UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# Petrology of Igneous Rocks and Wall Rock Alteration, Mayflower Mine, Wasatch County, Utah

## Part 1: Primary Rock and Mineral Compositions

by

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## Part 1: Primary Rock and Mineral Compositions

## Abstract

Small, predominantly granodioritic stocks of Tertiary age are the host and possibly the source of important Cu-Pb-Zn-Ag-Au deposits in the Mayflower mine. The two stocks exposed in the mine are part of a series of intrusive and extrusive centers of Eocene to Miocene age in the central Wasatch Range. Ore deposits in the Mayflower mine and elsewhere in the Park City district are localized along normal faults which cut the youngest igneous rocks. Prior to normal faulting there was a complex sequence of alteration and introduction of uneconomic quantities of sulfide minerals.

The oldest intrusion in the mine is the 41-m.y.-old Mayflower porphyry stock, a composite intrusion with pronounced lateral zonation of composition and texture. The marginal facies has vertical flow structure parallel to the intrusive contact and ranges in composition from diorite to monzodiorite. The core facies was pressure quenched to a create an aphanitic quartz-eye porphyry. The granodioritic core is somewhat more silicic-alkalic in composition than the marginal facies. Changes in texture and mineralogy over short lateral distance are interpreted to have been caused by variation in volatile content and by magma movement during crystallization.

The 34-m.y.-old Ontario porphyry stock intrudes the Mayflower porphyry stock below the 2,200 mine level. It is coarser grained than the Mayflower and more alkalic in composition (granodiorite to monzogranite). Discontinuous, thin stringers of felsite cut the Mayflower and Ontario stocks and represent volatile-rich differentiates released into dilatant zones during late magmatic stages.

Compositions of mafic silicates yield useful information about conditions of crystallization. Primary biotites are moderately magnesian (Fe: Fe+Mg+Mn = 0.35±0.05). Ferric iron content is at least 12 atom percent, based on wet chemical analyses and recalculated microprobe analyses. Biotite compositions suggest that crystallization occurred at about 900°C, $f_{O_2}$ about $10^{-11}$ bars, and $f_{H_2O}$ about 800 bars. Actinolite (amphibole) phenocrysts are relatively rich in Si and Mg with Fe+Mg+Mn ratios ranging from 0.35 to 0.13 and tetrahedral Al less than 0.5 atoms. These amphibole compositions are unusual for granitic rocks and may reflect subsolidus re-equilibration, although that is not evident texturally. The amphiboles probably formed close to minimum T and $P_{H_2O}$ conditions for their stability. Pyroxene occurs in a few samples from upper mine levels and may represent the breakdown products of amphibole. Of all the mafic minerals examined, biotite best retains its primary composition, and thus yields the most reliable information on primary conditions.

Textural and compositional features of the stocks in the Mayflower mine are similar to those in other copper-bearing "porphyry copper" stocks. As in some porphyry copper stocks, pyrite and chalcopyrite are disseminated in the highly porphyritic core facies. Although known concentrations in the Mayflower stock are too low to be economic, the disseminated copper sulfides may have been the source for the later postmagmatic vein ores. The abundance of anhydrite and important copper and gold in the mine could be the result of late-magmatic oxidation by loss of $H_2$. The oxidizing conditions would facilitate hydrothermal transport of copper and gold. Late-magmatic oxidation may have occurred as a result of the shallow depth of emplacement and pressure quenching with loss of volatiles.

## INTRODUCTION

The Mayflower mine, located about 45 km southeast of Salt Lake City, Utah, was an important producer of copper, gold, lead, zinc, and silver from 1939 until its closure in 1973. Although replacement and vein deposits in Mississippian sedimentary rocks in the Mayflower mine are similar to other typical ores of the Park City district, more than 80 percent of its production came from veins within Tertiary intrusive rocks (Quinlan and Simos, 1968). The intra-intrusive veins were rich in copper and gold, and the deposits in sedimentary rocks were rich in lead, zinc, and silver. The Mayflower mine afforded excellent exposures of the Tertiary intrusive rocks over a vertical interval of about 1,000 m (3400 ft), and the underground workings exposed features that could not be observed at the surface. Petrologic studies were done to describe the composition of the igneous rocks and effects of several stages of hydrothermal alteration which occurred both before and during ore deposition.

The Park City district has yielded more than $600 million from deposits rich in galena, sphalerite, and enargite. Only in the Mayflower mine were chalcopyrite and native gold important. Most ore has come from Permian and Mississippian carbonate rocks. Tertiary igneous rocks (Fig. 1) have been described by Boutwell (1912), Bromfield (1968), and Bromfield and others (1977). Intrusive rocks west of the Park City district (Fig. 1) are coarse-grained granodiorites about 41 and 35 m.y. old (Bromfield and others, 1977). In the Park City district there are at least six distinct porphyry intrusions including the Mayflower porphyry stock. The intrusions range in age from about 41 to 35 m.y. About 5 km east of the Mayflower mine, the 34-36 m.y. old Keetley Volcanics are intruded by slightly younger stocks. Hydrothermal biotite in the Mayflower mine yields ages about 33 m.y.; the hydrothermal biotite formed somewhat earlier than the intra-intrusive vein deposits. Potassium-argon ages indicate that intrusion, extrusion, and early hydrothermal alteration overlapped in time between about 41 and 33 m.y. ago (Bromfield and others, 1977).

The deposits in the Mayflower mine are localized along the Mayflower-fault zone (fig. 1), a series of bifurcating normal faults with about 30 m of vertical displacement (Quinlan and Simos, 1968). Most ore has come from the Mayflower, Pearl, and No. 3 veins. Samples described here come from the 800 to 3,000 mine levels, the numbers representing depth in feet below the surface; some samples are from a drill core that penetrated about 300 m below the deepest mine workings. Evidence from a fluid-inclusion study (Nash, 1973) suggests there was originally about 900 to 1,200 m of cover above the Mayflower vein outcrop. Thus the rocks and ores described here formed at about 1 to 2.5 km depth, or at about 300 to 750 bars lithostatic pressure.

"Unaltered" igneous rocks are the subject of this report. It is well known that no plutonic rocks escape sub-solidus alteration and re-equilibration. Plutonic rocks in the Mayflower mine are typical in this respect, and also underwent multiple periods of intrusion and vein formation. The purpose of this study is to identify the least altered rocks and determine the composition of the igneous rocks prior to several stages of

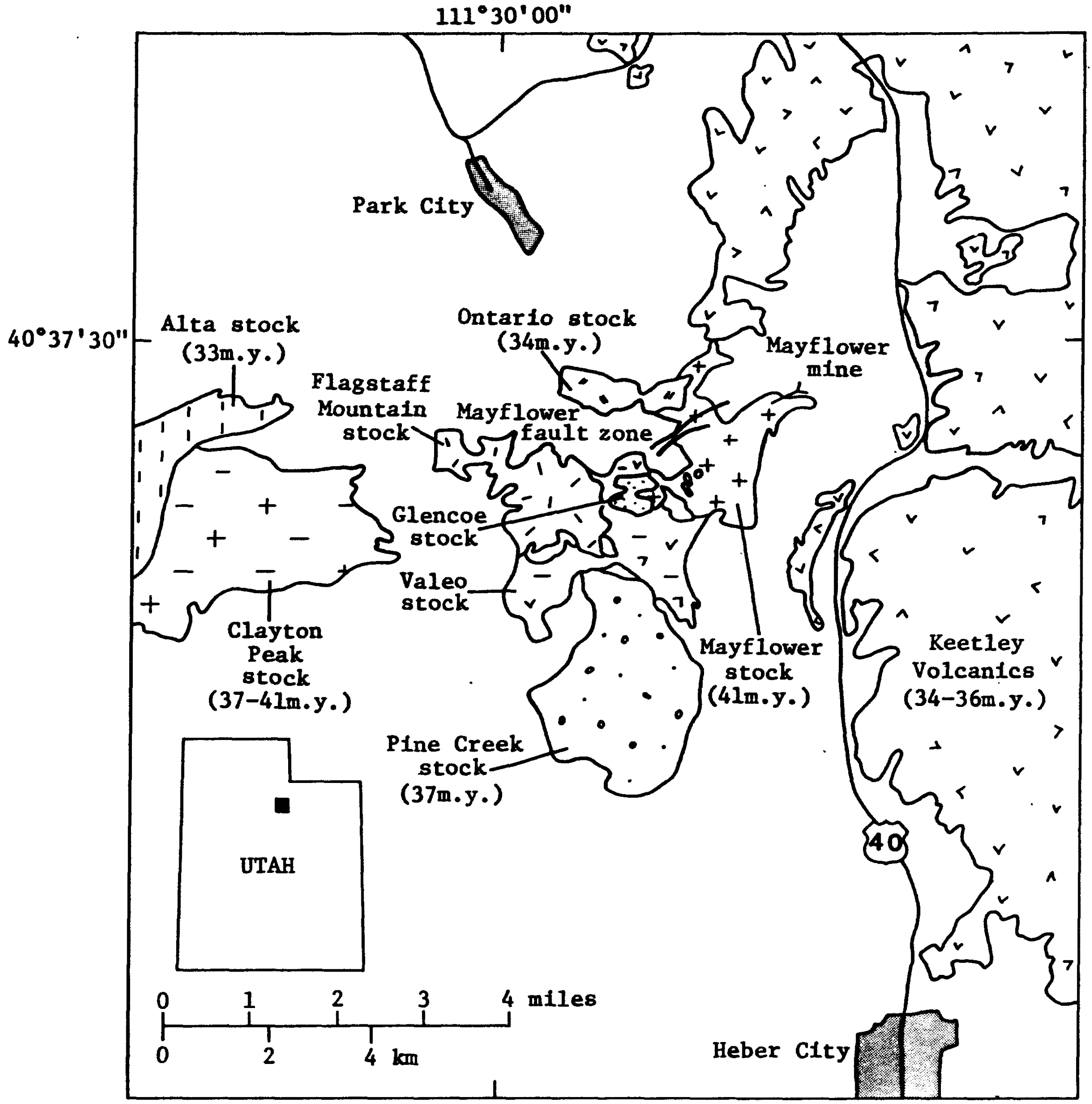

Figure 1.--Index map showing location of Mayflower mine and igneous rocks of the Park City district (geology after Baker and others, 1966; Bromfield and others, 1970; Bromfield and others, 1971). Ages of intrusive rocks are from Bromfield and others (1977).

hydrothermal alteration. The chemistry and mineralogy of the hydrothermally altered igneous rocks have been summarized previously (Nash, 1975) and are the subject of further study.

## ACKNOWLEDGEMENTS

This research was inspired by G. K. Czamanske who also offered guidance on the microprobe and numerous helpful discussions. W. J. Moore and Dawn Madden provided thorough reviews of the manuscript. This work was based largely on systematic geologic studies by C. S. Bromfield, and by J. G. Simos, former Chief Mine Geologist, Hecla Mining Co., who gave freely of their knowledge and information.

## METHODS OF STUDY

Fieldwork for this study began in 1969 and continued until the mine closed in 1973. Mine observations were made and sampling done in collaboration with Calvin Bromfield, U.S. Geological Survey, and John Simos and Walter Freeman, formerly with the Helca Mining Company. Most attention focused on active workings below the 1880 mine level. Limited studies were made of accessible portions of higher levels. One or more samples from about 400 localities were examined in the laboratory. Petrographic studies were made of more than 400 thin sections, and modal analyses made of 55 sections. Thin sections and ground slabs were generally stained to facilitate identification of feldspars. Several hundred X-ray diffraction analyses were used to identify ore, gangue, and alteration minerals. Chemical analyses performed on 40 rocks were done by rapid methods to determine major element contents (Shapiro and Brannock, 1956) and by atomic absorption, X-ray fluorescence, or spectrographic methods to determine minor elements contents.

Quantitative chemical analyses of approximately 250 mineral grains in 28 polished thin sections were made using an ARL model EMX microprobe[1]. Operating conditions were 15 kV accelerating voltage, $3X10^{-8}$ amp sample current, and fixed count of beam current to minimize instrumental drift. LiF,

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[1] Brand names used in this report are for descriptive purposes only and do not constitute endorsement by the U.S. Geological Survey.

ADP, and RAP crystals were used to analyze for Si, Al, Ti, Fe, Mg, Mn, Ca, Na, and K in sets of three for most samples. Beam diameter was close to 1 μm (micrometer) for maximum selectivity. Intensity data were corrected by computer for background, drift, atomic number, and matrix absorption (Beeson, 1967). Mineral standards included biotite, amphibole, magnetite, and ilmenite of established uniform composition, and a glass standard was used for feldspar analyses.

## FIELD RELATIONS

Four intrusive rock types occur in the Mayflower mine: the Mayflower porphyry stock, the Ontario porphyry stock, the Valeo porphyry stock, and local felsic dikes and stringers. Corresponding rock units have been mapped at the surface (Bromfield, 1968; Bromfield and others, 1970). The largest body exposed in the mine is the Mayflower porphyry stock (fig. 2), which crops out over approximately 5 $km^2$ at the surface. Megascopically, the Mayflower porphyry stock is dark green or gray and contains plagioclase, amphibole, biotite, and quartz phenocrysts in an aphanitic matrix. The western and central parts commonly exhibit an alinement of plagioclase and biotite phenocrysts. The foliation defined by biotite, and the lineation defined by plagioclase, are nearly vertical and are parallel to the intrusive contact. The eastern exposures of the Mayflower in the mine are more distinctly porphyritic than to the west and contain prominent quartz-eye phenocrysts.

The contact of the Mayflower porphyry stock with sedimentary wall rocks has local irregularities, but over the 2,400 feet (730 m) of vertical exposure in the mine the average dip is nearly vertical (fig. 2). Sedimentary strata show very little deformation near the contact. Contact zone metamorphism generally consists of silicification with local development of small amounts of garnet, chlorite, serpentine, and epidote. Only a few sedimentary xenoliths have been observed.

The Ontario porphyry stock is light gray and coarser grained than the Mayflower porphyry stock, and contains prominent books of biotite. The Ontario clearly intrudes the Mayflower as seen in excellent exposures below the 2,200 level (fig. 2). There is very little change in grain size at the contact. The Ontario has not been observed above the 2,200 mine level. This is the south edge of the Ontario stock, which outcrops over approximately

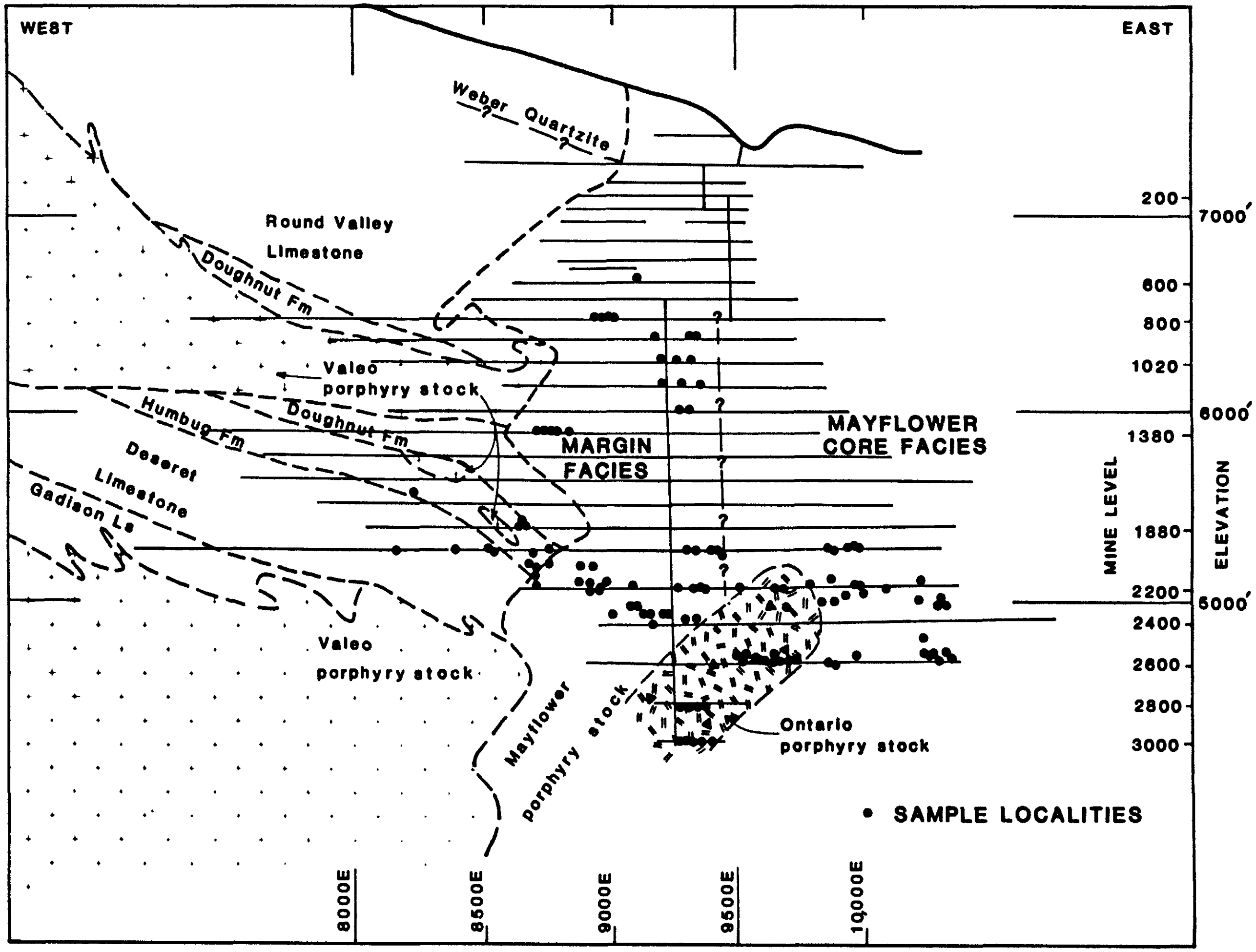

Figure 2.--Generalized longitudinal section of the Mayflower mine with geology projected on to the plane of the Mayflower vein. The contact between Mayflower porphyry core and margin facies is gradational. (Modified from Quinlan and Simos, 1968, with additions by the author.)

3 $km^2$ and enlarges with depth (Bromfield and others, 1970). Locally, the Ontario is altered to a friable, punky mass, resulting from pervasive replacement of plagioclase by montmorillonite or sericite. This alteration, which caused caving in mining, does not appear to be related to ore or to faults.

The Valeo stock is probably younger than the Mayflower, although contact relations are not clear underground or on the surface (Bromfield and others, 1970). The Valeo stock has prominent euhedral plagioclase phenocrysts and quartz "eyes". In the mine it occurs in small dikelike bodies that are highly altered. The Valeo has not been studied much and will not be considered further.

Numerous thin, erratic stringers and dikes of fine-grained pink felsite cut both the Mayflower and Ontario porphyry stocks. The felsite occurrences are widely scattered, but are most abundant in the vicinity of the Mayflower-Ontario contact and in the gradational transition between the core and margin facies of the Mayflower. None of the felsite bodies is large enough to be mapped for more than a few meters. There are probably two ages of felsite intrusion related to the Mayflower and Ontario intrusions, respectively. Some are clearly within and derived from the Ontario porphyry stock. Others show no relation to the Ontario stock and occur in the Mayflower stock in zones of sugary-textured felsic seams that have gradational contacts with the enclosing Mayflower porphyry stock.

## IGNEOUS PETROLOGY

According to petrographic and chemical descriptions, most Tertiary intrusive rocks in the Park City district (Boutwell, 1912; Bromfield, 1968; Bromfield and others, 1977) are granodiorites, or quartz diorite by Boutwell's classification. Because poor exposures and weathering severely hamper mapping and sampling for detailed petrologic studies, the deep and wide exposures of the Mayflower mine were used. Although rocks underground are much fresher than at the surface, all have experienced some hydrothermal alteration. The rocks described here are the freshest, least altered examples I could collect. Presence of magnetite and amphibole was one criterion used to select these rocks. These are not pristine samples, but serve as a datum against which altered rocks will be compared.

## Textures

Textures of the intrusive rocks are highly variable but are diagnostic for purposes of mapping. The fine grain size of many rock types precludes megascopic recognition of many features and especially hampers recognition of local variations during inspection of mine workings or core. Characteristic phenocryst and matrix features are the basis for recognizing five textural types in three units (table 1). The Mayflower porphyry stock has two textural variants.

Two distinctive phenocryst and matrix textures are observed in the Mayflower porphyry stock, one in the core and the other in the western margin. Gradations between the two end members occur across a transition zone to be described later. The core of the Mayflower intrusion is characterized by stubby, anhedral plagioclase phenocrysts (fig. 3a, 3b), 1-5 mm long. These are poorly twinned: pericline twinning is rare and less than 50 percent of the phenocrysts display albite twinning. Quartz phenocrysts are prominent and have euhedral, resorbed, or angular morphology. Biotite and amphibole also occur as phenocrysts. The matrix is an extremely fine grained (20-50 μm) intergrowth of quartz, K-feldspar, and untwinned plagioclase. Grain size of matrix minerals is locally as much as 250 μm. Rocks with the extremely fine-grained matrix occur in the eastern part of the mine (fig. 4), whereas rocks with the somewhat coarser (50-250 μm) microgranular matrix occur in the central part of the mine.

A second textural type of porphyry in the Mayflower occurs in the western part of the mine near the intrusive contact, hence is called the margin facies (fig. 4). In contrast to the core facies, plagioclase phenocrysts are smaller (1 to 3 mm), elongate, euhedral, and consistently well twinned according to albite, carlsbad, and pericline laws. Biotite and/or amphibole phenocrysts are present, but quartz phenocrysts are not observed. Plagioclase phenocrysts commonly are alined in a flow fabric (fig. 3c). Within the margin facies two matrix types are observed. One is seriate, consisting of relatively coarse granular quartz and K-feldspar approximately 100 to 800 μm size. Rectangular plagioclase commonly is present also and can be alined in the same manner as the phenocrysts. The other variety is microgranular with 40 to 100 μm plagioclase, K-feldspar and quartz. Quartz commonly is in crystallographic continuity for as much as 300 μm. The quartz-enclosed feldspar aggregate

Table 1.--SUMMARY OF TEXTURAL FEATURES

| | Phenocrysts | Groundmass |
|---|---|---|
| Ontario porphyry stock | Plagioclase up to 5 mm, average 1.1 mm; sharp twinning. No quartz phenocrysts. | Seriate, 1 to 0.2 mm. Graphic intergrowths common |
| Mayflower porphyry stock<br>Core facies | (1) Stubby, anhedral plagioclase, up to 5.5 mm, average 1.5 mm. Poorly developed twinning. Quartz phenocrysts common. | (a) Microgranular, 50 to 250 m<br>(b) Aphanitic, less than 50 m |
| Margin facies | (2) Elongate, euhedral plagioclase, up to 3.5 mm., average 1.1 mm. No quartz phenocrysts. Plagioclase commonly alined (trachytoidal). | (a) Seriate, average 250 m; if plagioclase-rich commonly trachitic; granular quartz and K-feldspar.<br>(b) Microgranular, less than 100 m; commonly trachitic; quartz rectangular. |

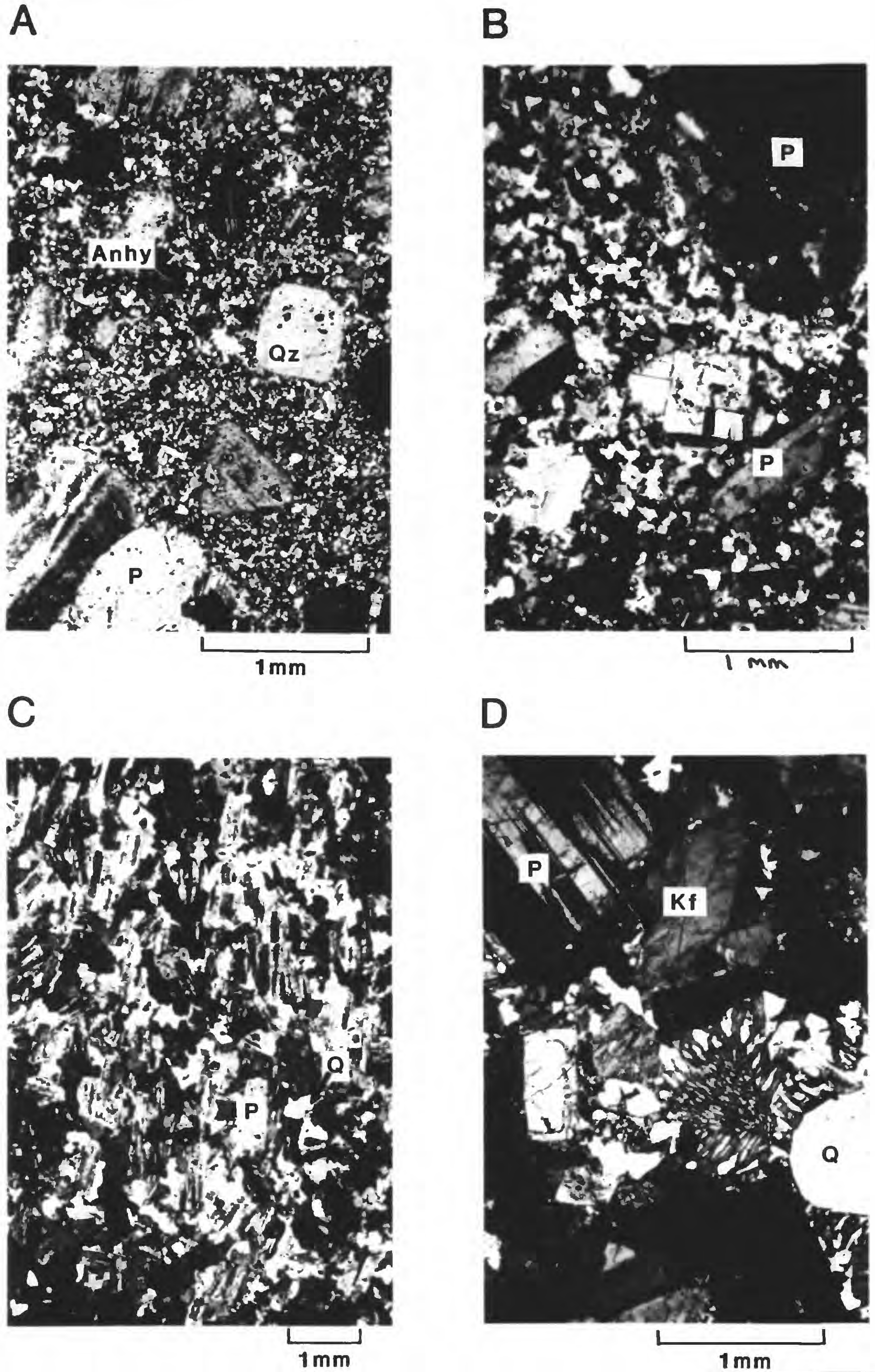

Figure 3.--Photomicrographs of igneous rocks from the Mayflower mine.

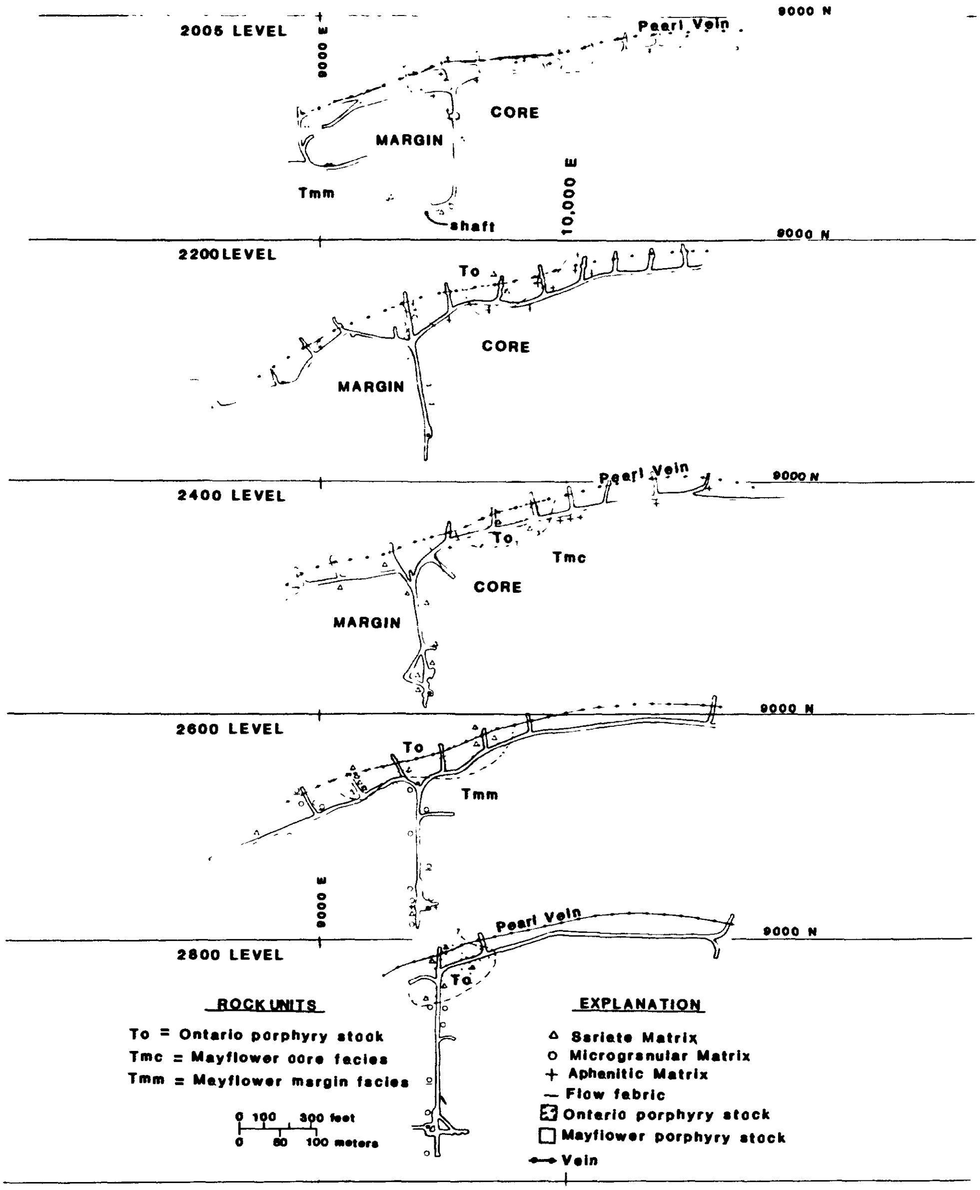

Figure 4.--Plan maps of levels of the Mayflower mine showing igneous rock lighology. (Base maps from Hecla Mining Co.)

resembles a granophyric intergrowth. No systematic distribution of matrix varieties in the margin facies is apparent.

Locally, equigranular, sugary-textured rocks grade into normal Mayflower porphyry. These equigranular rocks have textures identical to Mayflower matrix, but lack phenocrysts. Contacts are gradational over several meters. These rocks seem to have formed late in the crystallization of the Mayflower body, and are distinct from texturally and compositionally similar felsic dikes with sharp contacts.

The Ontario porphyry stock is distinctive in the mine for its lighter gray color, medium grain size, and prominent books of biotite. The Ontario is less porphyritic than other stocks in the Park City district because of its relatively coarse matrix and seriate texture. Graphic intergrowths of quartz and K-feldspar are commonly observed under the microscope (fig. 3d). Plagioclase phenocrysts in the Ontario are larger (2-4 mm) and more rounded than in the Mayflower.

The crystallization sequence of primary minerals in all the intrusive rocks is approximately the same, with the possible exception of the large quartz phenocrysts in the core facies of the Mayflower stock which could be earlier than the quartz in other rocks. Plagioclase, biotite, amphibole, and iron oxides occur primarily as phenocrysts, but also are present as matrix phases. Pyroxene occurs as phenocrysts in samples of the Mayflower stock from the 800 mine level and from surface exposures; the absence of pyroxene at greater depths probably means it was replaced by biotite or amphibole through igneous or hydrothermal reactions. Magnetite that occurs as poikilitic inclusions along growth zones of some amphibole and plagioclase phenocrysts must be primary and contemporaneous with the enclosing phases. The time of formation of shreddy biotite in amphibole, fine-grained matrix magnetite, and matrix feldspar is not clear, but may reflect subsolidus alterations.

Anhydrite occurs in the matrix of many samples. Rarely is there evidence for a replacement origin, such as anhydrite inside plagioclase, and coexisting matrix minerals generally appear unaltered. The texture of anhydrite in many rocks is like that of apatite and just as well could have been a primary magmatic phase. The presence of this possible primary anhydrite, as well as later vein-filling anhydrite, has implications for oxygen and sulfur fugacity, which will be considered later.

## Modal and chemical composition

Mineral abundances in 53 samples were determined by point counting to provide a measure of rock compositions. The porphyritic textures pose a problem for reliable modal analyses because counting fine matrix grains requires use of thin sections, whereas counting phenocrysts requires larger slabs. Modes on separate thin sections from a 5 cm sample differ by as much as 50 percent, so no individual mode is considered representative or reliable. Modal abundances are plotted on figure 5 and presented in table 2. The presence of a large range in modal composition is confirmed by visual estimates of mineral abundances in about 200 additional thin sections. Considering all rock types, modal plagioclase ranges from 12 to 60 volume percent; K-feldspar, from trace to 46 percent; quartz, from 6 to 35 percent; biotite, from 0 to 47 percent; amphibole, from 0 to 40 percent; anhydrite, from 0 to about 3 percent, and opaque minerals (chiefly magnetite) from about 1 to 3.5 percent. Perhaps the most significant variation is in total femic mineral and K-feldspar content (fig. 5). Most rocks are classified (Strekheisen, 1976) as grandiorite and monzodiorite, but a number of samples from the margin facies have very low K-feldspar content and are classified as diorite and quartz diorite. There was a general chemical evolution to a more silicic-alkalic composition, in time, from Mayflower margin facies to core facies to Ontario porphyry stock.

Chemical analyses (table 2) demonstrate a moderate range in chemical composition for the intrusive rock series. Sample locations are shown in figure 6. The ranges in abundance for some of the major constituents are: $SiO_2$, 56.4 to 75.6 wt percent; $Al_2O_3$, 12.4 to 17.0; CaO, 0.6 to 6.2; and $K_2O$, 1.6 to 7.3. Phosphorus and titanium contents are relatively consistent within each of the three major igneous units and decrease in successively younger phases. Sulfur content varies locally and reflects hydrothermal alteration. Variation within intrusive units, noted in modal analyses, is also apparent in chemical analyses. In particular, within each of the two units of the Mayflower porphyry stock, variation in constituents such as $SiO_2$, CaO, $Na_2O$ is considered to be large, whereas variation in other constituents ($Al_2O_3$, FeO, MgO, $TiO_2$, and $P_2O_5$) is generally small. The variation in the former group causes the calculated D.I. (differentiation index, Thornton and Tuttle, 1960) and amounts of normative corundum or wollastonite to vary considerably between

Table 2.--Chemical analyses, norms, and modal analyses of unaltered igneous rocks

[Chemical analyses by rapid rock method for major constituents except S; analysts: P. Elmore, H. Smith, J. Glenn, and J. Kelsey. Analyses for total S, Ba, Rb, and Sr by X-ray spectrometry; analysts: B. Fabbi and L. Espos. Quantitative analyses for Au, Cu, Hg, Pb, and Zn by atomic absorption spectrometry; analysts: C. Burton, L. Mei, B. McCall, and R. Moore. Semiquantitative analyses for other elements by emission spectrograph; analysts: C. Heropoulos and R. Mays]

| Margin facies of Mayflower porphyry stock | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample No. | 10-2 | 176 | 8-3 | 223 | 22-22 | 272 | 270 | 26-15 | 268 |
| Chemical analysis (weight percent) | | | | | | | | | |
| $SiO_2$ | 56.4 | 57.4 | 57.9 | 58.9 | 60.2 | 60.3 | 60.5 | 60.6 | 61.2 |
| $Al_2O_3$ | 16.5 | 16.5 | 16.4 | 15.4 | 17.0 | 16.6 | 16.1 | 16.4 | 16.4 |
| $Fe_2O_3$ | 3.6 | 3.1 | 3.0 | 1.9 | 2.6 | 2.7 | 2.8 | 2.6 | 3.1 |
| FeO | 4.1 | 4.3 | 3.7 | 2.6 | 3.4 | 2.5 | 3.2 | 3.4 | 3.0 |
| MgO | 4.1 | 4.0 | 4.5 | 4.4 | 3.1 | 2.6 | 3.2 | 3.1 | 3.0 |
| CaO | 6.2 | 5.7 | 5.3 | 5.6 | 5.2 | 5.0 | 4.6 | 4.9 | 4.6 |
| $Na_2O$ | 3.3 | 3.1 | 2.9 | 3.2 | 3.6 | 3.6 | 3.2 | 3.3 | 3.0 |
| $K_2O$ | 1.6 | 2.5 | 1.9 | 2.6 | 1.7 | 3.2 | 3.0 | 2.9 | 2.9 |
| $H_2O(+)$ | 1.4 | 1.0 | 1.6 | .73 | 1.3 | .72 | 1.4 | .88 | .15 |
| $H_2O(-)$ | .34 | .39 | .55 | .08 | .10 | .28 | .64 | .32 | .58 |
| $TiO_2$ | .96 | .97 | .85 | .81 | .78 | .69 | .82 | .32 | .85 |
| $P_2O_5$ | .38 | .37 | .34 | .36 | .32 | .33 | .36 | .35 | .37 |
| MnO | .14 | .16 | .10 | .03 | .06 | .07 | .09 | .13 | .10 |
| $CO_2$ | .30 | .12 | .22 | --- | .08 | <.05 | <.05 | .10 | <.05 |
| S, total | --- | .05 | .33 | --- | .53 | --- | --- | .11 | --- |
| F | .09 | .10 | .07 | .14 | .07 | .09 | .07 | .08 | .07 |
| Cl | | | | | | | | | |
| Total | 99 | 100 | 99 | | 99 | 98 | 99 | 100 | 99 |
| CIPW norms (weight percent) | | | | | | | | | |
| Quartz | 12.43 | 11.59 | 16.31 | 13.72 | 19.71 | 13.80 | 15.93 | 15.26 | 18.91 |
| Corundum | --- | --- | 1.27 | --- | .71 | --- | .19 | --- | .96 |
| Orthoclase | 9.55 | 14.88 | 11.34 | 15.89 | 9.76 | 19.22 | 17.85 | 17.21 | 17.36 |
| Albite | 28.21 | 26.42 | 24.78 | 28.01 | 29.61 | 30.96 | 27.26 | 28.04 | 25.72 |
| Amorthite | 25.75 | 23.90 | 22.90 | 20.67 | 22.55 | 20.00 | 20.33 | 21.46 | 20.40 |
| Wollastonite | .38 | .58 | --- | 2.01 | --- | 1.07 | --- | .01 | --- |
| Enstatite | 10.32 | 10.04 | 11.32 | 11.34 | 7.50 | 6.58 | 8.02 | 7.75 | 7.57 |
| Ferrosilite | 3.26 | 3.96 | 2.44 | 1.99 | 1.78 | 1.37 | 2.39 | 2.77 | 1.82 |
| Magnetite | 5.27 | 4.53 | 4.39 | 2.85 | 3.66 | 3.98 | 4.09 | 3.78 | 4.55 |
| Ilmenite | 1.84 | 1.86 | 1.63 | 1.59 | 1.44 | 1.33 | 1.57 | 1.56 | 1.56 |
| Pyrite | --- | .09 | .62 | --- | .96 | --- | --- | .21 | --- |
| Apatite | .91 | .88 | .81 | .88 | .74 | .79 | .86 | .83 | .89 |
| Fluorite | --- | --- | --- | .23 | --- | .13 | .08 | --- | .08 |
| Calcite | .69 | .28 | .50 | --- | .18 | | | .23 | |
| Total | 98.6 | 99.0 | 98.3 | 99.2 | 98.6 | 99.2 | 98.6 | 99.1 | 99.8 |
| Femic | 22.7 | 22.2 | 21.7 | 20.9 | 16.3 | 15.3 | 17.0 | 17.1 | 16.5 |
| D.I.[1] | 50.2 | 52.9 | 52.4 | 57.6 | 59.1 | 64.0 | 61.0 | 60.5 | 62.0 |

Table 2.--Continued

| Sample No. | 10-2 | 176 | 8-3 | 223 | 22-22 | 272 | 270 | 26-15 | 268 |
|---|---|---|---|---|---|---|---|---|---|
| Modal analysis (volume percent) | | | | | | | | | |
| Quartz | 15.1 | 6.0 | 9.2 | 11.4 | 12.3 | 12.2 | 11.2 | 10.8 | 13.4 |
| K-Feldspar | .8 | 8.0 | .8 | .5 | 3.1 | 24.7 | 19.9 | 15.8 | 22.2 |
| Plagioclase | 57.3 | 54.8 | 53.6 | 58.0 | 58.5 | 45.2 | 48.6 | 51.0 | 38.9 |
| Biotite | 12.0 | 10.8 | 24.9 | 25.9 | 20.8 | .6 | 3.2 | 7.3 | 9.6 |
| Amphibole | 12.0 | 18.4 | 5.4 | --- | 1.2 | 14.1 | 14.3 | 10.8 | 13.0 |
| Opaque | 2.3 | 2.0 | 4.2 | 2.0 | 2.7 | 3.4 | 2.8 | 3.9 | 2.9 |
| Accessories[2] | 1.0 | --- | 1.9 | 2.2 | 1.5 | .4 | --- | .4 | --- |
| Femics | 26 | 31 | 34 | 27 | 25 | 18 | 20 | 22 | 26 |
| Minor element analyses (parts per million) | | | | | | | | | |
| Ag | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Au | .9 | --- | --- | N.d. | --- | N.d. | N.d. | --- | N.d. |
| Ba | 920 | 1,350 | 1,100 | --- | 1,200 | --- | --- | 1,800 | --- |
| Co | 15 | 20 | 15 | 10 | 10 | 7 | 10 | 15 | 10 |
| Cr | 50 | 50 | 100 | 100 | 50 | 20 | 30 | 50 | 30 |
| Cu | 10 | 10 | 94 | 70 | 92 | 200 | 20 | 65 | 30 |
| Hg (PPB) | 12 | 27 | 7 | N.d. | 4 | N.d. | N.d. | 5 | N.d. |
| La | 70 | 70 | 70 | --- | 70 | 70 | 70 | 100 | 70 |
| Mo | 7 | --- | --- | --- | 5 | --- | --- | 5 | --- |
| Ni | 50 | 20 | 20 | 30 | 15 | 7 | 10 | 15 | 10 |
| Pb | 25 | 53 | 14 | --- | 13 | 20 | 20 | 35 | 20 |
| Rb | 52 | 73 | 64 | --- | 55 | --- | --- | 88 | --- |
| Sc | 15 | 20 | 20 | 10 | 15 | 7 | 10 | 15 | 10 |
| Sr | 820 | 775 | 810 | --- | 855 | --- | --- | 825 | --- |
| V | 70 | 150 | 150 | 70 | 100 | 50 | 70 | 100 | 70 |
| Y | 15 | 30 | 20 | 15 | 20 | 10 | 15 | 20 | 15 |
| Zn | 56 | 99 | 52 | N.d. | 53 | N.d. | N.d. | 80 | N.d. |
| Zr | 200 | 150 | 150 | 200 | 200 | 150 | 150 | 200 | 150 |

[1] D. I. Differentiation Index of Thornton and Tuttle (1960)

[2] Accessories: apatite, calcite, and anhydrite

Table 2.--Continued

Core facies of Mayflower porphyry stock--continued

| Sample No. | 26-23 | 20-12 | 22-16 | 22-10 | 22-13 | 266 | 265 | 20-14 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 57.9 | 59.3 | 59.6 | 61.2 | 61.6 | 63.2 | 63.6 | 64.8 |
| $Al_2O_3$ | 15.7 | 16.5 | 15.5 | 16.2 | 16.1 | 16.6 | 17.0 | 16.4 |
| $Fe_2O_3$ | 2.9 | 2.2 | 2.5 | 2.3 | 2.5 | 2.2 | 1.6 | 1.0 |
| FeO | 2.8 | 3.0 | 3.0 | 2.6 | 2.8 | 2.2 | 2.2 | 2.5 |
| MgO | 3.0 | 3.6 | 3.4 | 3.1 | 3.0 | 2.2 | 2.2 | 2.5 |
| CaO | 6.3 | 5.0 | 4.7 | 4.8 | 3.6 | 2.8 | 4.4 | 3.4 |
| $Na_2O$ | 3.3 | 3.5 | 3.1 | 3.6 | 3.2 | 3.2 | 3.6 | 4.1 |
| $K_2O$ | 3.1 | 2.8 | 3.2 | 2.7 | 3.0 | 3.4 | 2.5 | 2.0 |
| $H_2O(+)$ | 1.1 | 1.9 | 1.5 | 1.0 | 1.6 | 1.4 | 1.1 | 1.2 |
| $H_2O(-)$ | .75 | .69 | .57 | .57 | .70 | .90 | .16 | .36 |
| $TiO_2$ | .66 | .70 | .72 | .65 | .65 | .60 | .59 | .61 |
| $P_2O_5$ | .35 | .33 | .33 | .30 | .32 | .28 | .27 | .26 |
| MnO | .19 | .12 | .14 | .11 | .10 | .05 | .03 | .06 |
| $CO_2$ | 1.1 | --- | .90 | <.05 | --- | --- | --- | --- |
| S, total | .01 | .17 | .03 | .02 | .57 | --- | --- | --- |
| F | .06 | .12 | .09 | .08 | .15 | --- | --- | --- |
| Cl | | | | | | | | |
| Total | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |

CIPW norms (weight percent)

| | 26-23 | 20-12 | 22-16 | 22-10 | 22-13 | 266 | 265 | 20-14 |
|---|---|---|---|---|---|---|---|---|
| Quartz | 12.84 | 12.50 | 16.68 | 15.64 | 20.08 | 23.13 | 20.68 | 22.31 |
| Corundum | --- | --- | 1.28 | --- | 1.94 | 3.50 | 1.18 | 2.06 |
| Orthoclase | 18.62 | 16.68 | 19.17 | 16.18 | 17.89 | 20.45 | 14.90 | 11.92 |
| Albite | 28.38 | 29.86 | 26.60 | 30.88 | 27.33 | 27.56 | 30.72 | 34.98 |
| Amorthite | 19.18 | 21.22 | 15.69 | 20.35 | 15.60 | 11.72 | 19.82 | 14.98 |
| Wollastonite | 1.33 | .54 | --- | .62 | --- | --- | --- | --- |
| Enstatite | 7.59 | 9.04 | 8.59 | 7.83 | 7.54 | 5.58 | 5.52 | 6.28 |
| Ferrosilite | 2.02 | 2.43 | 2.49 | 1.99 | 1.03 | 1.35 | 1.82 | 2.29 |
| Magnetite | 4.27 | 3.21 | 3.68 | 3.38 | 3.66 | 3.25 | 2.34 | 1.46 |
| Ilmenite | 1.27 | 1.34 | 1.39 | 1.25 | 1.25 | 1.16 | 1.13 | 1.17 |
| Pyrite | .02 | .32 | .06 | .04 | 1.08 | --- | --- | .55 |
| Apatite | .84 | .79 | .79 | .72 | .76 | .68 | .64 | .62 |
| Fluorite | --- | --- | --- | --- | --- | .16 | .12 | --- |
| Calcite | 2.54 | --- | 2.08 | --- | --- | --- | --- | --- |
| Total | 98.9 | 98.1 | 98.5 | 98.9 | 98.3 | 98.5 | 98.9 | 98.7 |
| Femic | 19.9 | 17.8 | 19.1 | 15.9 | 15.4 | 12.2 | 11.6 | 12.5 |
| D.I.[1] | 59.8 | 59.0 | 62.5 | 62.7 | 65.3 | 71.1 | 66.3 | 69.2 |

Table 2.--Continued

Modal analysis (volume percent)

| Sample No. | 26-23 | 20-12 | 22-16 | 22-10 | 22-13 | 266 | 265 | 20-14 |
|---|---|---|---|---|---|---|---|---|
| Quartz | 11.6 | 21.3 | 14.6 | 16.8 |  | 19.5 | 15.5 | 21.7 |
| K-fledspar | 24.0 | 34.3 | 19.0 | 19.7 |  | 16.5 | 15.1 | 9.2 |
| Plagioclase | 46.0 | 30.9 | 43.7 | 45.9 |  | 48.9 | 50.9 | 48.6 |
| Biotite | --- | 6.5 | 5.3 | 3.3 |  | 13.2 | 16.5 | 18.5 |
| Amphibole | 16.0 | 4.3 | 14.6 | 11.9 |  | --- | --- | --- |
| Opaque | 2.4 | 2.6 | 2.0 | 2.5 |  | 1.1 | 1.1 | .8 |
| Accessories[2] | --- | --- | .8 | --- |  | .8 | 1.0 | 1.2 |
| Femics | 18 | 14 | 22 | 18 |  | 18. | 18. | 20. |
| Minor element analyses (parts per million) |  |  |  |  |  |  |  |  |
| Ag | --- | --- | --- | --- | 2. | --- | --- | 1.5 |
| Au | --- | .09 | .3 | .1 | 3.9 | --- | --- | .5 |
| Ba | 1,650 | 1,500 | 1,600 | 1,550 | 1,600. | --- | --- | 1,300. |
| Co | 10 | 7 | 15 | 15 | 15. | 7. | 7. | 10. |
| Cr | 150 | 100 | 150 | 70 | 70. | 20. | 30. | 50. |
| Cu | 13 | 95 | 65 | 70 | 2,000. | 300. | 300. | 1,490. |
| Hg (PPB) | 27 | 27 | 19 | 4 | 34. | N.d. | N.d. | 24. |
| La | 50 | 70 | 70 | 100 | 150. | 50. | 50. | 100. |
| Mo | --- | 7 | 7 | 5 | --- | 7. | 10. | 3. |
| Ni | 30 | 30 | 50 | 30 | 50. | 10. | 10. | 15. |
| Pb | 95 | 35 | 23 | 61 | 19. | 20. | 20. | 64. |
| Rb | 64 | 72 | 98 | 73 | 103. | --- | --- | 62. |
| Sc | 15 | 15 | 15 | 15 | 10. | 7. | 7. | 10. |
| Sr | 810 | 855 | 730 | 820 | 760. | --- | --- | 880. |
| V | 100 | 100 | 70 | 100 | 100. | 50. | 50. | 70. |
| Y | 15 | 20 | 15 | 20 | 15. | 10. | 10. | 15. |
| Zn | 130 | 83 | 140 | 89 | 79. | N.d. | N.d. | 180. |
| Zr | 100 | 100 | 200 | 150 | 150. | 150. | 150. | 150. |

Table 2.--Continued

| | Ontario porphyry stock | | | | Felsic stringers | | |
|---|---|---|---|---|---|---|---|
| Sample No. | 28-7 | 30-1 | 30-8 | UP-51 | 26-16 | 22-19 | 30-7 |
| $SiO_2$ | 63.5 | 64.5 | 68.3 | 76.1 | 56.8 | 65.8 | 75.6 |
| $Al_2O_3$ | 16.5 | 16.2 | 15.7 | 12.4 | 13.5 | 14.6 | 12.8 |
| $Fe_2O_3$ | 1.5 | 1.4 | 1.4 | .60 | 1.5 | 1.6 | .52 |
| FeO | 2.5 | 2.1 | .96 | .16 | 3.5 | 1.8 | .44 |
| MgO | 2.3 | 2.0 | 1.0 | .19 | 5.6 | 1.8 | .10 |
| CaO | 4.1 | 4.0 | 3.0 | 1.4 | 5.1 | 1.9 | .60 |
| $Na_2O$ | 3.2 | 3.3 | 3.3 | 2.0 | 1.6 | 1.7 | 2.8 |
| $K_2O$ | 2.7 | 2.9 | 3.8 | 6.0 | 7.3 | 5.8 | 5.8 |
| $H_2O(+)$ | 1.5 | 1.5 | 1.0 | .33 | 1.3 | 2.1 | .37 |
| $H_2O(-)$ | .26 | .13 | .12 | .22 | .84 | .69 | .07 |
| $TiO_2$ | .58 | .58 | .37 | .23 | 1.3 | .46 | .11 |
| $P_2O_5$ | .26 | .24 | .12 | .02 | .73 | .16 | --- |
| MnO | .06 | .12 | .02 | --- | .13 | .33 | --- |
| $CO_2$ | .18 | .11 | --- | --- | .10 | .34 | .65 |
| S, total | .70 | .36 | 1.03 | --- | .10 | .71 | --- |
| F | .09 | .06 | .02 | .01 | .35 | .05 | .02 |
| Cl | | | | | | | |
| Total | 99 | 99 | 99 | 100 | 99 | 99 | 99 |

CIPW norms (weight percent)

| | 28-7 | 30-1 | 30-8 | UP-51 | 26-16 | 22-19 | 30-7 |
|---|---|---|---|---|---|---|---|
| Quartz | 23.15 | 23.23 | 27.13 | 38.52 | 3.75 | 28.42 | 36.02 |
| Corundum | 1.90 | 1.20 | .93 | .14 | --- | 3.27 | .95 |
| Orthoclase | 16.00 | 17.26 | 22.66 | 35.66 | 43.79 | 34.58 | 34.55 |
| Albite | 27.15 | 28.12 | 28.17 | 17.02 | 13.74 | 14.52 | 23.89 |
| Amorthite | 17.55 | 17.70 | 14.41 | 6.79 | 8.22 | 6.29 | 2.68 |
| Wollastonite | --- | --- | --- | --- | 5.14 | --- | --- |
| Enstatite | 5.74 | 5.02 | 2.51 | .48 | 14.16 | 4.52 | .25 |
| Ferrosilite | 1.06 | 1.23 | .03 | --- | 3.12 | .38 | .20 |
| Magnetite | 2.33 | 2.04 | 2.05 | [4] | 2.21 | 2.04 | .76 |
| Ilmenite | 1.11 | 1.11 | .71 | .34 | 2.51 | .88 | .21 |
| Pyrite | 1.31 | .68 | [3] | --- | .19 | 1.34 | [3] |
| Apatite | .62 | .57 | .29 | .05 | 1.76 | .38 | --- |
| Fluorite | --- | --- | --- | --- | --- | --- | --- |
| Calcite | .41 | .25 | --- | --- | --- | .78 | --- |
| Total | 98 | 98 | 99 | 100 | 99 | 98 | 100 |
| Femic | 12.6 | 10.9 | 5.7 | 1.5 | 29.2 | 10.6 | 1.5 |
| D.I.[1] | 66.3 | 68.6 | 77.9 | 91.2 | 61.3 | 77.5 | 94.5 |

Table 2.--Continued

Modal analyses (volume percent)

| Sample No. | 28-7 | 30-1 | 30-8 | UP-51 | 26-16 | 22-19 | 30-7 |
|---|---|---|---|---|---|---|---|
| Quartz | 19.9 | 29.5 | 24.7 | 34.5 | 10.6 | 24.8 | |
| K-feldspar | 13.4 | 16.1 | 32.1 | 46.0 | 43.8 | 27.5 | |
| Plagioclase | 47.1 | 40.6 | 34.1 | 16.5 | 12.4 | 40.8 | |
| Biotite | 15.3 | 10. | 7.1 | --- | 11.9 | 4.2 | |
| Amphibole | --- | --- | --- | 1.5 | 18.1 | 1.5 | |
| Opaque | 1.5 | 1.1 | .7 | .8 | 1.8 | 1.1 | |
| Accessories[2] | 2.7 | 2.7 | 1.4 | .8 | 1.3 | --- | |
| Femic | 16. | 11. | 8. | 2. | 32. | 7. | |
| Minor element analyses (parts per million) | | | | | | | |
| Ag | --- | --- | --- | --- | --- | 1.5 | --- |
| Au | .09 | --- | --- | N.d. | .2 | --- | --- |
| Ba | 1,100. | 2,150. | 1,850. | --- | 2,700. | 4,400. | 880. |
| Co | 5. | 7. | 2. | --- | 15. | 10. | 2. |
| Cr | 20. | 20. | 10. | --- | 300. | 20. | 1.5 |
| Cu | 22. | 8. | 23. | 15. | 290. | 150. | 14. |
| Hg (PPB) | 25. | 20. | 15. | N.d. | 11. | 26. | 23. |
| La | 70. | 70. | 50. | --- | 150. | 70. | 50. |
| Mo | --- | --- | 15. | --- | --- | 10. | 15. |
| Ni | 10. | 10. | 10. | --- | 150. | 10. | 2. |
| Pb | 22. | 92. | 16. | 70. | 19. | 280. | 19. |
| Rb | 79. | 69. | 54. | --- | 181. | 147. | 113. |
| Sc | 10. | 7. | 5. | 2. | 15. | 10. | --- |
| Sr | 615. | 660. | 670. | --- | 680. | 430. | 157. |
| V | 70. | 70. | 30. | --- | 100. | 50. | 7. |
| Y | 15. | 15. | 10. | 10. | 20. | 20. | 20. |
| Zn | 83. | 58. | 18. | N.d. | 85. | 240. | 14. |
| Zr | 100. | 100. | 70. | 70. | 500. | 100. | 70. |

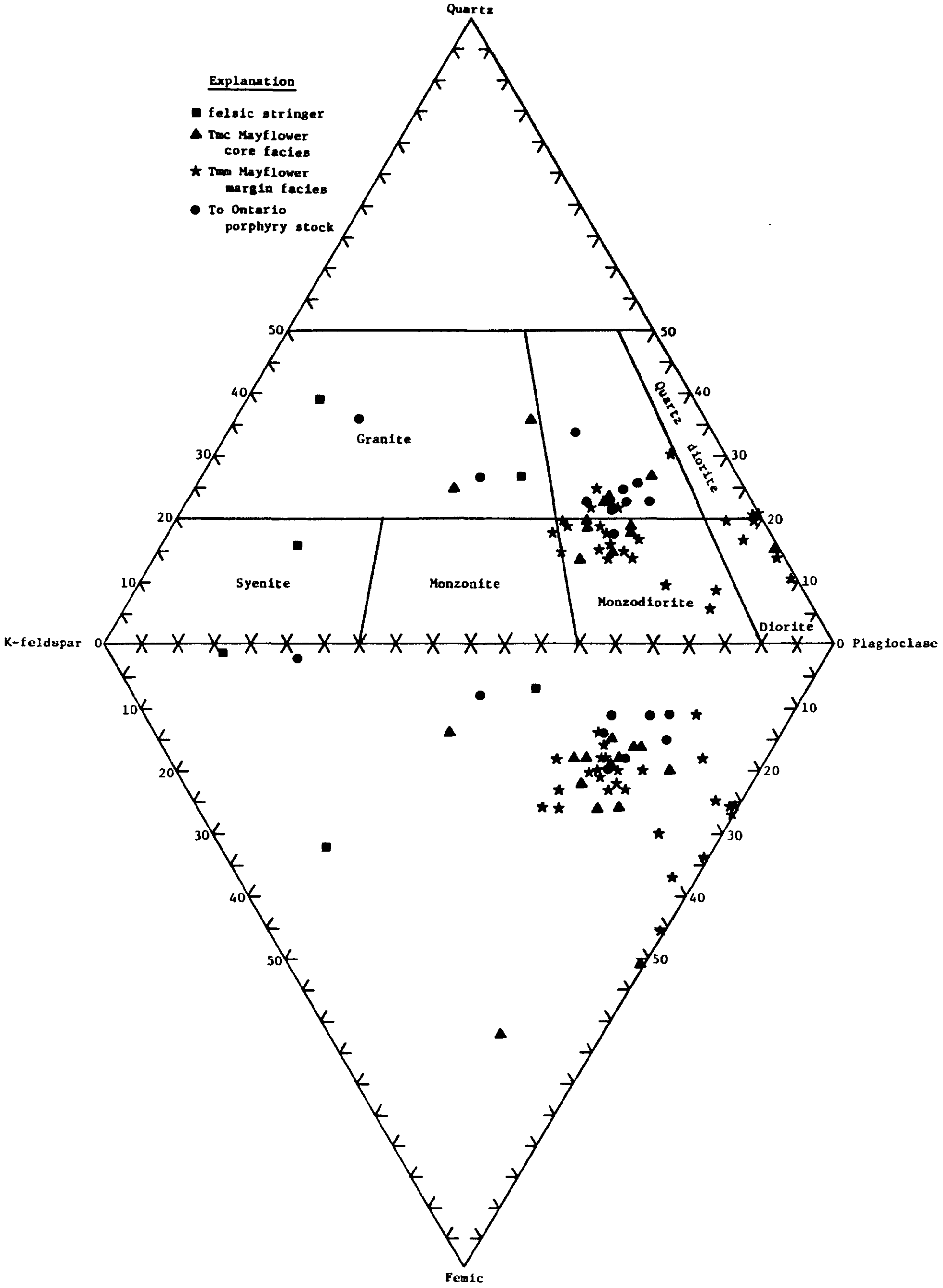

Figure 5.--Modal mineralogical composition of 53 igneous rocks from the Mayflower mine (classification is that of Strekweissen, 1976).

closely spaced samples (fig. 6). The local variation in D.I., from 50.2 to 64.0 in the margin facies and 59.0 to 71.1 in the core facies of the Mayflower porphyry stock is considered to be large.

The felsic stringers are diverse chemically and mineralogically, and only locally do some have the composition of aplite (No. 30-7, table 2). Some have pink color, sucrose texture, and fill erratic discontinuous spaces. Others are darker colored from abundant biotite and amphibole, which commonly are alined in a flow fabric, and have corresponding mafic composition (e.g. No. 26-16, table 2). The latter have gradational contacts, rare phenocrysts, and have textures resembling the matrix of nearby porphyritic rocks. Their composition and structure may have originated by shear during crystallization (Willshire, 1969).

Calculated normative mineral compositions from chemical analyses (table 2) show differences in composition that are not obvious in the chemical data. Excess aluminum and calcium is reflected in normative corundum or wollastonite. Normative corundum correlates positively with modal biotite, and normative wollastonite with modal amphibole. The norms vary less than modes, chiefly because the hydrous phases biotite and amphibole are not calculated and all potassium is allocated to orthoclase. Consequently, ternary ratios of normative felsic constituents are shifted toward orthoclase and no samples are classified as diorite (compare figs. 5 and 7).

## Statistical tests on petrochemical data

Petrochemical data from table 2 was subjected to several statistical tests to evaluate relationships between compositional variables and rock types. These tests considered 24 samples described by 28 variables consisting of 16 major element, 8 modal and 4 normative mineral values. It was known *a priori* that many of the variables were redundant. Relations between the 28 variables were tested using R-mode factor analysis. Data grouped according to the four rock types of table 1 were tested by Q-mode factor analysis and cluster analysis to evaluate variation within and between groups.

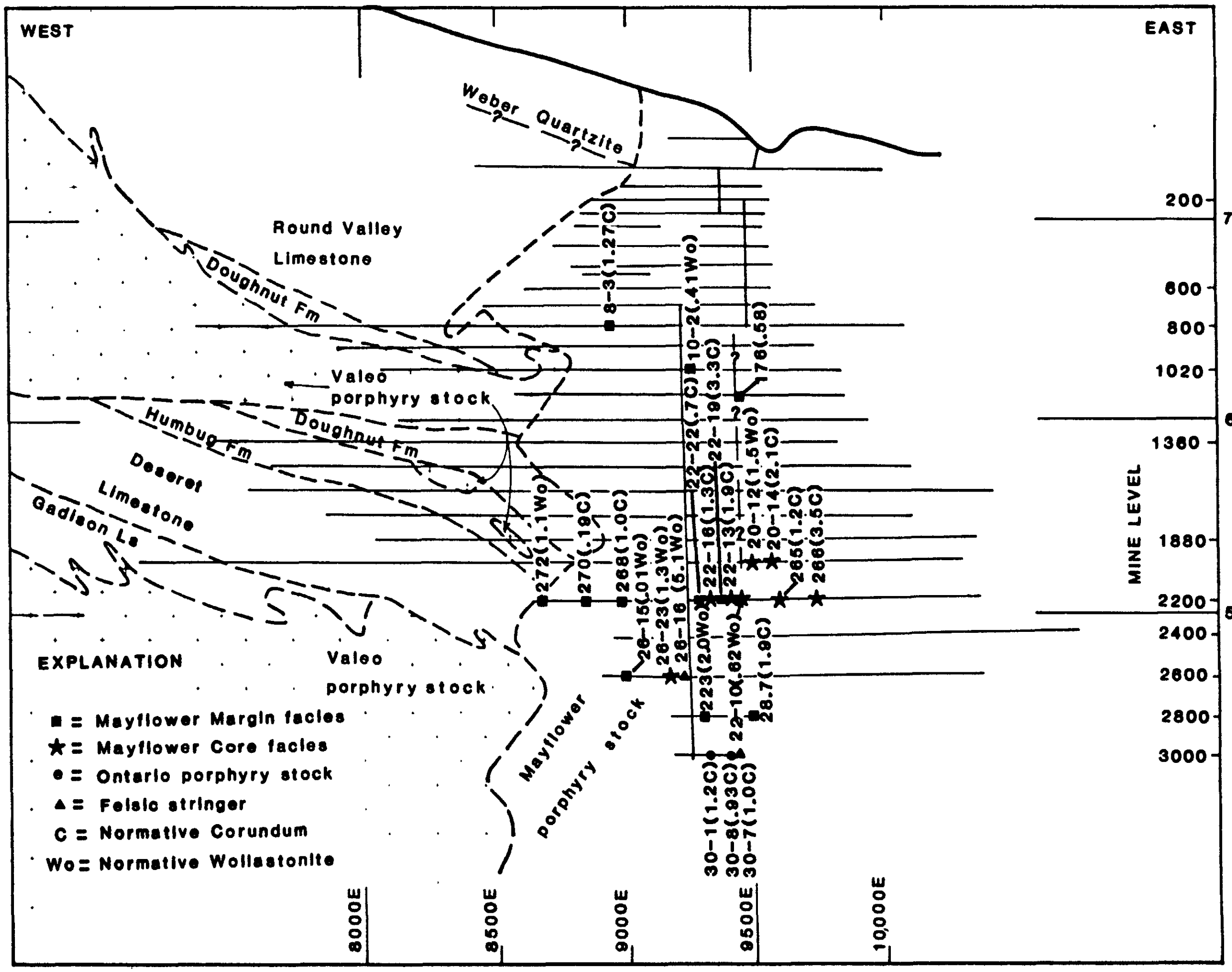

Figure 6.--Generalized logitudial section of the Mayflower mine showing location of analyzed samples. Numbers in parentheses indicate content of normative corundum (C) or wollastonite (Wo).

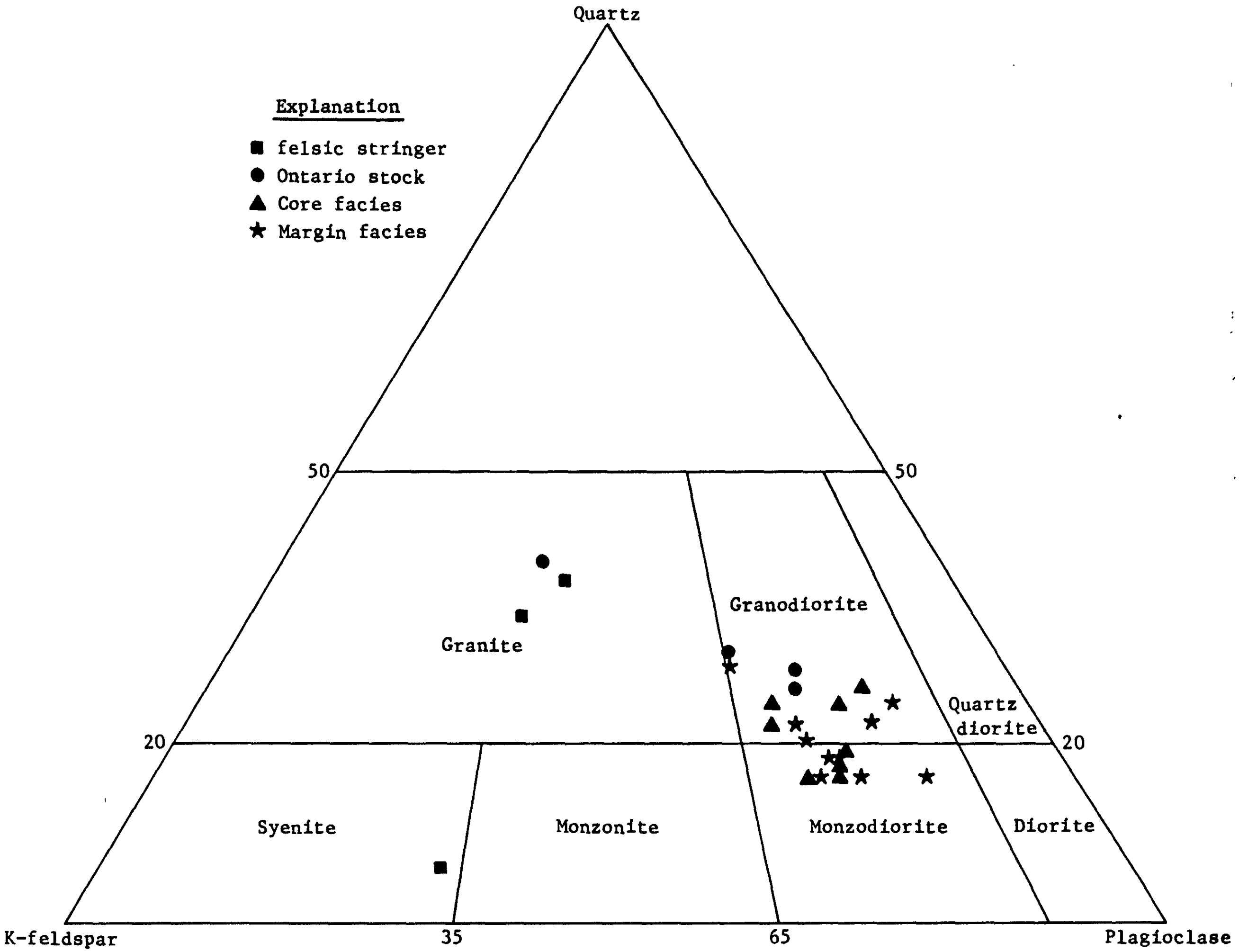

Figure 7.--Normative composition of 24 igneous rocks from the Mayflower mine calculated from chemical analyses in table 1.

## Relations between variables

Factor analysis in the R-mode (Krumbein and Graybill, 1965; Harbaugh and Merriam, 1968) has been employed to search the 28 x 28 correlation matrix of petrochemical variables for fundamental interrelationships. Although statistical tests indicate that 12 factors are significant at the 95-percent confidence level and that nine factors would be required to convey 95 percent of the information, three factors show relations much more simply and still carry 72 percent of the information. The communalities of 23 variables are greater than 0.6, hence there is not severe distortion or loss of information for these individual variables when projected onto three factor vectors. The five other variables, such as $CO_2$ and $H_2O+$, are independent and require their own factor to obtain a high communality. A simplified version of the rotated oblique R-mode factor matrix is in table 3. The three factors point out strong compositional-mineralogical relations not apparent *a priori*. Factor 1, with amphibole as its end member, carries major information for 17 variables, of which 13 are "mafic" in character. Factor 1 also contains large negative loadings for quartz, $SiO_2$, and normative corundum. Factor 2 is chiefly represented by feldspar. The contrasting loadings of $K_2O$, orthoclase, quartz, and $SiO_2$ compared with $Na_2O$, $Ca_2O$, $Al_2O_3$, and plagioclase are as expected in magmatic differentiation. The loadings of FeO and $Fe_2O_3$ with the "plagioclase group" of variables probably reflects similar controls by original magma compositions. Factor 3, with modal biotite as its end member, carries accessories (chiefly anhydrite), total sulfur, and chlorine, and negative loadings of amphibole, MnO and $CO_2$. The group on factor 3 suggests that rock compositions or geochemical processes favorable for biotite formation also were important for anhydrite and sulfide minerals; this may in part reflect hydrothermal activity, which will be considered later. Factor analysis points out three features which bear on the occurrence of amphibole and biotite: amphibole-rich rocks are rich in fluorine, iron oxides, and normative wollastonite; whereas, biotite-rich rocks are characterized by chlorine, iron sulfides, and normative corundum. Amphibole in these rocks is much richer in $SiO_2$ than biotite, as will be described ahead; atomic Si/Al is about 11 in amphibole and about 2.3 in biotite. Crystallization of amphibole and biotite in these rocks apparently is very sensitive to compositional variables Si, Al, Ca, K, F, and Cl, some of which were mobile in postmagmatic fluids.

Table 3.--R-mode factor matrix of petrochemical data
[Data for 28 variables from table 1. Factor loadings represented as: ++, 1.0 to 0.75; +, 0.74 to 0.50; -, -0.50 to -0.74; --, -0.75 to -1.0]

| Variable | Factor | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Amphibole | ++ | | -- |
| $TiO_2$ | ++ | | |
| $P_2O_5$ | ++ | | |
| MgO | ++ | | |
| Ferrosilite | ++ | | |
| FeO | ++ | - | |
| Femics | ++ | | |
| CaO | ++ | - | |
| F | ++ | + | |
| Wollastonite | ++ | + | |
| Opaques | + | - | - |
| Enstatite | | | |
| Corundum | - | + | + |
| Quartz | -- | + | |
| $SiO_2$ | -- | + | |
| $K_2O$ | | ++ | |
| Orthoclase | | ++ | |
| $H_2O^+$ | | | |
| $Na_2O$ | | -- | |
| $Fe_2O_3$ | + | -- | - |
| Plagioclase | | -- | |
| $Al_2O_3$ | | -- | |
| Biotite | | | ++ |
| Accessories | | | ++ |
| S | - | | ++ |
| Cl | | | + |
| MnO | + | | - |
| $CO_2$ | | | - |

## Relations between samples

Factor and cluster analyses in the Q-mode were made to test the sample classification used in geologic mapping. Factor analysis of the 24 x 24 sample correlation matrix demonstrated that only three factors are needed to convey 94 percent of the information. Twenty samples are carried on the first vector because of their great similarity and two samples are carried on each of the second and third vectors. In this situation cluster analysis (Parks, 1966; Harbaugh and Merriam, 1968; Obial and James, 1973) provides a highly simplified version of the correlation matrix that is relatively free from distortion. In the cluster analysis data were normalized to give equal weight to all variables, and the correlation coefficient (r) is used as a measure of similarity. Four clusters of samples are apparent on the dendritic diagram (fig. 8) resulting from cluster analysis; only positive associations are shown. Cluster A contains nine samples, of which six are margin facies and three are core facies rocks of the Mayflower porphyry stock. Cluster B contains ten samples, of which five are from the core facies, three are from the margin facies, and two are from the Ontario porphyry stock. Cluster C contains only one sample--the mafic aplitic dike with extreme chemical and modal composition. Cluster D represents four felsic rocks from the Ontario porphyry stock and aplite dikes. Linkages between samples at various levels of r show the degree of similarity, from close (e. g., samples of porphyry from the Ontario stock 30-1 and 28-7, at $r = 0.9$) to divergent (e. g., sample 26-16 and the majority of porphyry samples from the Mayflower stock, at $r = 0.3$). The clusters reflect compositional similarity. Cluster A consists of rocks which are relatively calcic but low in silica, hence most have normative wollastonite. Rocks in cluster B are relatively more alkalic and most have normative corundum. The one sample in cluster C is uniquely rich in mafic constituents. Cluster D consists of the most silicic-alkalic samples. Cluster D does not correlate positively with the others, which is consistent with its formation by fractionation. The mixing of rock units in clusters A, B, and D does not necessarily imply that some samples have been misclassified; rather it demonstrates the large within-group compositional variation.

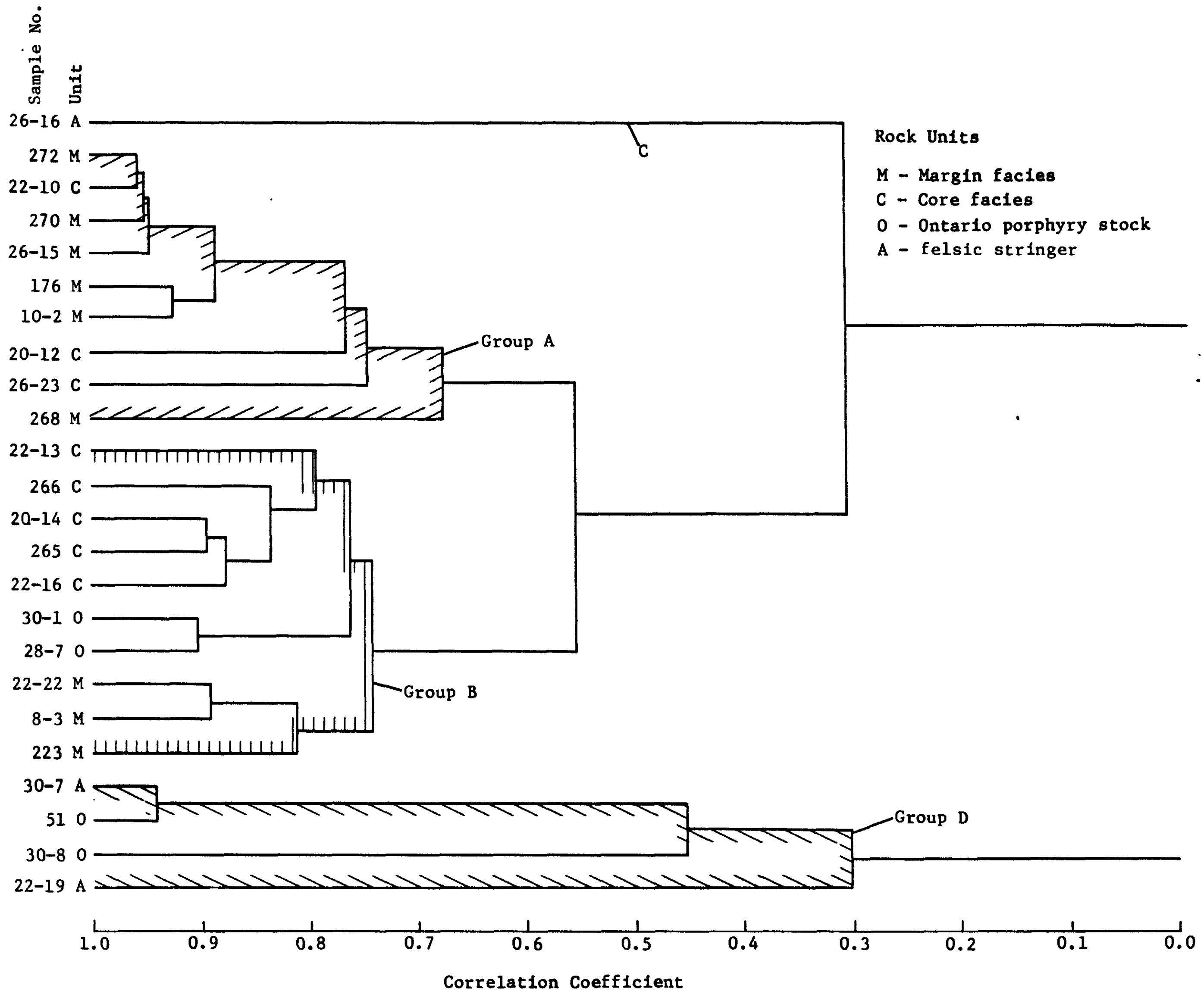

Figure 8.--Dendritic diagram showing correlation coefficients from cluster analysis of petrochemical data for unaltered rocks.

## MINERAL RELATIONS AND CHEMISTRY

### Plagioclase

Plagioclase phenocrysts in these porphyritic rocks are characteristically zoned, and some are mantled by sodic plagioclase. Partial microprobe analyses confirm the zonation observed optically; compositions commonly oscillate by 20 percent An. Phenocrysts tend to have cores near $An_{50}$ but some are as calcic as $An_{61}$; intermediate growth zones tend to be in the range $An_{50}$ to $An_{30}$ and rims are as sodic as $An_{17}$ in the crystals analyzed. Smaller plagioclase crystals in the matrix have compositions in the range $An_{25}$-$An_{33}$, generally overlapping the range of outer zones of phenocrysts from the same rock. The substitution of potassium is relatively consistent, equivalent to approximately $Or_{1.5}$, and there is less than 0.1 percent BaO. Systematic differences in plagioclase compositions between the several intrusive and textural facies cannot be documented from the analyses made on 12 samples. There are some suggestions that plagioclase from rocks near sedimentary wall rocks may be slightly more calcic, but the variation within crystals is much larger than between different rock types. The oscillatory zonation is generally interpreted in terms of variations in temperature or water pressure in the ascending magma, but this will not be considered further.

### Potassium feldspar

Potassium-feldspars in porphyritic rocks of the Mayflower mine occur only in the matrix. Some relatively large grains (>1/4 mm) contain optically detectable microperthite. No Carlsbad or microcline-grid twinning has been observed. Microprobe analyses of seven samples indicate compositions in the range $Or_{75}$ to $Or_{85}$, and 0.6 to 0.9 wt percent Ba (table 4). X-ray studies were made of K-feldspar separated from eight rocks using the suggestions of Wright and Stewart (1968), including least squares cell refinement. Calculated cell parameters are in table 4. No efforts were made to obtain "original bulk compositions" by homogenizing the mineral separates because perthitic albite probably was lost during the density separations--hence annealed compositions would be more potassic than original. The original compositions presumably were more sodic than given here ($\sim Or_{70}$?).

Table 4A.--Structural state and composition of K-feldspars

| Sample | Lithology[1] | Cell parameter in Å a | b | c | B | V | Comp. wt % Or[2] | No. lines used |
|---|---|---|---|---|---|---|---|---|
| 239 | To | 8.566 | 12.985 | 7.191 | 116° 1.04' | 718.876 | 84.5 | 19 |
| 28-1 | To | 8.565 | 12.991 | 7.196 | 116° 2.94' | 719.378 | 85.6 | 20 |
| 26-24 | To | 8.563 | 12.991 | 7.196 | 116° 1.51' | 719.334 | 85.5 | 20 |
| 28-8 | To | 8.581 | 12.991 | 7.192 | 116° 3.93' | 720.180 | 87.5 | 19 |
| 20-12 | Tf | 8.579 | 12.985 | 7.194 | 116° 1.64' | 720.141 | 87.4 | 17 |
| 241 | Tmc | 8.553 | 13.000 | 7.191 | 115°57.66' | 718.860 | 84.5 | 14 |
| 261 | Tmm | 8.556 | 12.990 | 7.194 | 116° 2.65' | 718.433 | 83.5 | 21 |
| 272 | Tmm | 8.556 | 12.982 | 7.189 | 116° 0.26' | 717.734 | 81.9 | 23 |

[1] Lithology: To = Ontario porphyry stock; Tf = felsic stringer; Tmc and Tmm = Mayflower porphyry stock, core and margin facies

[2] Based on cell volume and chemically determined compositions in Wright and Steward (1968, Table 7).

Table 4B.--Microprobe analyses of orthoclase
[Structural formulas based on 32 oxygen atoms]

| Sample no. | 8-8 Matrix | 30-3 Perthitic | 28-1 Granophyric |
|---|---|---|---|
| $SiO_2$ | 64.9 | 65.0 | 64.3 |
| $Al_2O_3$ | 18.0 | 18.2 | 18.4 |
| $Fe_2O_3$ | .05 | .01 | .12 |
| MgO | .01 | .00 | .01 |
| CaO | .03 | .02 | .07 |
| BaO | .49 | .95 | 1.56 |
| $Na_2O$ | .99 | 1.22 | 2.11 |
| $K_2O$ | 15.4 | 15.0 | 14.3 |
| Total | 99.9 | 100.4 | 100.9 |
| Structural formula | | | |
| Si | 12.02 | 11.98 | 12.01 |
| Al | 3.94 | 3.96 | 4.05 |
| $Fe^{+3}$ | .02 | ------ | .02 |
| $\Sigma$iv | 15.98 | 15.94 | 16.08 |
| CaO | .00 | .00 | .01 |
| BaO | .04 | .07 | .12 |
| NaO | .36 | .43 | .38 |
| K O | 3.60 | 3.54 | 3.41 |
| $\Sigma$xii | 4.00 | 4.04 | 3.92 |

The structural state determinations (table 4) indicate that the K-feldspar is orthoclase. The (131) peak is not split, hence the phase is not monoclinic. For the compositions determined by microprobe, the cell volume is closest to the orthoclase series, specifically the P50-56 series of Wright and Stewart (1968). The small variations within the data (table 4) do not appear to correlate with rock type or location. For instance, cell volumes are the same for extremely fine grained K-feldspar of Mayflower core facies (sample 241) and for much coarser K-feldspar from the Ontario porphyry stock (sample 239). Potassium feldspars from porphyritic intrusives of Ely, Nevada (Fournier, 1967) have similar structural ratios to those reported here.

## Biotite

Three types of biotite occur in igneous rocks of the Mayflower mine: (1) phenocrysts, commonly euhedral, up to 4 mm in diameter; (2) aggregates of fine shreddy flakes, pseudomorphous after amphibole, and occasionally after biotite phenocrysts; and (3) fine shreds in the matrix. Types 2 and 3 are not primary and probably formed by subsolidus hydrothermal reactions. Optically, all three types have similar pleochroic colors (honey yellow to medium brown), but biotite in some heavily pyritized and argillically altered rocks is more reddish.

About 90 microprobe analyses were made of primary biotite occurring in 16 samples to determine variations in composition. Analyses of primary biotite are in table 5; locations are shown in figure 9. Analyses of secondary biotites will be presented elsewhere. The biotite analyses in table 5 are of phenocrysts in eight rocks which are texturally fresh and contain magnetite, and only minor pyrite; amphibole is present in many samples. The ratio Fe:Fe+Mg+Mn also has been used to screen data: biotites which are judged to have retained their original compositions have values in the range 0.39 to 0.30, whereas texturally secondary or recrystallized biotites have values lower than 0.30.

Important chemical constituents that cannot be distinguished by microprobe are lithium, $H_2O^+$ or $OH^-$, and ferrous and ferric iron. Fluorine and chlorine contents were not determined because of their estimated low concentration and poor precision in microprobe analysis. These constituents were determined by wet chemical methods on mineral separates of two samples of primary biotite. The wet chemical analyses indicated 0.30 and 0.15 weight

Table 5.--Microprobe analyses and formula of primary biotite

| Sample No. | 181b | 30-1n | 28-7a | 176a | 126a | 26-16a | 26-16b | 123a |
|---|---|---|---|---|---|---|---|---|
| Unit[1] | Tmm | To | To | Tmm | To | Tf | Tf | Tf |
| $SiO_2$ | 38.7 | 37.5 | 37.8 | 37.6 | 37.5 | 38.7 | 39.0 | 38.3 |
| $Al_2O_3$ | 13.4 | 13.8 | 14.7 | 13.6 | 14.7 | 12.9 | 12.9 | 15.0 |
| $TiO_2$ | 3.87 | 4.48 | 4.08 | 3.75 | 4.49 | 2.99 | 3.06 | 3.23 |
| $Fe_2O_3$ | --- | --- | --- | --- | --- | --- | --- | --- |
| FeO | 15.1 | 15.2 | 15.3 | 15.4 | 14.1 | 14.5 | 13.7 | 13.0 |
| MgO | 14.4 | 14.0 | 14.0 | 14.4 | 14.5 | 16.1 | 16.3 | 15.8 |
| MnO | .26 | .23 | .28 | .23 | .08 | .22 | .10 | .13 |
| CaO | .08 | .10 | .12 | .11 | --- | .07 | .03 | .01 |
| $Na_2O$ | .10 | .16 | .11 | .13 | .25 | .07 | .15 | .21 |
| $K_2O$ | 9.56 | 9.44 | 9.16 | 9.85 | 9.29 | 9.84 | 10.10 | 9.51 |
| Total | 95.5 | 94.9 | 95.5 | 95.1 | 94.9 | 95.4 | 95.3 | 95.2 |
| Si | 5.77 | 5.64 | 5.62 | 5.67 | 5.59 | 5.78 | 5.80 | 5.66 |
| Al | 2.23 | 2.36 | 2.38 | 2.33 | 2.41 | 2.22 | 2.20 | 2.34 |
| ΣIV | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Al | .13 | .09 | .21 | .09 | .18 | .05 | .07 | .28 |
| Ti | .43 | .51 | .46 | .43 | .50 | .34 | .34 | .36 |
| $Fe^{+3}$ | --- | --- | --- | --- | --- | --- | --- | --- |
| $Fe^{+2}$ | 1.88 | 1.91 | 1.90 | 1.94 | 1.76 | 1.81 | 1.70 | 1.61 |
| Mg | 3.20 | 3.14 | 3.12 | 3.22 | 3.23 | 3.57 | 3.62 | 3.48 |
| Mn | .03 | .03 | .04 | .03 | .01 | .03 | .01 | .02 |
| ΣVI | 5.67 | 5.69 | 5.72 | 5.61 | 5.68 | 5.80 | 5.74 | 5.75 |
| K | 1.82 | 1.81 | 1.74 | 1.90 | 1.77 | 1.87 | 1.92 | 1.79 |
| Na | .03 | .05 | .03 | .04 | .07 | .02 | .04 | .06 |
| Ca | .01 | .02 | .02 | .02 | ----- | .01 | ----- | ----- |
| ΣXII | 1.86 | 1.88 | 1.79 | 1.96 | 1.85 | 1.90 | 1.96 | 1.85 |
| $\frac{Fe}{Fe+Mg+Mn}$ | .368 | .376 | .376 | .373 | .315 | .334 | .319 | .315 |

---

[1] Unit abbreviations: To, Ontario porphyry; Tmm, Mayflower porphyry margin facies; Tf, felsic stringer.

Table 5.--Microprobe analyses and formula of primary biotite (continued)

| Sample No. | D991a | 176b | 26-10a | 28-7B | 30-36 | 123d | D991f |
|---|---|---|---|---|---|---|---|
| Unit[1] | Tmm | Tmm | Tmm | To | To | Tf | Tmm |
| SiO | 37.6 | 37.5 | 38.2 | 38.8 | 37.3 | 37.9 | 38.9 |
| $Al_2O_3$ | 14.6 | 13.8 | 13.0 | 14.0 | 14.2 | 15.1 | 14.2 |
| $TiO_2$ | 3.83 | 3.47 | 3.81 | 3.38 | 4.14 | 4.29 | 3.51 |
| $Fe_2O_3$ | --- | | | | | | |
| FeO | 12.8 | 15.6 | 14.7 | 13.4 | 15.4 | 13.4 | 12.8 |
| MgO | 16.3 | 14.6 | 14.8 | 15.0 | 13.5 | 15.0 | 16.0 |
| MnO | .13 | .36 | .29 | .28 | .21 | .10 | .12 |
| CaO | --- | .11 | .11 | .12 | .06 | .04 | .06 |
| $Na_2O$ | .18 | .08 | .11 | .11 | .22 | .20 | .15 |
| $K_2O$ | 9.59 | 9.55 | 9.30 | 9.33 | 9.55 | 9.18 | 9.24 |
| Total | 95.0 | 95.06 | 94.32 | 94.49 | 94.63 | 95.08 | 94.97 |
| Si | 5.58 | 5.65 | 5.76 | 5.79 | 5.64 | 5.61 | 5.75 |
| Al | 2.42 | 2.35 | 2.24 | 2.21 | 2.36 | 2.39 | 2.25 |
| ΣIV | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Al | .14 | .10 | .07 | .25 | .17 | .24 | .23 |
| Ti | .43 | .39 | .43 | .38 | .47 | .48 | .39 |
| $Fe^{+3}$ | --- | | | | | | |
| $Fe^{+2}$ | 1.59 | 1.97 | 1.85 | 1.68 | 1.95 | 1.66 | 1.59 |
| Mg | 3.60 | 3.28 | 3.33 | 3.34 | 3.04 | 3.30 | 3.51 |
| Mn | .02 | .05 | .04 | .04 | .03 | .01 | .02 |
| ΣVI | 5.78 | 5.79 | 5.72 | 5.69 | 5.66 | 5.69 | 5.74 |
| K | 1.82 | 1.84 | 1.79 | 1.78 | 1.84 | 1.74 | 1.74 |
| Na | .05 | .02 | .03 | .03 | .06 | .06 | .04 |
| Ca | ----- | .02 | .02 | .02 | .01 | .01 | .01 |
| ΣXII | 1.87 | 1.88 | 1.84 | 1.83 | 1.92 | 1.81 | 1.79 |
| $\frac{Fe}{Fe+Mg+Mn}$ | .305 | .372 | .355 | .332 | .389 | .334 | .310 |

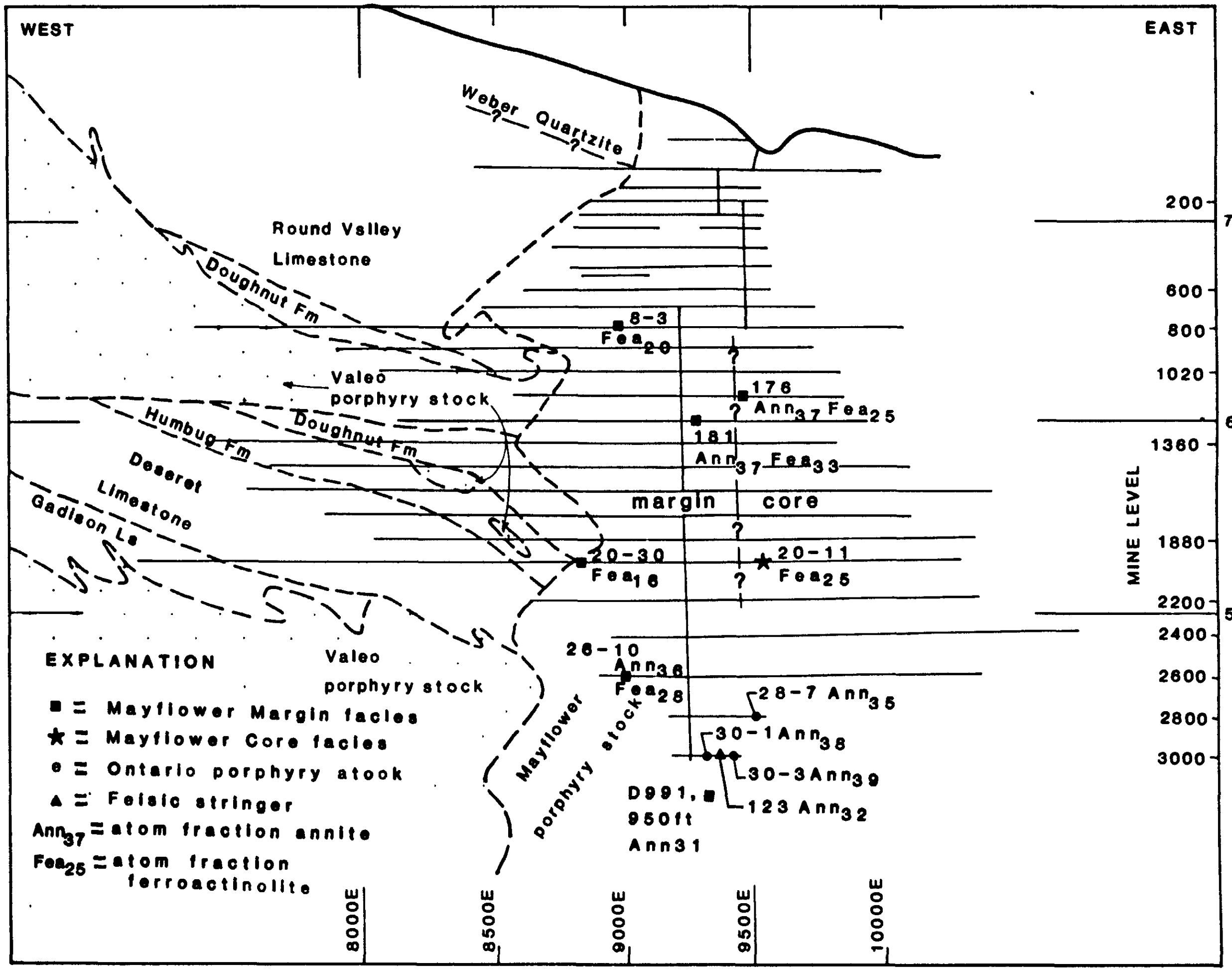

Figure 9.--Locations and compositions of analyzed primary biotite and amphibole.

percent Cl; 0.49 and 0.41 wt percent F; less than 0.05 wt percent $Li_2O$; and $Fe^{+3}:Fe^{+2}+Fe^{+3}$ 0.111 and 0.124. These values are not necessarily representative of all primary biotite of igneous rocks in the mine or to those in table 5, but will serve as approximations.

Structural formulas in table 5 have been calculated by the method of oxygen equivalents, as used by Foster (1960), in which 22 oxygen atoms or 44 anion charges per cell are assumed. The full cell is employed here, rather than half cell (cf., Foster, 1960), in which biotite has the general formula $K_2\ (R^{+2}, R^{+3})_6\ (R^{+3}, Si)_8O_{20}(OH)_4$, in which divalent cations $Fe^{+2}$, $Mg^{+2}$, or $Mn^{+2}$ substitute in $R^{+2}$ octahedral sites and $Al^{+3}$ and $Fe^{+3}$ substitute for $R^{+3}$; $Ti^{+4}$ and $Li^{+2}$ occupy octahedral sites. Because the wet chemical determinations of $Fe^{+2}:Fe^{+3}$, Cl, and F may not be generally representative, all iron has been calculated as FeO and no anions are considered in table 5. Calculations with these approximations yield satisfactory, albeit incomplete formulas. All primary biotite contains sufficient Al to fill the tetrahedral layer and occupy a small number of octahedral sites. $TiO_2$ contents range from 4.49 to 2.99 weight percent or 0.51 to 0.34 of six octahedral sites. Although significant differences occur in the bulk titanium content of the igneous rock units, no corresponding variation is evident in titanium content in analyzed biotites. Iron and magnesium contents vary inversely and are relatively uniform: 1.37 to 1.97 positions $Fe^{+2}$ and 3.62 to 3.04 positions $Mg^{+2}$. Only a small amount of manganese is present (0.36 to 0.08 percent), and low values near 0.10 percent are suspected to reflect subsolidus alteration. The low octahedral occupancy, generally about 5.7 of six sites, appears to be largely real but could in part reflect the method of formula calculation (see ahead). Although failure to analyze lithium can produce low totals of octahedral cations (Foster, 1960), the low lithium concentrations determined by wet chemical methods on representative biotite samples suggest only about 0.02 $Li^{+1}$ cations in octahedral sites. Calcium and sodium substitution for potassium in interlayer positions is small; sodium content is somewhat higher in primary biotite from the Ontario porphyry stock and from a felsic stringer. Hydroxyl sites appear to be mainly filled by $OH^-$ since F and Cl analyses of two primary biotites indicate about 0.21 F and 0.06 Cl atoms in the four sites.

The amount of ferric iron in biotite, which determines the amount of oxyannite molecule (K $Fe^{+2}$ $Fe^{+3}$ Al $Si_3$ $O_{10}.O_2$), is of interest because it is an indicator of oxygen fugacity during crystallization (Wones and Eugster, 1965). Because ferric iron cannot be distinguished from ferrous iron on the microprobe, two indirect methods have been employed to derive values of possible ferric iron content. One approach is to use the $Fe^{+2}:Fe^{+3}$ ratio determined by wet chemistry from two samples of primary biotite. The wet chemical determinations suggest that about 14 atom percent of total iron is ferric; this value has been used to recalculate microprobe analyses from table 5 (table 6). By this approximation $Fe^{+2}$ contents of primary biotite range from 1.93 to 1.38 octahedral positions and $Fe^{+3}$ ranges from 0.26 to 0.19 positions. These values are close to those from biotites synthesized on the nickel-nickel oxide (NNO) oxygen fugacity buffer (fig. 10). An alternate approach has been to recalculate biotite formulas from table 4 assuming full occupancy (stoichiometry), of 6 atoms in the octahedral layer. This is accomplished by recalculating appropriate amounts of ferrous iron to ferric; results are shown in table 6. Unlike the calculations by oxygen equivalents in which total charges were fixed at 44, this procedure allows charges to change and leads to about 0.6 additional charges per cell. The amount of ferric iron and the $Fe^{+3}$:Fe ratio calculated by stoichiometry probably are maximum limits because some octahedral vacancies generally occur (Farmer and others, 1971). The amount of $Fe^{+3}$ calculated by stoichiometry is higher than from wet chemical determinations (table 6; fig. 10); the latter will be accepted as the best approximation. In summary, primary biotites have Fe:Fe+Mg+Mn atom ratios of about 0.35 ± 0.05 and about 4 atom percent oxyannite molecule. This will be considered again later.

## Amphibole

Two types of amphibole occur in the intrusive rocks. One is relatively light colored, pleochroic pale yellow to green, and has the general appearance of hornblende; the other is much darker in color, pleochroic green to bluish green, with the appearance of an iron-rich amphibole. The former is primary and occurs chiefly as phenocrysts but may also be in the matrix, whereas the later is texturally secondary and commonly occurs in veinlets with magnetite, anhydrite, and pyrite or chalcopyrite. Primary amphibole occurs in approximately 60 percent of the rocks collected outside of the Mayflower ore

Table 6.--*Recalculation of total iron in primary biotite analyses*

| | | Calculated $Fe^{+2}$ and $Fe^{+3}$ atomic positions | | | | |
|---|---|---|---|---|---|---|
| | | By analogy to chemically analyzed[1] | | By stoichiometry[2] | | |
| Analysis | Fe total wt percent | $Fe^{+2}$ | $Fe^{+3}$ | $Fe^{+2}$ | $Fe^{+3}$ | $\frac{Fe^{+3}}{Fe^{+2}+Fe^{+3}}$ |
| 30-3B | 12.0 | 1.93 | 0.26 | 1.61 | 0.68 | 0.30 |
| 181b | 11.7 | 1.64 | .22 | 1.55 | .66 | .28 |
| 30-1a | 11.8 | 1.66 | .23 | 1.60 | .62 | .28 |
| 28-7a | 11.9 | 1.65 | .23 | 1.62 | .56 | .26 |
| 28-7b | 10.4 | 1.46 | .20 | 1.37 | .62 | .31 |
| 176a | 12.0 | 1.69 | .23 | 1.55 | .78 | .33 |
| 176b | 12.1 | 1.71 | .24 | 1.76 | .42 | .19 |
| 26-10b | 11.4 | 1.61 | .22 | 1.57 | .56 | .26 |
| 126a | 11.0 | 1.76 | .24 | 1.44 | .64 | .31 |
| 26-16a | 11.3 | 1.57 | .21 | 1.61 | .40 | .20 |
| 26-16b | 10.6 | 1.48 | .20 | 1.44 | .52 | .27 |
| 123a | 10.1 | 1.40 | .19 | 1.36 | .50 | .27 |
| 123d | 10.4 | 1.44 | .20 | 1.35 | .62 | .31 |
| D991a | 9.94 | 1.38 | .19 | 1.37 | .44 | .24 |
| D991f | 9.94 | 1.38 | .19 | 1.33 | .52 | .28 |

[1] $Fe^{+3}$:Fe = 0.12, determined by wet chemical analyses.

[2] Stoichiometry of octahedral layer assumed; calculated by converting $Fe^{+2}$ to $Fe^{+3}$ until all sites full.

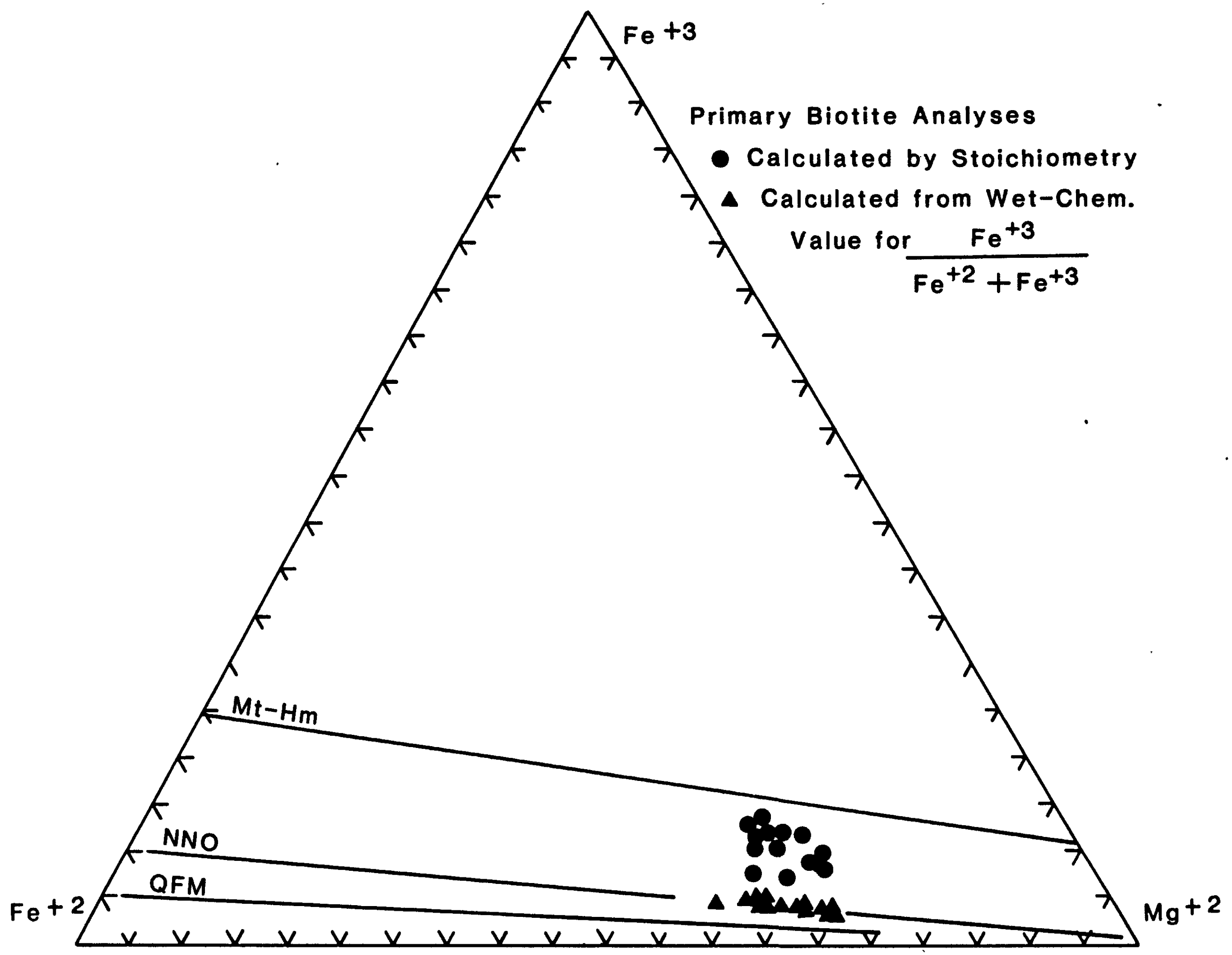

Figure 10.--Composition of biotite grains as calculated from microprobe analyses. Dashed lines represent composition of biotites on oxygen fugacity buffers (Wones and Eugster, 1965).

zone, in all rock types. It characteristically occurs in rocks with fresh feldspars and in which magnetite abundance is greater than pyrite; the magnetite is often present as poikilitic inclusions. Only rarely is amphibole present if all magnetite has been sulfidized. A general amphibole alteration sequence can be recognized: the first sign is bleaching, particularly parallel to (001) as noted by Bose (1959); then there is incipient alteration to biotite at grain margins; ultimately there is a mat of interlocking fine-grained biotite with the general morphology of the original hornblende grain. Amphibole is more resistant to alteration than is biotite. In many hydrothermally altered rocks amphibole remains relatively fresh whereas biotite is altered to chlorite.

Amphibole phenocrysts in the Mayflower porphyry stock (table 7; fig. 11) are characterized by low contents of aluminum, sodium, and potassium and low ratios of Fe:Fe+Mg+Mn. Several subsitutional types are noted in the general structural formula $X_2Y_5Z_8O_{22}(OH)_2$, in which X represents large cations in the $M_4$ site, Y represents intermediate-sized cations in $M_1$-$M_3$ octahedral sites, and Z represents Si and Al in tetrahedral sites. In these rocks the $M_4$ site is mainly occupied by Ca, hence these amphiboles are the calcic type. The $M_1$-$M_3$ sites are prediminantly filled by Mg and Fe, hence most are in the tremolite-ferrotremolite series. Because Fe:Fe+Mg+Mn ratios range from 0.35 to 0.13, the term actinolite is appropriate. Amphiboles with more than 0.5 atoms of $Al_{iv}$ could be considered hornblende or subaluminmous hornblende (fig. 11); the division is obviously arbitrary and all will be called "actinolite."

Coupled substitutions occur to balance charge discrepancies when $Al_{iv}$ substitutes for Si in the tetrahedral layer, and when $Al_{iv}$ is not equal to $Al_{vi}$. One coupled substitution is monovalent sodium + potassium and trivalent aluminum. In figure 11 it is apparent that for each two $Al_{iv}$ positions, there is substitution of one Na or K atom in the A site. A similar substitution pattern was observed by Czamanske and Wones (1973). A 1:1 ratio is expected for simple edenitic substitution. Hence, the 2:1 ratio indicates other coupled substitutions also are operative, in particular four $Al_{iv}$ for one Ti.

Partial chemical analysis of amphibole separated from sample 26-23 gave the following results (in wt percent): $Fe_2O_3$, 2.07; FeO, 6.74; $Li_2O$, <0.05; F, 0.27; Cl, 0.06. Structural calculations employing this data indicate the

Table 7.--*Microprobe analyses and structural formulas of amphibole phenocrysts*
[*Total iron expressed as FeO. Structural formulas based on 23 oxygen atoms*]

| Sample No. | 181b | 181a | 26-10a | 26-16b | 26-16a | 176b | 26-23a | 20-11a | 176a | 8-86 | 8-3a | 20-30a | 20-30b | 20-30c |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Microprobe analysis in weight percent | | | | | | | | |
| $SiO_2$ | 48.50 | 55.01 | 49.92 | 51.44 | 51.00 | 52.63 | 50.39 | 51.27 | 52.79 | 55.24 | 54.59 | 54.07 | 55.91 | 54.69 |
| $Al_2O_3$ | 6.30 | .76 | 4.18 | 3.89 | 4.14 | 3.16 | 3.94 | 3.75 | 3.40 | 1.58 | 1.65 | 2.62 | .99 | 2.59 |
| $TiO_2$ | 1.20 | .05 | .74 | .47 | .58 | .35 | .54 | .40 | .36 | .11 | .18 | .09 | .10 | .10 |
| MgO | 13.71 | 16.17 | 15.96 | 16.37 | 16.37 | 16.80 | 16.74 | 16.74 | 16.86 | 18.38 | 18.48 | 18.62 | 19.11 | 20.13 |
| FeO | 13.92 | 11.96 | 11.07 | 10.62 | 10.53 | 10.33 | 10.25 | 10.05 | 9.70 | 8.98 | 7.91 | 7.75 | 6.79 | 5.61 |
| MnO | .40 | .54 | .49 | .18 | .17 | .36 | .46 | .39 | .42 | .58 | .50 | .48 | .49 | .43 |
| CaO | 11.08 | 12.16 | 11.58 | 12.04 | 11.98 | 11.61 | 10.75 | 11.96 | 11.98 | 12.07 | 12.14 | 12.64 | 12.32 | 12.78 |
| $Na_2O$ | 1.14 | .29 | .98 | .66 | .98 | .46 | .92 | .71 | .49 | .17 | .39 | .52 | .53 | .42 |
| $K_2O$ | .56 | .01 | .40 | .36 | .45 | .19 | .22 | .29 | .20 | ------- | .09 | .18 | .13 | .15 |
| Total | 96.81 | 96.95 | 95.32 | 96.03 | 96.20 | 95.89 | 94.21 | 95.56 | 96.20 | 97.11 | 95.93 | 96.97 | 96.37 | 96.90 |
| | | | | | | Structural formula | | | | | | | | |
| Si | 7.16 | 7.94 | 7.39 | 7.50 | 7.44 | 7.64 | 7.48 | 7.50 | 7.63 | 7.85 | 7.83 | 7.69 | 7.93 | 7.70 |
| Al | .84 | .06 | .61 | .50 | .56 | .36 | .52 | .50 | .37 | .15 | .17 | .31 | .07 | .30 |
| Σ tet | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Al | .26 | .07 | .12 | .17 | .15 | .18 | .17 | .15 | .21 | .11 | .11 | .13 | .10 | .13 |
| $Fe^{+2}$ | 1.54 | 1.37 | 1.22 | 1.20 | 1.21 | 1.09 | 1.01 | 1.11 | 1.07 | .91 | .86 | .85 | .78 | .58 |
| $Mg^{+2}$ | 3.02 | 3.48 | 3.52 | 3.56 | 3.56 | 3.64 | 3.70 | 3.65 | 3.63 | 3.89 | 3.95 | 3.95 | 4.04 | 4.22 |
| $Ti^{+4}$ | .13 | .01 | .08 | .05 | .06 | .04 | .06 | .04 | .04 | .01 | .02 | .01 | .01 | .01 |
| $Mn^{+2}$ | .05 | .07 | .06 | .02 | .02 | .04 | .06 | .05 | .05 | .07 | .06 | .06 | .06 | .05 |
| Σ $M_1$-$M_3$ | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| $Fe^{+2}$ | .18 | .07 | .15 | .10 | .08 | .16 | .26 | .12 | .10 | .15 | .09 | .07 | .02 | .08 |
| $Ca^{+2}$ | 1.75 | 1.88 | 1.84 | 1.88 | 1.87 | 1.81 | 1.71 | 1.88 | 1.85 | 1.84 | 1.87 | 1.93 | 1.87 | 1.93 |
| $Na^{+1}$ | .07 | .05 | .01 | .02 | .05 | .03 | .03 | ------- | .05 | .01 | .04 | ------- | .11 | ------- |
| Σ $M_4$ | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| $K^{+1}$ | .11 | ------- | .08 | .07 | .08 | .04 | .04 | .05 | .04 | ------- | .02 | .03 | .02 | .03 |
| $N^{+1}$ | .26 | .03 | .27 | .17 | .23 | .10 | .23 | .20 | .09 | .04 | .07 | .14 | .03 | .11 |
| Σ A | .37 | .03 | .35 | .24 | .31 | .14 | .27 | .25 | .13 | .04 | .09 | .17 | .05 | .14 |
| Fe/Fe+Mg+Mn | .359 | .289 | .277 | .266 | .264 | .254 | .253 | .250 | .241 | .212 | .191 | .187 | .164 | .134 |

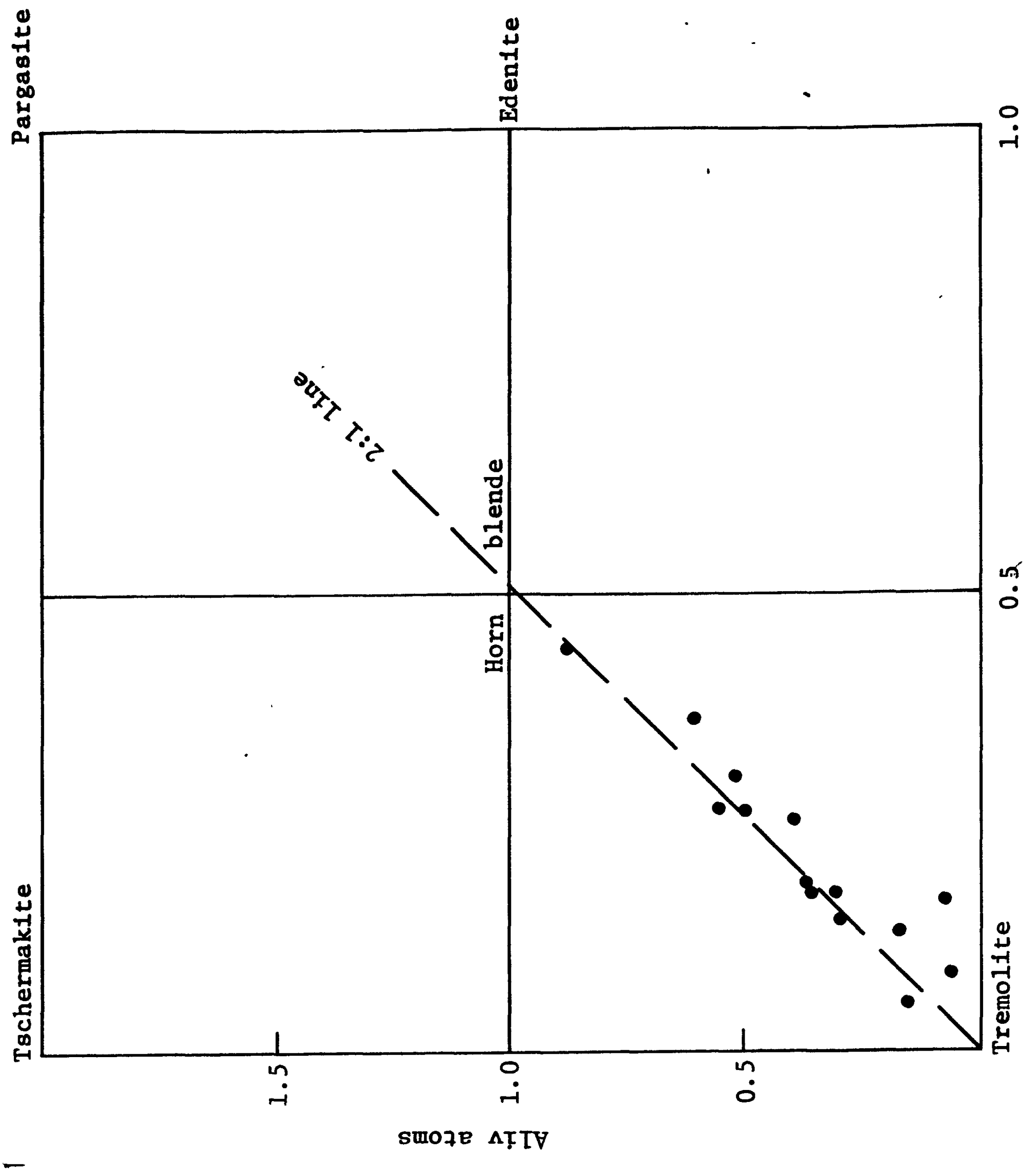

Figure 11.--Composition and classification of amphibole grains.

following number of positions: $Fe^{+2}$, 0.98; $Fe^{+3}$, 0.28; $Li_2O$, <0.02; F, 0.13; Cl, 0.02. The atom ratio of $Fe^{+3}/Fe$ is 0.22, and fluorine and chlorine occupy 6.5 and 0.8 percent of hydroxyl sites. If the wet chemical analyses of primary amphibole and biotite are correct and representative, then primary amphibole contains a higher $Fe^{+3}$:Fe ratio than primary biotite, and a higher percentage of OH sites filled by F, but fewer by Cl.

## Iron Oxides

Opaque iron oxide minerals are present in relatively unaltered porphyritic rocks from the Mayflower mine, and also are present in some hydrothermal veins. A study of twenty polished sections indicates that magnetite is the dominant iron oxide. Ilmenite occurs in small amounts as discrete grains or as exsolution lamellae in magnetite. Thin rims of sphene commonly enclose magnetite. The iron oxides generally occur near or within mafic silicates, especially amphibole. Some of the iron oxides are corroded, and some occurs as very fine disseminations in rock matrices--these are probably subsolidus effects.

Partial microprobe analyses were made of the iron oxides to provide information on possible conditions of crystallization and reequilibration (Buddington and Lindsley, 1964). Analyses of iron oxides in 12 samples demonstrate that the major oxide is a relatively pure magnetite containing 70 ± 1 weight percent Fe, 0.1 to 0.2 weight percent $TiO_2$, 0.1 to 0.2 weight percent MnO, and traces of MgO. Some small grains of ilmenite contain 41 to 55 weight percent $TiO_2$ and 5 to 10.6 weight percent MnO, suggesting appreciable amounts of hematite solid solution in ilmenite in the hexagonal $FeTiO_2$ - $Fe_2O_3$ system. Similar manganese enrichment in ilmenite has been noted previously and interpreted to reflect oxidizing conditions (Buddington and Lindsley, 1964; Czmanske and Mihalik, 1972).

## Anhydrite

Anhydrite is commonly present in the Mayflower and Ontario porphyry stock. Some samples contain as much as 5 percent anhydrite disseminated through the matrix; in such samples replacement textures are rare. The habit of anhydrite closely resembles that of apatite, which is commonly closely associated. Shreddy biotite, fine-grained magnetite, and pyrite also tend to occur with the matrix anhydrite. Thin veinlets up to 1 cm across containing anhydrite, quartz, pyrite, ± chalcopyrite, ± green amphibole, ± biotite, ± K-feldspar may be related to the matrix anhydrite or could be a somewhat later hydrothermal assemblage.

Anhydrite appears to be restricted to igneous rocks below the 1,880 level. It has not been observed in veinlets or rock matrix above the 1,880 level or in igneous rocks and sedimentary rocks or western portions of deeper mine levels. Anhydrite is most abundant, coarsest, and most "primary-appearing" in the Mayflower core facies and in felsic stringers with gradational contacts with Mayflower porphyry stock. The distribution of anhydrite in space and within the matrix of certain rock types suggests that anhydrite crystallized under magmatic conditions in both the Mayflower and Ontario intrusions. Alternatively, the matrix anhydrite may be a hydrothermal phase related to one or more stages of pre-main stage veining.

## INTERPRETATION AND DISCUSSION

### Emplacement

Emplacement in the epizone is suggested by features such as discordant contacts, minor metamorphism of wall rocks, presence of associated volcanic rocks, porphyritic and granophyric textures, and thin dikes with aplitic texture (Buddington, 1959). Because wall rocks show little deformation or folding, and evidence for assimilation (such as presence of xenoliths) is sparse, space for the stocks may have been provided by uplift of the roof. The porphyritic stocks exposed in the Mayflower mine are a small part of a larger complex of intrusive and extrusive rocks which formed over a period of about 8 m.y. (Bromfield and others, 1977).

The Mayflower stock is interpreted to be a zoned intrusion, only part of which is exposed in the mine. The margin facies, adjacent to sedimentary wall rocks, crystallized first, followed by the core facies which crystallized upon release of volatiles. Alinement of phenocrysts in the margin facies probably reflects shear in the partly crystallized magma that was caused by drag along the intrusive contact (Reeser, 1958; White, 1973). The boundary between Mayflower core and margin facies is variably sharp or gradational; the sharp contacts could form by injection of magma into hot but crystallized rock, whereas the gradational contacts could by injection of magma into partially crystallized rock (Bateman, 1965, p. 104). Movements in the magma chamber could cause the injection of fractionated (Ab-Or-Qz-rich) melt into dilatant zones to create felsic dikes with either sharp or gradational contacts.

The aphanitic matrix of the porphyritic stocks, especially the core facies of the Mayflower stock, was probably produced by pressure quenching (Fournier, 1967; Burnham, 1967). Release of water pressure causes the magma to freeze suddenly. Textures suggestive of water saturation such as pegmatites or miarolytic cavities have not been observed. Rupture of the wall rocks could cause a great reduction in fluid pressure and cause boiling and the postulated pressure quenching. Such venting of volatiles and boiling would have important chemical consequences, possibly including the development of very saline hydrothermal fluids (Nash, 1973) and oxidation. Oxidation can occur when water separates from the melt, dissociates, and $H_2$ is released (Czamanske and Wones, 1973).

## Crystallization conditions

The intensive parameters temperature, pressure, $H_2O$ fugacity, and $O_2$ fugacity during crystallization can be estimated from some chemical equilibria and mineral compositions. For intrusive rocks in general these estimates often are unreliable because subsolidus reequilibration changes compositions. The problem of reequilibration is particularly grave in this study because all rocks in the mine have experienced at least some hydrothermal alteration.

Relations in the "granite tetrahedron" Ab-Or-An-Qz offer insights to conditions of crystallization of felsic constituents. Normative values for albite, orthoclase, anorthite, and quartz, calculated from chemical analyses of rocks (table 2) are plotted on ternary diagrams Ab-Or-Qz (fig. 12) and Ab-An-Qz (fig. 13). The norms show considerable scatter on figure 12 and do not cluster in a minimum melting region. The scatter is consistent with crystal-melt fractionation, but there was not enough fractionation to reach minimum melting compositions. The most felsic compositions are not far from the 1 kilobar minimum. Crystallization of the matrix of the porphyries, rich in quartz and K-feldspar, can be approximated by the Ab-Or-Qz solidus which is at about 720°C for 1,000 bars $P_{H_2O}$ or 770°C for 500 bars $P_{H_2O}$ (Tuttle and Bowen, 1958). The solidus for rocks of granodiorite composition has been determined

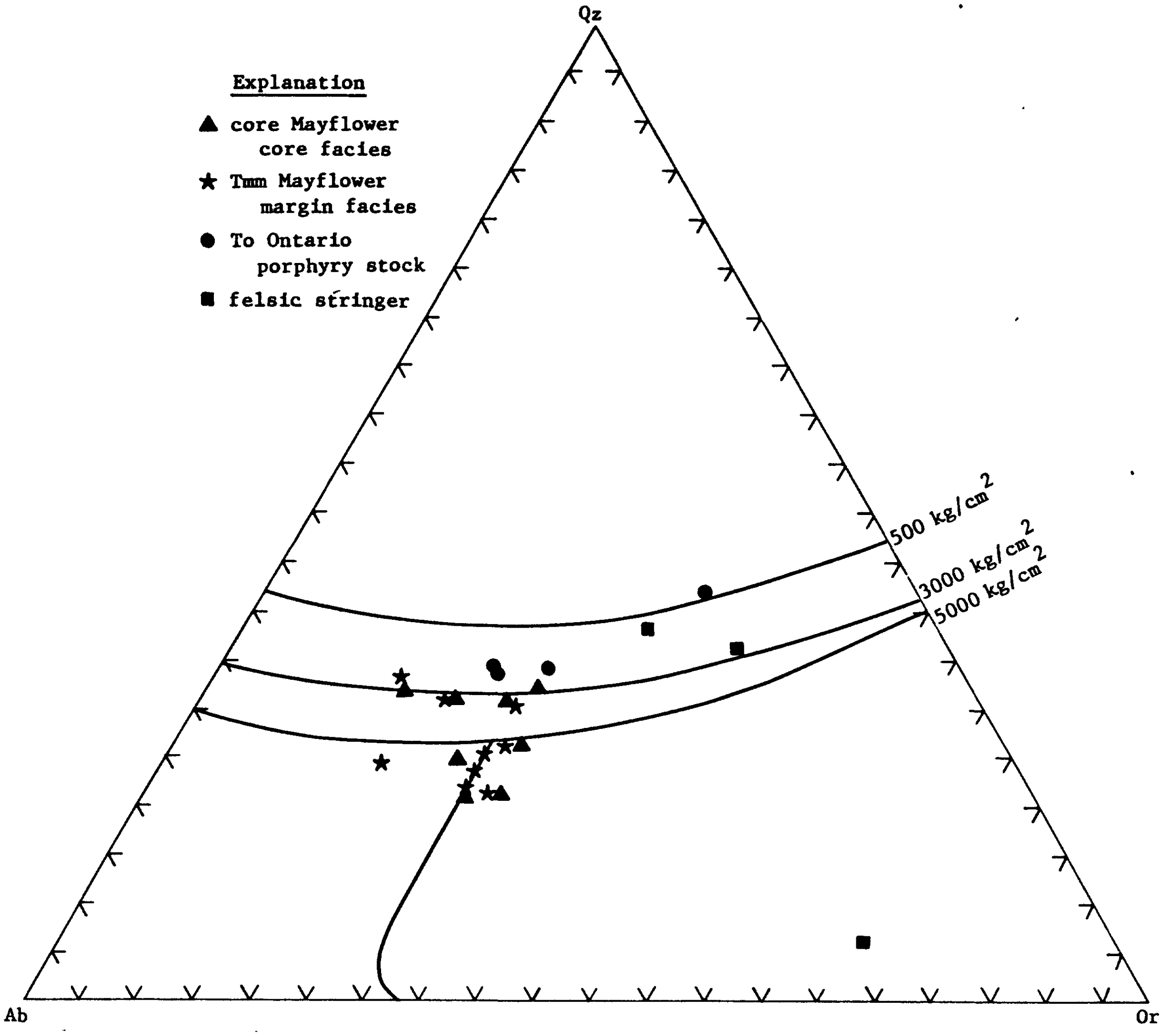

Figure 12.--Plot of normative rock compositions in the tertiary system AB(NaAlSi$_3$O$_8$)-Or(KAlSi$_3$O$_8$)-Qz(SiO$_3$). Dashed lines are the quartz-feldspar boundary at 500, 3000, and 5000 kg/cm$^2$. (Diagram from Tuttle and Bowen, 1958).

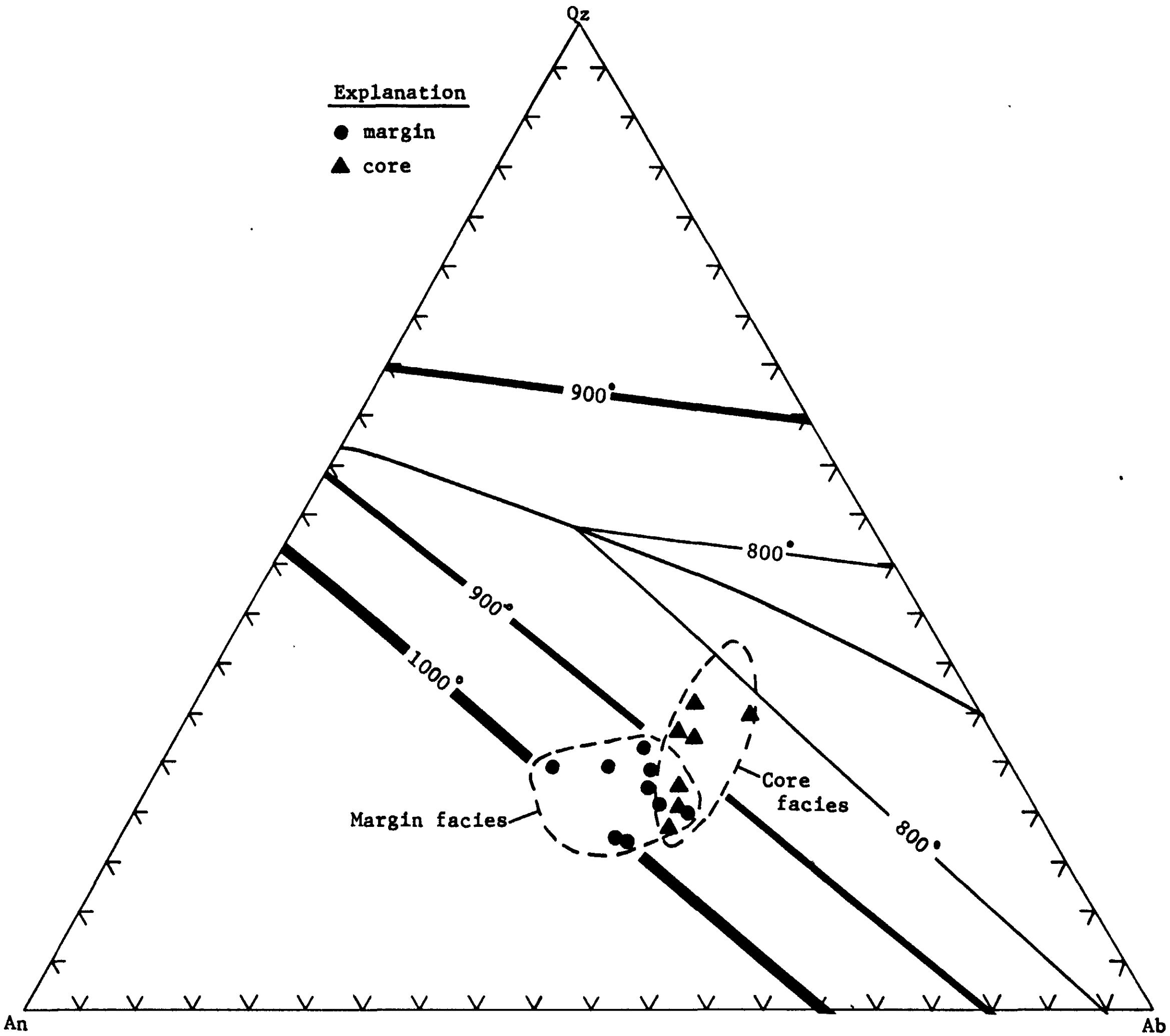

Figure 13.--Plot of normative rock compositions of Mayflower porphyry samples in the ternary system Ab($NaAlSi_3O_8$)-An($CaAl_2Si_2O_8$)-Qz($SiO_2$). The quartz-feldspar boundary (solid line) shifts toward quartz at higher pressure (Diagram from James and Hamilton; 1969)

to be 750°C at 1,000 bars pressure with excess water present (Piwinskii, 1968).

Normative compositions plotted on figure 13 fall in the field of plagioclase, consistent with the observed early crystallization of that phase. Although the Mayflower core facies rocks are more silicic than those of the margin facies (fig. 13), those compositions do not plot in the field of primary quartz. Higher water pressures at depth might have been sufficient to cause the crystallization of quartz phenocrysts in the core facies, and release of water pressure during emplacement would explain the observed resorption of quartz phenocrysts.

The relatively sodic rims on some plagioclase phenocrysts (An 17-25) probably are late magmatic or hydrothermal products. When rock compositions and feldspar compositions are plotted on the ternary diagram Ab-An-Or, the tie lines between sodic plagioclase and matrix K-feldspar fall far below the normative rock composition.

Experimental studies have demonstrated that compositional variations in iron oxides (Buddington and Lindsley, 1964) and in biotite (Wones and Eugster, 1965) reflect intensive variables temperature, oxygen fugacity, and water fugacity. Application to plutonic rocks, however, is complicated by problems of postmagmatic reequilibration and the inability of the electron microprobe to discriminate between ferrous and ferric iron. Despite these problems, compositions of iron-bearing phases in igneous rocks from the Mayflower mine yield useful information.

Most primary biotite in the igneous rocks under study coexists with potassium feldspar and magnetite, thus these biotite-bearing assemblages can be compared with experimental ones. As discussed previously, primary biotites have Fe:Fe+Mg+Mn ratios of about 0.35 ± 0.05. Ferric iron content is at least 12 atom percent, estimated from two wet chemical analyses, and possibly higher according to recalculated microprobe analyses using the assumption of stoichiometry in octahedral sites. These compositions are similar to those synthesized on the nickel-nickel oxide (NNO) oxygen fugacity buffer. Biotite phenocrysts with Fe:Fe+Mg+Mn ratio of about 0.35, $f_{O_2}$ of the NNO buffer, and 1,035 bars pressure, suggest a temperature of crystallization of about 900°C (Wones and Eugster, 1965, Fig. 2). For this temperature and composition the oxygen fugacity is about $10^{-11}$ bars.

Fugacity of water can be calculated from the previously determined value of $f_{O_2}$, and compositions of coexisting orthoclase, magnetite, and biotite (Wones and Eugster, 1965). Calculations, using the revised equation in Czamanske and Wones (1973) yield a value of about 800 bars at the Ab-Or-Qz minimum (Tuttle and Bowen, 1958). The uncertainty of this $fH_2O$ estimate is about ± 150 bars, due chiefly to uncertainties in estimates of ferric iron in biotite and the influence of that parameter on the calculated $f_{O_2}$.

Relations of amphibole in igneous rocks of the Mayflower mine also yield information on conditions of crystallization. Recalling that sparse pyroxene occurs in two samples from the 800 level, and also in surface samples, the divariant breakdown curves of amphibole to pyroxene may provide some limiting information regarding temperature and water pressure. The maximum thermal stability of actinolite with composition $Ca_2Mg_{3.7}Fe_{1.3}Si_8O_{22}OH_2$ is about 750°C at 1,000 bars $P_{H_2O}$ or about 700°C at 500 bars $P_{H_2O}$ (Ernst, 1968). Substitution of iron for magnesium lowers maximum divariant curves of actinolite to pyroxene plus other phases, and an increase in the partial pressure of $CO_2$ decreases the thermal stability of the hydrous phase for a given total fluid pressure. The fluorine content of the actinolite is not sufficient to be a significant factor. Some preliminary experiments suggest that amphibole and biotite do not form below water pressures of about 510 to 714 bars (Khitarov and others, 1969). It appears that water pressures at emplacement were near minimum values for amphibole stability. The Si-rich actinolite phenocrysts are unusual for granitic igneous rocks which typically contain hornblende (Deer and others, 1963a; Dodge and others, 1968; Czamanske and Wones, 1973). Siliceous amphiboles are characteristic of lower grade metamorphism or late stage replacements of pyroxene or hornblende. The low titanium and high silica content of these amphibole phenocrysts is common in amphiboles, particularly those of metamorphic origin (Leake, 1965), and is suggestive of, but not necessarily, a function of temperature. Although textural evidence suggests that the amphiboles are "unaltered," late magmatic-stage or subsolidus reactions may well have produced the observed compositions.

Magnetite must have been altered after primary liquidus crystallization because it is far too impoverished in titanium compared with synthetic oxides crystallized at 700° to 800°C (Buddington and Lindsley, 1964). The very low titanium content of magnetite in igneous rocks of the Mayflower mine is not unusual as magnetite in plutonic rocks commonly has such composition, and has been explained by recrystallization or alteration at subsolidus temperatures under oxidizing conditions (Anderson, 1968; Czamanske and Mihalik, 1972). The 25- to 50-fold enrichment of manganese in ilmenite recorded here is also consistent with subsolidus oxidation (Anderson, 1968; Czamanske and Mihalik, 1972). It is concluded that primary oxides reequilibrated during cooling; conditions recorded in the oxide compositions appear to be about 500° and $10^{-20}$ bars $f_{O_2}$ (extrapolated from Buddington and Lindsley, 1964, fig. 5). Evidence here suggests that biotite "retains" its primary composition much more effectively than the iron oxides, a relationship noted by Czamanske and Wones (1973); the unusual compositions of primary actinolite phenocrysts suggest that amphibole is not as resistant to alteration as biotite.

## Implications for mineral resources

Porphyritic textures, lateral zonation, and intrusive and gradational contacts similar to those in the Mayflower stock have been noted in many copper-bearing stocks as at (a) the Liberty pit, Ely, Nevada (Fournier, 1967), (b) Chino mine, Santa Rita, New Mexico (Nielsen, 1968), (c) the Laramide stock at Mineral Park (Eidel and others, 1968), (d) the Cornelia stock, which was offset by faulting from the Ajo mine (Wadsworth, 1968), and (e) Mount Fubilan, New Guinea (Bamford, 1972). The Rocky Hill stock, California, is similar texturally although it contains no recognized ore deposits (Putnam and Alfors, 1969). The origin of these textural features cannot be specified precisely, but most writers believe that they reflect changes in crystallization due to variations in water pressure. The fine-grained matrix indicates sudden crystallization by a pressure quench, following crystallization of the more equigranular rocks near the stock margins. Pressure quenching probably occurred as a result of fracturing of enclosing wall rocks and loss of water pressure (cf., Burnham, 1967; Fournier, 1967; Putnam and Alfors, 1969).

The recognition of systematic textural zonation in the Mayflower stock may have potential economic implications in the search for disseminated sulfide mineralization in the Park City district. A characteristic feature of many "porphyry copper" stocks is the occurrence of disseminated pyrite and chalcopyrite in the fine-grained matrix of the pressure-quenched core facies.

The disseminated sulfides of possible primary origin occur in the highly porphyritic facies of deposits at Ely, Chino, Mineral Park, and Mount Fubilan. Fournier (1967, p. 79) reasoned that "Where the magma mush was quickly chilled, sulfides (mainly chalcopyrite) were trapped as grains disseminated in a groundmass composed mainly of quartz and K-feldspar [and] * * * where cooling was more gradual, most of the sulfur and copper escaped from the rock." Expulsion of water during quenching could easily explain the microveins of quartz with sulfides here (Nash, 1973) and in many porphyry copper deposits. Available analyses of the Mayflower core facies (table 2; Al-Shaieb, 1972) demonstrate that it contains much higher copper concentrations than other facies, commonly greater than 1,000 ppm.

An alternate hypothesis is that the porphyritic intrusions contained no significant mineral deposits at the magmatic stage, but that later hydrothermal activity produced the known economic mineral deposits. However, the geochemistry of the magmatic stage and subsequent hydrothermal system may have been crucial for making the ore deposits. In particular an oxidation trend and anhydrite-rich veins may have started at the magmatic stage. The primary magmatic phases such as biotite do not appear to be unusually oxidized, but the later hydrothermal assemblages are. The cause of this may have been release of volatiles during pressure quenching, and auto-oxidation by dissociation of water and loss of $H_2$ (Czamanske and Wones, 1973). Such oxidation could have enhanced the transport of copper and gold, thereby explaining the rich copper and gold values in the Mayflower mine compared to other deposits in the Park City district.

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