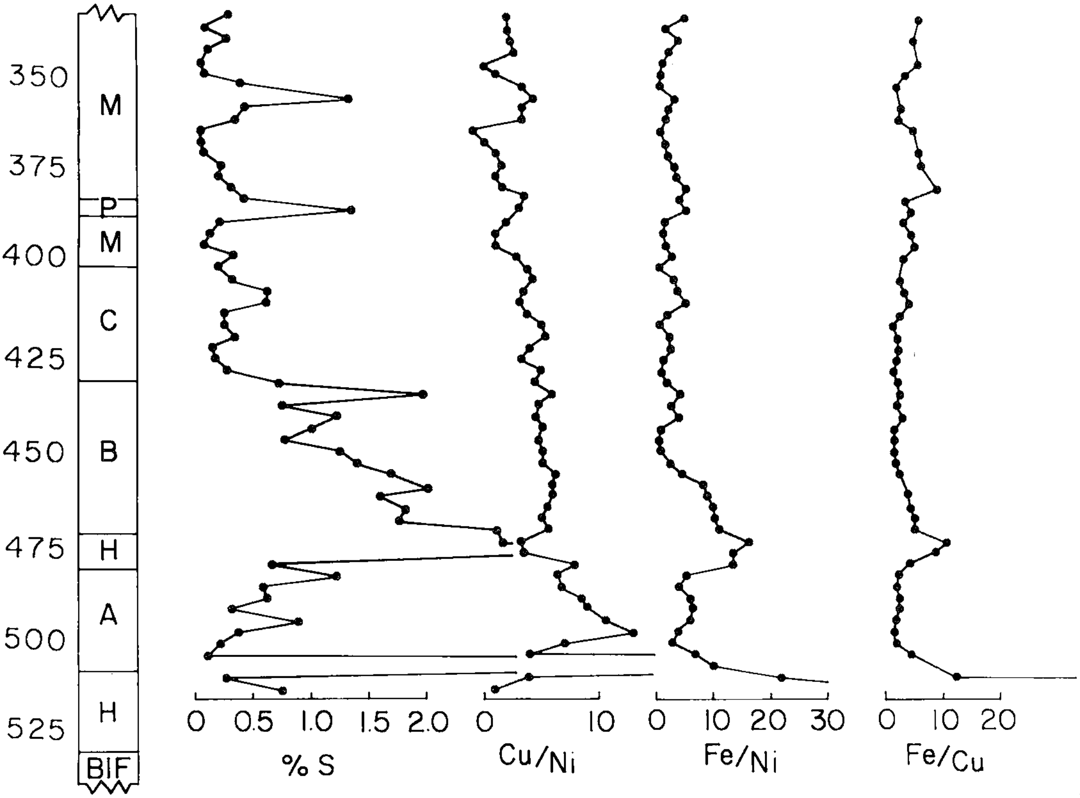

FIG. 13. Copper-nickel, iron-nickel and iron-copper ratios in the sulfides and the sulfur content *versus* depth in DDH-297. The petrographic units (defined in Fig. 8) and the depth in metres are shown at left. The raw data from which these curves were derived are confidential and property of the company. These curves are interpreted in the text.

the surrounding rocks in unit M. Unit M near the contact lacks high-temperature metamorphism or even metamorphic textures.

2. No chilled margins are evident in Unit P.
3. Unit P is highly serpentinized, whereas the olivine in the surrounding rocks is fresh. The serpentinizing fluids affected only unit P and not the enclosing troctolites, suggesting that unit P is older than unit M and was altered prior to the emplacement of unit M.
4. Unit P is cut by dykes of unserpentinized rock similar to those found in the enclosing troctolites.
5. The foliation of the rocks in unit P and their height above the basal contact vary from core to core. Locally, they can be found on the base of the complex (Hardyman 1969).
6. Unit P is commonly associated with hornfels derived from the Virginia Formation and the Keweenawan basalts.
7. Unit P is not found throughout the Partridge River troctolite.
8. Pieces of unit P may be found at more than one depth within unit M in any one core.

The rocks making up unit P are probably xenoliths from an ealier intrusive phase of the Duluth Complex in the Ely–Hoyt Lakes region. Unit P was initially intruded along the contact between rocks of the earlier Anorthositic Series and the older Precambrian rocks (Fig. 14). In this position, the rocks of unit P crystallized, forming the rhythmic layers seen. They were then serpentinized. With the intrusion of the Partridge River troctolite, pieces of unit P formed as a result of this earlier intrusion were ripped off the floor and rafted up into the magma chamber. The present height of unit P above the base is a function of its rate of sinking and the number of intrusive pulses pushing it up.

PETROGENESIS OF UNITS, A, B AND C

The mineralogical and chemical trends exhibited by the silicates and the sulfides in the basal zone (units A, B anb C) are probably a result of the addition of material to the Partridge River troctolite from the underlying Virginia Formation. The addition was accomplished in two ways. A partial melt, formed

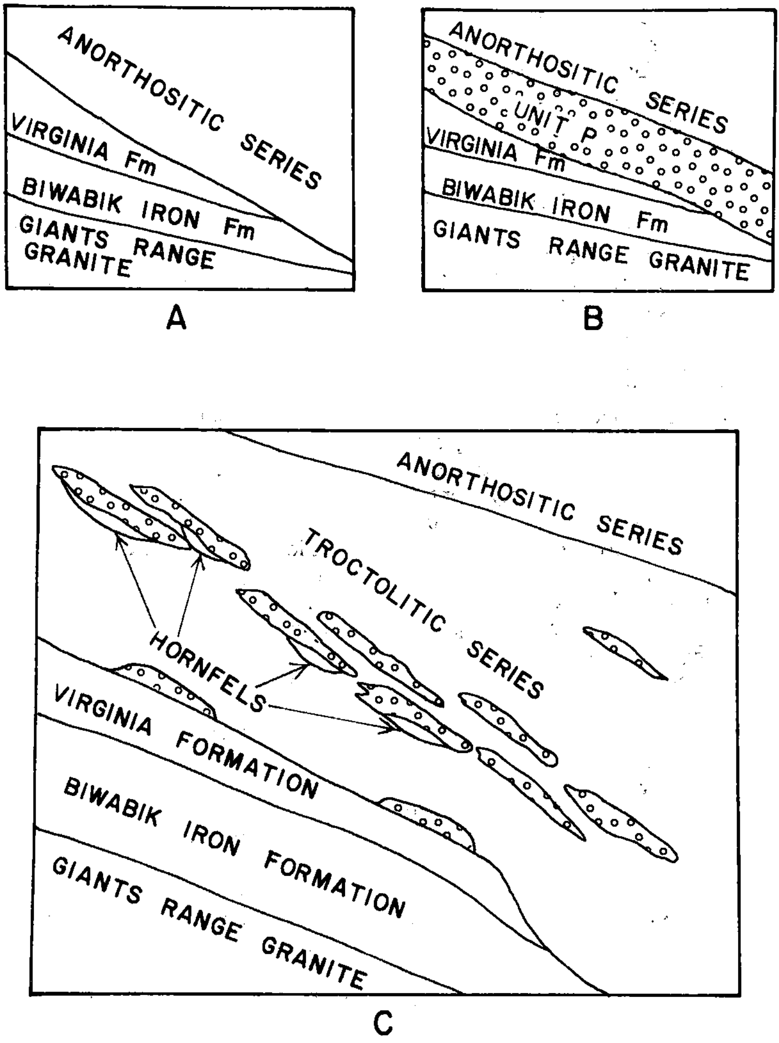

FIG. 14. The proposed model for the emplacement of unit P. This is a hypothetical cross-section drawn along A–A' in Figure 1. Part A shows the situation prior to the emplacement of unit P. Part B is a hypothetical view of unit P in place after its emplacement. Part C shows the present occurrence of unit P. Details of this model are presented in the text.

due to heating during the intrusion of basic magma, was derived from the Virginia Formation, mixed with and contaminated the magma. Secondly, sulfur in the Virginia Formation was mobilized by the heat of the intrusion and contaminated the basal zone of the Partridge River troctolite. Both mechanisms were important, but to varying degrees in the core samples studied.

Partial melting

The enrichment of silicon, sodium and potassium exhibited by the troctolites in the basal zone (these elements have been added, as indicated by the crystallization of hypersthene instead of olivine, the enrichment in Na and Si of plagioclase and the increase in the abundance of biotite with depth) are what would be expected should a granitic melt be mixed with the magma. Experimental work on the melting of shale in the presence of water indicates that melting commences at about 700°C at a pressure of 2.5 kbar (Wyllie & Tuttle 1961). The initial liquid has a granitic composition, rich in Na, K and Si. The refractory material is composed of quartz, mullite, cordierite, hypersthene and, if sufficient calcium is present, Ca-plagioclase.

Evidence for such a process is also available from natural occurrences. In his study of the basal zone of the Stillwater Complex, Barker (1975) noted that metasediments in the contact aureole consist of cordierite, orthopyroxene, plagioclase and quartz. He proposed that water, K, Rb, Na, Si and Zr were lost from the metasediments and migrated into the magma *via* a partial melt. Similar effects were noted in the metamorphic aureole of the Cashel - Lough Wheelaun intrusive complex in Eire (Leake & Skirrow 1960, Evans 1964). In both cases, the partial melts caused contamination of the basal part of the pluton. Is there evidence supporting the occurrence of this process in the basal Partridge River troctolite?

The Virginia Formation rocks, which have been unaffected by heat from the Duluth Complex, are composed of chlorite, plagioclase, muscovite, quartz, carbonates and pyrite. Xenoliths of these rocks within the Duluth Complex commonly contain plagioclase, cordierite, quartz and biotite, similar to Wyllie's & Tuttle's (1961) refractory assemblage. Renner (1969) described the basal igneous rocks of the South Kawishiwi intrusive body and the footwall Virginia Formation in the Erie Mining Company's Dunka River mine (Fig. 1). The contact-zone intrusive body has been enriched in sodium and silicon relative to the overlying igneous rocks (Renner 1969). Renner estimated that some of the Virginia Formation must have been melted to produce the contamination noted. The partial melt, he proposed, then moved into the magma and contaminated it, forming the contact zone.

Bonnichsen (1972) investigated the chemistry of the Virginia Formation in the contact zone and in xenoliths. The metamorphosed Virginia Formation contained progressively more Ca, Al, Mg and Fe as the metamorphic grade increased from the footwall up to the contact, and from large to small xenoliths. The enrichment could be explained by depleting the metasediments and enriching the magma in Na, K, P, Si and CO_2 (Bonnichsen 1972). Bonnichsen proposed that a partial melt of the Virginia Formation, originating at the contacts of the slates with the troctolites and from xenoliths, was responsible for the movement of these materials out of the metasediments. The abundance of xenoliths in a portion of the magma would dictate how much contamination occurred (Bonnichsen 1972).

One major problem with the hypothesis is the high temperature required for the formation of a granitic partial melt (700°C: Wyllie & Tuttle 1961). However, such a temperature may have been achieved as a result of three closely spaced events occurring in the following sequence: (1) Initially, the intrusion of the Anorthositic Series would have raised the temperature of the Virginia Formation near the contact. (2) The next intrusive event was the emplacement of unit P. This caused the temperature in the upper portion of the Virginia Formation to increase to about 600°C. At this temperature, some of the chlorite in the metasediments at the contact would have been converted to biotite, which caused a release of water (Deer *et al.* 1966). The water migrated into unit P, where serpentinization occurred during the later stages of, or shortly after, crystallization. (3) When the troctolites were intruded, the rise in temperature of the immediate footwall rocks and xenoliths of the Virginia Formation only had to be on the order of 100–200°C to allow partial melting to occur.

A second objection to the partial-melting hypothesis is based on oxygen-isotope (Rao & Ripley 1980, Ripley & Rao 1980) and strontium-isotope data (Grant & Molling 1981); these data indicate that large-scale assimilation of material from the Virginia Formation by the intrusive complex is highly unlikely. However, contamination by a partial melt derived from the country rocks on the basal contact and xenoliths of the Virginia Formation could take place on a local scale (Rao & Ripley 1980, Ripley & Rao 1980). Rare granitic veins and selvages, remnants of this melt, are present in the troctolites and around xenoliths (Fig. 15). Contamination did not occur throughout the intrusive complex, but only in the basal 100 m. Here the concentration of xenoliths of Virginia Formation is greatest, and the textural evidence of partial melting is strongest.

Two major contaminants that remain unexplained by the partial-melting hypothesis are iron and sulfur. Grant & Molling (1981) suggested that the high content of iron in olivine near the base is due to the reaction of cumulus olivine with an intercumulus liquid rich in iron. As noted in this study, the olivine in the basal zone is not a cumulus mineral but rather an intercumulus phase. There is no evidence indicating that crystals accumulated in this portion of the Partridge River troctolite. No rhythmic layering is present, and there is no foliation of the plagioclase, the first phase to crystallize. The rocks appear to have crystallized in place. A more reasonable hypothesis is that the iron enrichment is associated with the sulfur enrichment.

Sulfide contamination

The sulfides typically occur interstitially to the silicates and locally show textures indicative of replacement of the silicates (Fig. 10). Layers of massive sulfide with graphite may have formed by gravity accumulation of an immiscible sulfide liquid. However, most of the sulfides in the basal zone of the Partridge River troctolite formed by crystallization from the magma. The sulfides solidified late in the sequence of crystallization of the magma, as indicated by the interstitial nature of the sulfides and their local replacement of the silicates.

Evidence from the present study and other investigations indicates that the bulk of the sulfur in the Partridge River troctolite was derived from the Virginia Formation. The increase in abundance of sulfur with depth in the basal zone supports this hypothesis. Sulfur-isotope studies (Mainwaring & Naldrett 1977, Ripley 1981) indicate that the sulfur originated from a sedimentary source, inferred to be the Virginia Formation. The Virginia Formation is a likely source, owing to the presence of pyrite-rich bands and tabular bodies in it and its stratigraphic equivalents (Morey 1972a, Matlack 1980).

Ripley (1981) proposed that sulfur was released as a result of the breakdown of pyrite to pyrrhotite. Other volatiles, liberated from the Virginia Formation at the same time (by the heat of the intrusion), mixed with the sulfur to yield a fluid composed of CO_2, CH_4, H_2S and H_2O. Aided by the turbulent nature of the intrusion, this fluid migrated into the magma owing to lower partial pressure of water and sulfur in the silicate liquid. It then dissolved in the magma, contaminating it.

The increase of the copper–nickel and iron–nickel ratios in the sulfides with depth (Fig. 13) has not been addressed by previous workers. The trends of the ratios could be explained by nickel entering olivine preferentially with depth. Hence, there would be less nickel to enter the sulfides. However, other studies of the basal zone of the Troctolitic Series reveal that the amount of nickel entering olivine does not increase markedly with depth, and the amount of NiO present in olivine is rarely greater than 0.20 wt.% (Fukui 1976, Bonnichsen *et al.* 1980). Secondly, the whole-rock analyses for iron show that this element is increasing in abundance with depth (Fig. 8) and is being introduced to the basal part of the magma column. By analogy, the trend seen in the copper–nickel ratio could be due to the addition of copper to the basal zone.

The Virginia Formation, in the contact zone, contains thin stratiform bands composed of pyrrhotite and graphite, which were interpreted to be syngenetic with the sediments (Matlack 1980). The presence (or absence) of copper within these bands was not established by chemical analysis. However, Morey (1972b) reported on pyrite- and pyrrhotite-rich tabular bodies within the Thomson Formation (the stratigraphic equivalent of the Virginia Formation to the southwest), which had been investigated as a possible source of sulfur. Other sulfides present in the bodies include minor amounts of chalcopyrite and sphalerite. Zinc averages 0.029% of the rock and copper about 0.05% (Morey 1972b). As the Thomson and Virginia Formations are stratigraphically equivalent and petrographically similar, the bands present in the Virginia Formation could be expected to have a mineralogical composition similar to the bodies in the Thomson Formation.

Much of the copper present would be removed by the sulfide-bearing fluid formed from these bands, as would zinc. The hydrous fluid proposed by Ripley (1981) would have contained HS^- and OH^- owing to the dissociation of H_2S and H_2O. Iron and copper from the sulfide bands would complex with these radicals and be transported by the fluid into the magma and mixed with it. Zinc would behave in a similar manner. As a result, zinc should (and does) follow the trend displayed by copper (Fig. 8).

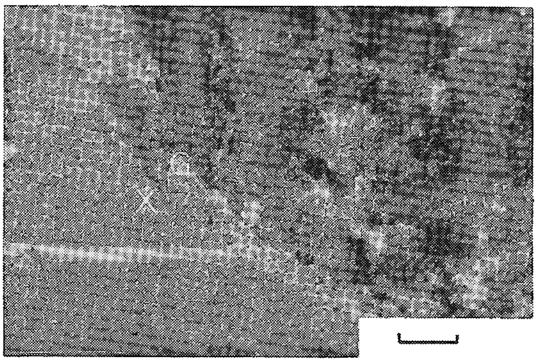

FIG. 15. A portion of drill core showing a xenolith (X, in the lower left portion) of Virginia Formation and augite troctolite containing sulfide and biotite. The two rock-types are separated by a selvage (G) of light material having a granitic composition. Note the accumulation of granitic material in the upper-left-hand portion of the photograph. Incident light. Scale bar is 5 mm.

Nickel, on the other hand, is not reported as occurring in the Virginia Formation or its equivalents. It was probably derived from the magma and appears in the sulfides, owing to its affinity for sulfur. Additional data indicating that copper and nickel had two different sources are contained in a report on the copper–nickel resources in the Ely–Hoyt Lakes region (Fig. 1) by Listerud & Meineke (1977). Although values of the copper–nickel ratio vary within each area, the averages for each area are significant. To the northwest of Birch Lake, the ratio is 2.7:1. In that area, no Virginia Formation is exposed on the surface, and only short intervals of it were encountered in drill cores. In the area of the Dunka mine, southwest of Birch Lake but northeast of the present study-area (Fig. 1) and near Renner's (1969) study-area, the ratio is 3.2:1. Here a limited amount of Virginia Formation is present. In the area of the present study, the ratio is 4:1, and extensive amounts of Virginia Formation are present. Ripley (1981) reported that in the Dunka Road deposit to the southwest (Fig. 1), the copper–nickel ratio is greater than 5:1. From these data, it can be inferred that the abundance of copper relative to nickel is related not only to the presence but also the abundance of the Virginia Formation in xenoliths and the footwall.

Could there be any other components of the hydrous sulfide-bearing fluid? Shamazaki & Clark (1973) and Burnham (1979) suggested that alkalis could also be a component of this type of fluid. If sodium were present in the fluid, it would be dissolved in the magma with the other components. It should appear enriching some phase; as noted above, plagioclase does show an increasing content of sodium with depth. Potassium may also have been added to the magma by the same mechanism. Potassium enrichment is indicated by the increasing abundance of biotite with depth. The common association of biotite with the sulfides could be explained by their coprecipitation. However, the increase in the abundance of biotite roughly parallels the abundance of sulfur and suggests that potassium may be a part of Ripley's (1981) sulfide-bearing fluid (Shamazaki & Clark 1973). The increase in the abundance of rubidium with depth in the contaminated zone (Fig. 8; Grant & Molling 1981) and its decrease in xenoliths and Virginia Formation in the contact zone (Grant & Molling 1981) may be explained in the same way because Rb, an alkali, would be expected to behave similarly to Na and K.

The hydrous S-bearing fluid may also provide the mechanism for the addition of iron to olivine. The abundance of rubidium in the contact zone parallels the iron enrichment in olivine (Grant & Molling 1981), suggesting a similar source. We propose that iron was also carried in from the Virginia Formation by this fluid. When the fluid was dissolved in the magma, iron was also. If the fluid was added early in the crystallization sequence of the magma, as suggested by the sodium enrichment of plagioclase, iron would partition into the olivine when it crystallized.

CONCLUSIONS

The Partridge River troctolite can be divided into five stratigraphic units on the basis of mineralogy, textures and chemical data. Unit P is the only cumulate present; it represents xenoliths from an earlier related intrusive body. Enveloping unit P is unit M. Its textures, mineralogy and chemical trends are very complex; it probably formed by more than one intrusive pulse. The bottom three units (A, B and C) are correlatable along strike for a distance of about 1 km. This basal zone is the result of contamination from the underlying Virginia Formation and its xenoliths within the intrusive body. Upon emplacement of the magma that gave the Partridge River troctolite, a fluid rich in sulfur, water, alkalis, iron and copper was formed. It migrated into and was dissolved into the magma. This dissolution probably occurred during the crystallization of plagioclase, the first phase to form. It enriched the plagioclase in sodium. Later, as crystallization of the magma proceeded and olivine started to form, a small amount of granitic partial melt was produced in the Virginia Formation along the troctolite contact and in xenoliths. This partial melt only affected the magma in the vicinity of the Virginia Formation, and thus remnants of melt have been preserved as veins or selvages around xenoliths (Fig. 15). This partial melt added Si to the magma and caused the formation of orthopyroxene in place of olivine. During the last stages of crystallization, the sulfides solidified. They either formed an immiscible liquid or solidified directly from the magma; evidence for both processes is present. As most of the sulfide was added to the basal section and did not have the opportunity to completely mix with the magma, it is in the basal zone that the sulfide is most concentrated. The lack of complete mixing accounts for the chemical trends seen in the silicates and the sulfides. It indicates that not only was sulfur derived from the footwall rocks but alkalis, iron and copper were as well. This is borne out by the regional values of the copper–nickel ratio, which correlate well with the proportion of Virginia Formation present in the footwall.

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