THE GEOLOGY AND ECONOMIC PETROLOGY OF THE ARCHEAN NEWTON LAKE FORMATION BOULDER BAY AREA, ST. LOUIS COUNTY, MINNESOTA

A THESIS

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BY

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ABSTRACT

The Boulder Bay area is located one and a half miles west of Ely, Minnesota, near the western shore of Shagawa Lake. This one square mile area is underlain by part of the Archean Newton Lake Formation. Eight rock types were mapped in the area and include metabasalt flows, gabbro intrusions, banded iron formation, muscovite phyllite, schistose metagreywacke, rhyolite intrusions, a granodiorite with associated apophyses, and dacite dikes, in addition to quartz veins. All rocks are metamorphosed to greenschist facies and show varying degrees of cataclasis.

Two periods of deformation are recognized in the Boulder Bay area. The first is indicated by a prominent east-northeast strike of steeply dipping volcanic and sedimentary units, which is parallel to the strike of rocks present throughout the Vermilion District. Folds of this deformation are isoclinal. Six high-angle east-northeast trending faults of unknown displacement are recognized. The second period of deformation, with a major axis roughly at right angles to the first deformation, is indicated by west-northwest trending open folds in the limbs of the isoclinal folds and by locally abundant crenulations in rock cleavage.

In the central portion of the area, an epizonal syntectonic (Algoman orogeny, 2.7 b.y.) granodiorite stock intrudes metabasalt flows. A narrow contact-metamorphic aureole surrounds the stock.

Zoned alteration accompanied the development of gold and sulphide-bearing quartz veins in the granodiorite. Ore minerals occur as fracture fillings in these veins which were subjected to repeated periods of shearing.

Similarities between Boulder Bay mineralization and ore in various gold mines in the Canadian Shield suggest a low to moderate temperature mineralizing fluid. Sulphide and gold deposition may have occurred from hydrothermal fluids migrating from depth and along deep seated fault zones.

Rock types in the Boulder Bay area are typical of part of an Archean metavolcanic-metasedimentary pile and were probably deposited under subaqueous conditions. Whole rock analyses indicate the majority of the rocks are tholeiitic. The similarity of rock chemistry in the Boulder Bay area to that in other portions of the Superior Province suggests a continental orogenic or island arc origin for the area.

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Setting

Sulphide-bearing veins occur in a granodiorite stock which is exposed in the Boulder Bay area west of Shagawa Lake, St. Louis County, Minnesota. The stock intrudes Archean metavolcanic and metasedimentary rocks of the Newton Lake Formation. Drilling has indicated small amounts of gold and silver mineralization in sheared quartz veins within the granodiorite. A narrow zone of contact metasomatism is developed in the metavolcanic rocks surrounding the pluton. A detailed geological study of the stock and adjacent rocks was undertaken to examine the composition and distribution of the rocks, and to determine the origin of the sulphide deposits.

Location

The Boulder Bay area is located 1.5 miles west of Ely, Minnesota, adjacent to Shagawa Lake in St. Louis County (Figure 1). The area studied encompasses 0.9 square mile and lies within the NE¼ of section 36 and the SE¼ of section 25, in T. 63 N., R. 13 W., and in the southern half of section 30 and the NW¼ of section 31, in T. 63 N., R. 12 W.

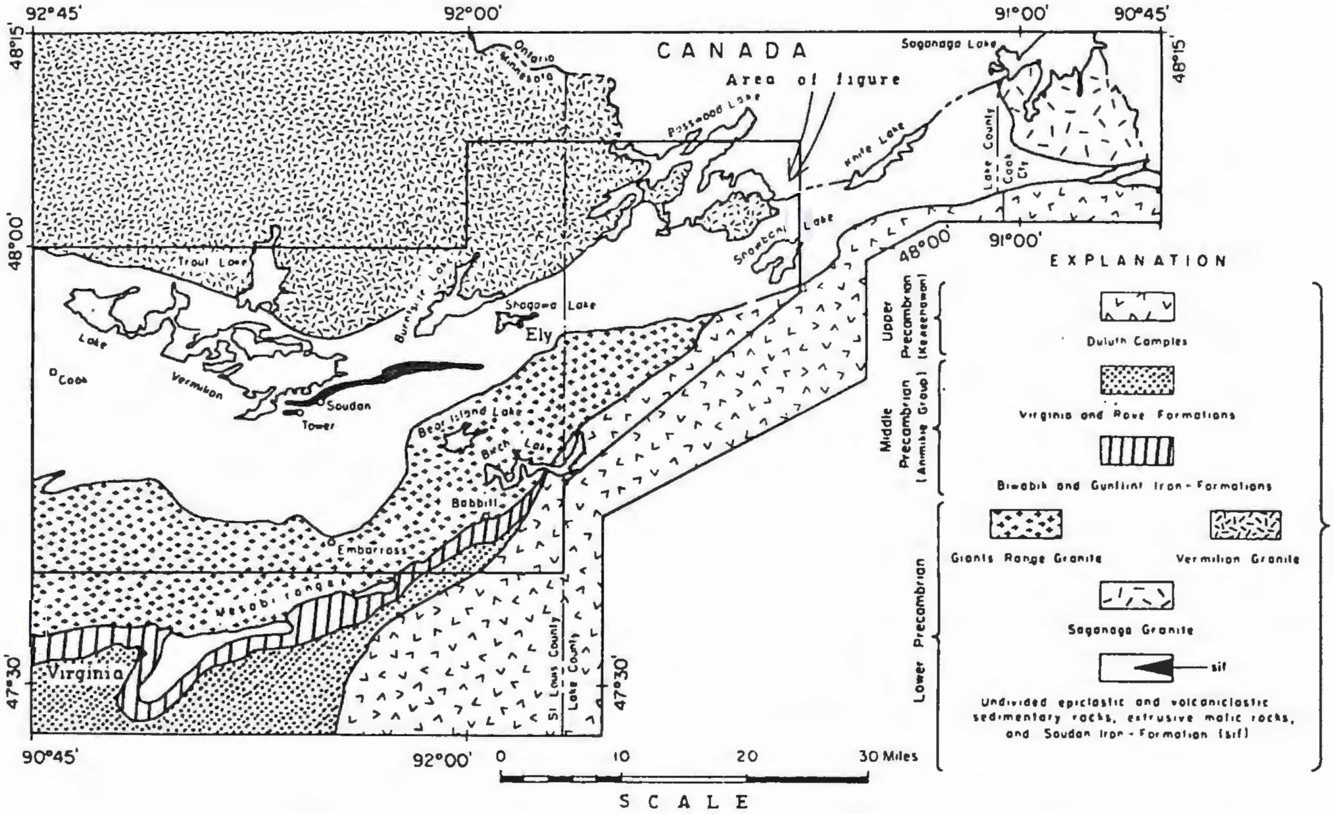

FIGURE 1 - MAP SHOWING GEOLOGIC SETTING OF THE VERMILION DISTRICT, MINNESOTA (After Sims, 1972).

Nature of Study

Field sampling and mapping was carried out in a ten week period during the summer of 1979. Field work included detailed geological mapping, sampling, and the collection of data using a variety of geophysical methods to aid in the geologic interpretation of the area. Horizontal loop electromagnetic, very low frequency electromagnetic, and flux-gate magnetometer surveys were completed during this period. Induced polarization and gravity surveys were completed during a one week period in September.

All mapping, sampling, and geophysical work was done on a series of cut lines for location control. Mapping was done on a scale of 1 inch = 200 feet. The cut lines provided access to all portions of the map area and allowed rapid and accurate location.

Geophysical surveys were conducted by Gold Fields Mining Corporation personnel and by geophysical companies contracted to do the work. Surveys were undertaken to locate potential subsurface sulphide zones, to delineate local structures, and to establish the nature of the contact between the granodiorite stock and the metabasalts.

Laboratory work and the compilation of data began in the fall of 1979 and continued into 1980. One hundred forty thin sections and forty-five polished sections were studied. A petrographic study was made to determine specific rock compositions, textures, and changes in mineralogy and texture as a result of contact and regional metamorphism. Polished section studies were undertaken to identify opaque minerals, establish their paragenesis, and to determine their relationship to the host rock.

Drill core from three previous mineral exploration programs was available for study. Core from eleven diamond drill holes was logged and sampled. Thin and polished sections from surface and drill core samples were studied. Thin section heels not used for making polished sections were etched with hydrofluoric acid and stained with sodium cobaltinitrite, as an aid in determining the amount of potassium feldspar present and to help outline primary textures. These heels and thin sections were then stained with amarand red for calcium feldspar determination.

Twelve rock samples were sent to X-Ray Labs, Don Mills, Ontario, for whole rock analysis. The oxides of Si, Al, Ca, K, Ti, Mn, Mg, Na, P, and Fe were determined by x-ray fluorescence spectrometry. Loss on ignition was determined by the change in weight of a sample when it was roasted for 30 minutes at 1000°F. Corrections in the data were made for matrix interference effects. These data are presented in Table 3.

Previous Geologic Work

The Newton Lake Formation was distinguished from the older Ely Greenstone Formation by detailed mapping, petrographic study, and major element analysis of volcanic and metasedimentary rocks in the Newton Lake area (Green, 1970). Green divided the Newton Lake Formation into informal mafic and felsic members. These rocks had previously been mapped as a portion of the Ely Greenstone and were thought to constitute the north limb of a syncline cored by the Knife Lake Group (Clements, 1903).

In 1972, Sims concluded from a compilation of available major element analyses of Vermilion district volcanic rocks that the Newton Lake Formation was chemically distinct from the Ely Greenstone. He found the Ely Greenstone basalts to represent either a low potash tholeiitic, or a basic, calc-alakaline rock series, whereas the Newton Lake volcanics exhibit a definite calc-alkaline trend.

Detailed geochemical work on the mafic portions of the Newton Lake Formation was done by Schulz (1977). He divided the basalts into two distinct chemical types: one characterized by high MgO, varying Al_2O_3/TiO_2 ratios and marked iron enrichment with decreasing Al_2O_3; the other by high MgO, FeO (total), CaO, and incompatible elements (except Y), with low, but constant, Al_2O_3/TiO_2 ratios and marked iron enrichment with increasing Al_2O_3. The most magnesiam members of both basalt types are compositionally similar to basaltic komatiites.

Sims and Mudrey (1978), in cooperation with the Minnesota Geological Survey, published a geologic map of the Shagawa Lake Quadrangle, (in which this study area is located), which was a compilation of the field work and geological interpretations of P. K. Sims (1966 to 1975), G. M. Mudrey (1969 to 1974), and K. J. Schulz (1974 to 1975). A geologic map by Green and Schulz of the Ely Quadrangle, immediately to the east, has also been published (Minnesota Geological Survey, 1982).

Mineral Exploration

The presence of gold in quartz veins within a small granodiorite stock in the Boulder Bay area has been known since the late 1800's. The 18th Annual Report of the Minnesota Geological Survey (1890) mentions gold assays averaging a dollar per ton from samples of veins taken by members of the geological survey corps. Sporadic work in the area continued from 1894 till 1935.

In 1935, the property owners sank a number of test shafts into several mineralized quartz veins. Only one shaft is accessible at the present time. It is approximately 15 feet deep with a 20 foot adit extending northwestwards at the bottom of the shaft (Plate 1).

In 1962 and 1963, R. V. Whiteside drilled nine holes into and around the granodiorite stock, but found only trace amounts of gold and silver. Drill core from six of these holes was available for study. Late in 1969, Bear Creek Mining Company leased the area on the basis of airborne geophysical surveys made as part of its search for copper-zinc deposits in Minnesota. The Boulder Bay area was mapped, and ground electromagnetic and magnetic surveys were made. Three holes were drilled to test geophysical conductors. Since no commercial deposits of sulphides were located, Bear Creek Mining Company surrendered its leases. In 1972, American Shield Corporation leased the property from R. V. Whiteside. Two years later American Shield undertook an extensive geochemical survey of the area with North Central Mineral Ventures. This work resulted in the discovery of another mineralized quartz vein at the surface in the granodiorite stock. Six holes were drilled near this newly discovered quartz vein and the existing test shafts. Drill core from these six holes was sampled and logged in this study. Although three of the holes encountered mineralization, the lack of continuity of the mineralization led North Central Mineral Ventures to drop its agreement with American Shield in 1975 (Ulland, 1979).

Acknowledgements

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REGIONAL GEOLOGY

Introduction

The Boulder Bay area is located in the east-central portion of the Vermilion district in an Archean (~2.7 b.y.) greenstone-granite terrain. The area is in the southern portion of the Superior Province of the Canadian Shield and lies within the Shebandowan-Wawa volcanic belt. Rocks of the district comprise a nearly linear belt of steeply dipping and complexly folded and faulted greenschist facies metavolcanic and metasedimentary units. These rocks are bounded on the north by the Vermilion batholith, on the east by the Saganaga batholith, and on the south by the Giants Range batholith (Figure 1). Regional metamorphism, folding, and local faulting is thought to have occurred with the emplacement of the granitic batholiths during the Algoman orogeny (2.7 b.y.) (Sims, 1972). Regional faulting occurred at the end of the orogeny (Sims, 1972).

Greenschist facies metamorphic assemblages are typical of the Vermilion district. Most rocks are lower greenschist in grade and show widespread evidence of incomplete recrystallization, including relict textures and minerals (Green, 1970; Sims, 1972).

Amphibolite facies grade of metamorphism is locally developed adjacent to the Vermilion and Giants Range batholiths, along some regional faults, and in association with younger monzonitic plutons. Regional metamorphism within the Vermilion district is thought to have occurred contemporaneously with the emplacement of the granitic batholiths during the Algoman orogeny (Sims, 1976).

The development of folds in the Vermilion district was largely dependent upon the physical characteristics of the rock. Well-layered sedimentary rocks typically exhibit steep isoclinal folds whereas more massive volcanic rocks tended to develop steeply dipping and dominantly homoclinal folds (Sims, 1976). The development of two generations of folds has been recognized in the western portion of the Vermilion district (Hooper and Ojakangas, 1971). Evidence for multiple folding is also found in other areas of the district, although few detailed structural analyses have been undertaken. Folding is thought to be contemporaneous with the intrusion of granitic batholiths during the Algoman orogeny (Sims, 1976).

Rocks in the Vermilion district underwent a major period of faulting which was regional in extent and followed the regional folding. Three major fault sets have been observed in the district (Sims, 1976): (1) dip-slip faults, (2) strike-slip faults which trend longitudinal to the district, and (3) transverse strike-slip faults, which trend northeasterly. The longitudinal strike-slip faults are the major faults in the area. They are steep, have associated cataclastic zones as much as 150 meters wide, and are commonly marked by topographic depressions. The third fault set, transverse strike-slip faults, transect both the batholithic and the supracrustal rocks in the district. They are expressed topographically as depressions in the metamorphic rocks, and as low ridges in the plutonic rocks. Where the faults are exposed, cataclastic and altered zones are observed. Cross-cutting relations among the fault sets have not been observed, but the available geologic data suggest that both sets of strike-slip faults formed approximately at the same time, after the main movements on the dip-slip faults (Sims, 1976).

Stratigraphy

Metavolcanic and Metasedimentary Rocks

The Newton Lake Formation, as defined by Morey and others (1970) and Sims (1976), is the youngest of four formally designated units in the east-central portion of the Vermilion district (Figure 2). The oldest unit, the Ely Greenstone, is stratigraphically overlain by the Knife Lake Group in the center of the district and by the Lake Vermilion Formation in the western segment. The Ely Greenstone is dominantly composed of mafic

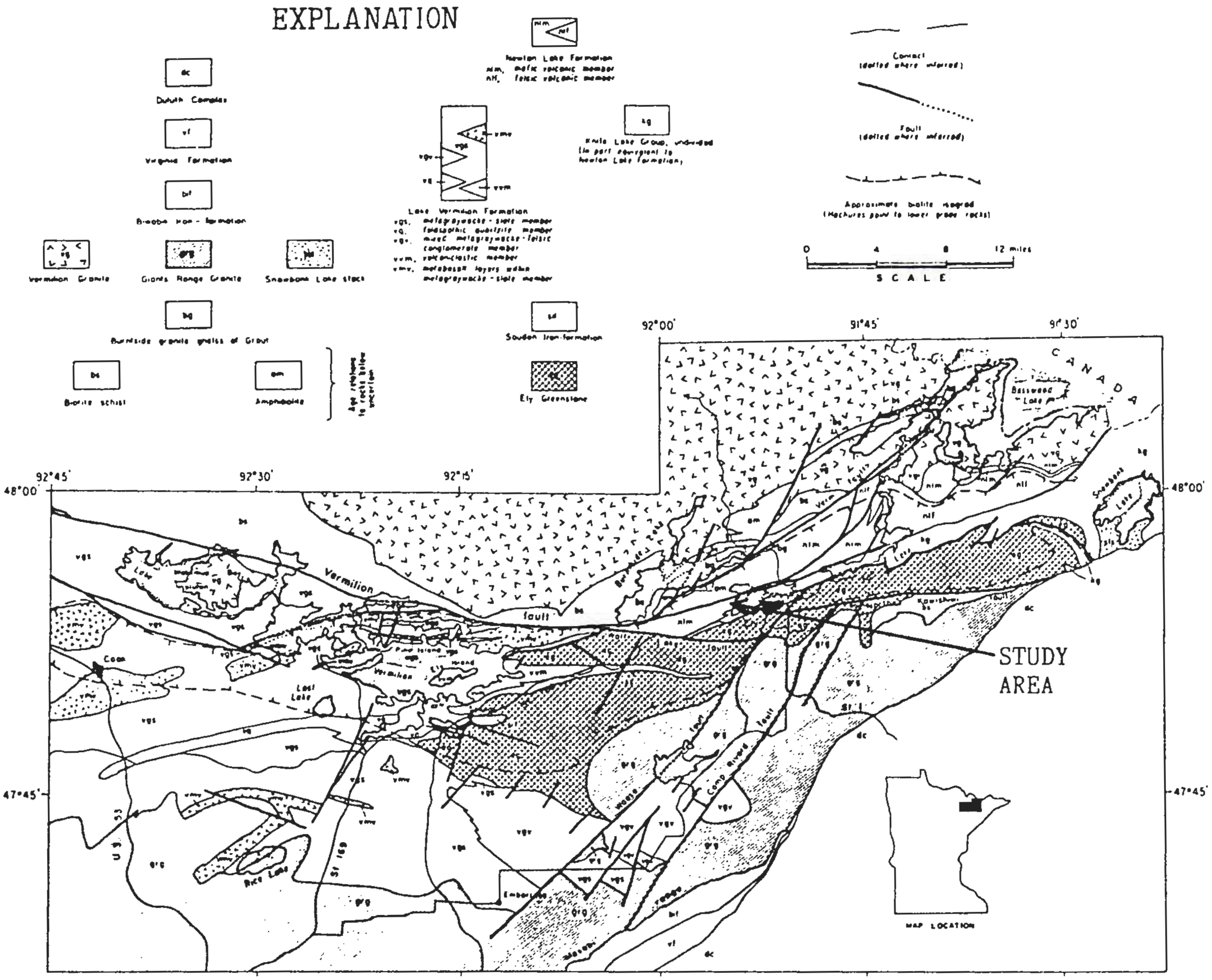


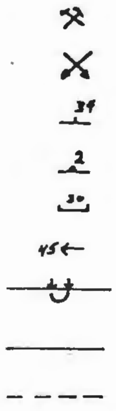
FIGURE 2 - GEOLOGIC MAP OF THE VERMILION DISTRICT AND ADJACENT AREAS OF NORTHEASTERN MINNESOTA (After Sims, 1972).

pillowed and massive flows and diabase sills, whereas both the Knife Lake Group and the Lake Vermilion Formation consist primarily of metagraywacke-slate and felsic volcaniclastic rocks.

The Newton Lake Formation comprises a second major mafic volcanic succession. It is believed to conformably overlie the Knife Lake Group in the central part of the district and may intertongue with it to the east. Felsic to intermediate volcaniclastic rocks make up the Newton Lake Formation east of Newton Lake, while west of it, mafic flows and sills dominate. The various rock types interfinger in the Newton Lake area (Green, 1970). Schulz (1977) has suggested a second interfingering just southwest of Shagawa Lake, based on mapping by Sims and Mudrey (1978) (Figure 3). It is likely that the Newton Lake Formation consists of two similar felsic rock units in the northeast and southwest ends of the formation, separated by mafic rocks.

The felsic member of the Newton Lake Formation is described in detail at its type locality in the Newton Lake area (Green, 1970). Although the thickness of the felsic member is difficult to determine, Schulz (1977) estimates that the maximum thickness is greater than 1,000 meters. The dominant rock types of the felsic member are calc-alkaline andesites and dacites. These rocks are commonly porphyritic and fragmental, occurring

VERMILION GRANITIC COMPLEX	Wvbs	Biotite Schist
	Wvam	Amphibolite
NEWTON LAKE FORMATION	Wm	Monzonite and Porphyritic Granite
	Wng	Metagabbro
	Wnbg	Bronzite Metagabbro
	Wnsp	Serpentinized Peridotite
	Wnsm	Siliceous Marble
	Wnmd	Metadiabase and Associated Rocks
	Wni	Banded Iron Formation
	Wntf	Felsic-Intermediate Tuff
	Wnb	Basaltic Flows
	Wnbv	Variolitic Basaltic Pillow Flows
	Wnct	Pyroxene Crystal Tuff
KNIFE LAKE GROUP	Wkl	Felsic Tuff
ELY GREENSTONE	Webg	Gray Basaltic Pillow Flows



Quarry
Gravel Pit
Strike and Dip of Bedding
Strike and Dip of Foliation
Strike and Dip of Cleavage
Bearing and Plunge of Lineation
Overturned Syncline Axis
Geologic Contacts
Inferred Fault Traces

FIGURE 3 - EXPLANATION OF GENERALIZED GEOLOGIC MAP OF BOULDER BAY AREA WEST OF SHAGAWA LAKE (After Sims and Mudrey, 1978). All of the above units are Precambrian W (Archean).

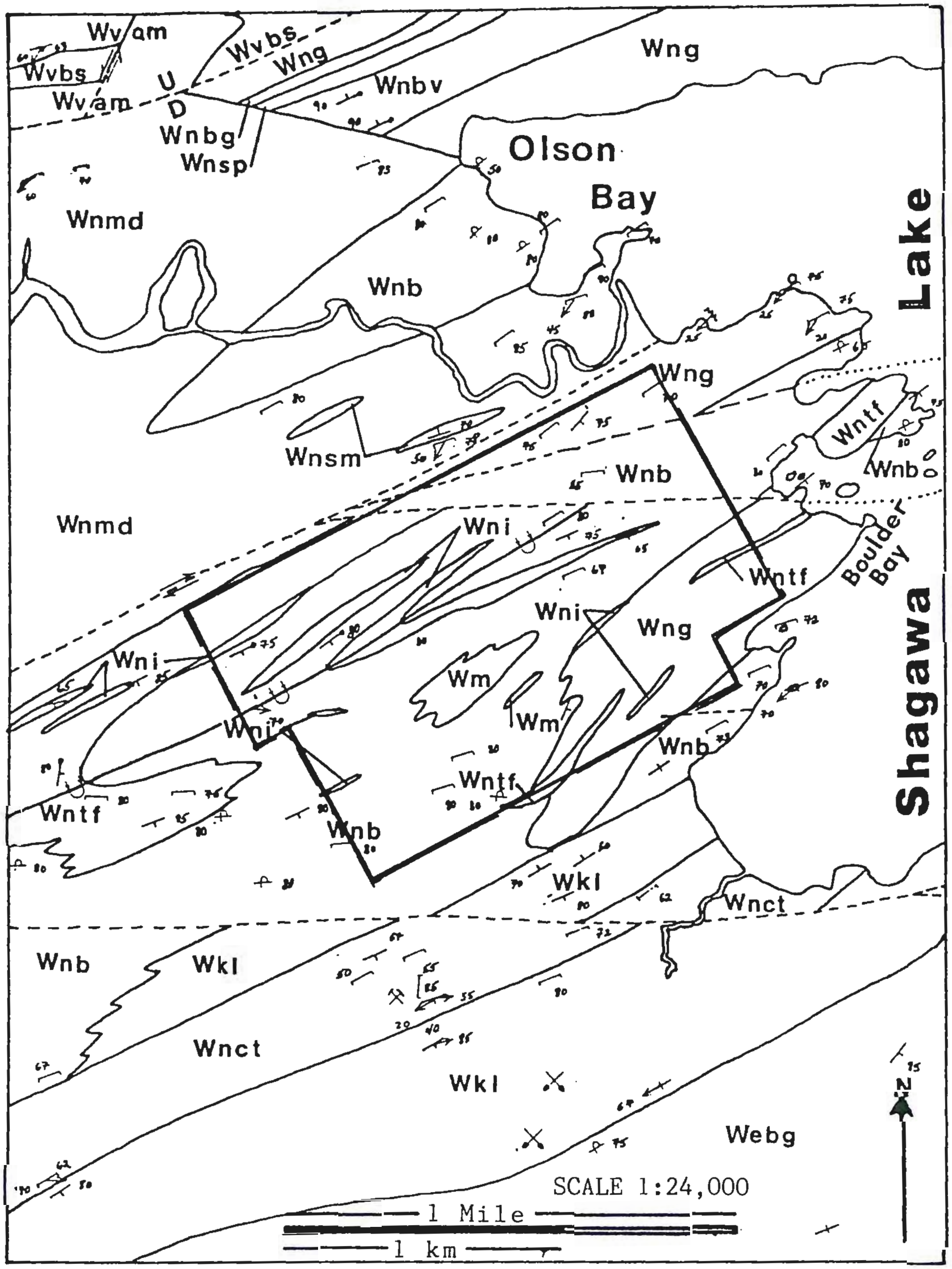


FIGURE 3 - GENERALIZED GEOLOGIC MAP OF THE BOULDER BAY AREA WEST OF SHAGAWA LAKE (After Sims and Mudrey, 1978). Heavy lines indicate boundaries of study area.

as breccias, tuff breccias and tuffs. Lesser amounts of massive felsic to intermediate lava, volcanic-arkosic wacke, and graywacke are also found (Green, 1970).

The mafic volcanic member, estimated at greater than 1,350 meters in maximum thickness, consists of mafic pillowed to massive flows and layered to non-layered mafic-ultramafic sills. Locally, quartz-rich tonalite paraconglomerate and thin basaltic tuff units have been found (Schulz, 1977).

A variety of rock types are present in the Newton Lake and Shagawa Lake areas where interfingering occurs between the felsic and mafic members. These include tuffs, siliceous marble, and iron formation. Andesitic tuff units tend to be small and lenticular, although some are exposed for a kilometer or more, as in the Shagawa Lake quadrangle (Arth and Hanson, 1975; Schulz, 1977). A layer of siliceous marble, 150 meters thick and at least 1.6 kilometer long, crops out in the area of Upper Pipestone Falls (Green, 1970). Smaller lenticular bodies of the same rock types are found in the Shagawa Lake quadrangle (Figure 3) (Sims and Mudrey, 1978). Well banded hematite-chert and magnetite-chert units of iron formation are found in the felsic member northeast of Wood Lake (Green, 1970) and in the Shagawa Lake quadrangle (Sims, 1972).

Intrusive Rocks

Four distinct Lower Precambrian magmatic episodes have been recognized in the Vermilion district (Morey and others, 1970; Sims, 1972; and Sims and others, 1972). Plutonic rocks were emplaced during or following the Algoman orogeny. Hypabyssal and plutonic rocks, in approximate order of age from oldest to youngest, are: (1) synvolcanic bodies, including metadiabase and hypabyssal porphyries having a wide range in composition; (2) syntectonic granitic rocks of the Saganaga, Giants Range, and Vermilion batholiths; (3) late- or post-tectonic syenitic rocks and related lamprophyres; and (4) the post-tectonic alkalic Linden pluton, west of Tower, and the Icarus pluton east of Saganaga Lake in Ontario. In addition, diabasic dikes of Middle Precambrian and basaltic dikes of Late Precambrian age cut the Lower Precambrian rocks.

The synvolcanic intrusive bodies form small, irregular plutons, sill-like bodies, and dikes, and range in composition from gabbro to rhyodacite. Abundant andesite is found, although metadiabase is the most common rock type.

The rocks of the three granitic batholiths border and partially surround the volcanic-sedimentary sequence, and have profoundly affected the supracrustal rocks. The Giants Range batholith (Figure 1) transects the sequence and in areas southwest and east of Ely has cut out its lower part. The batholith consists of several distinct plutons; the eastern part is composed primarily of hornblende adamellite and granodiorite, while the western part is more varied in composition and ranges from tonalite to granite. The Vermilion Granite complex, on the northern side of the district, cuts the upper part of the volcanic-sedimentary sequence. It is composed dominantly of biotite granite, but locally contains more mafic plutonic rocks. The Saganaga batholith at the eastern end of the district consists mainly of tonalite. It intrudes mafic volcanic rocks and is overlain by the Knife Lake Group. All the batholiths were emplaced synchronously with regional deformation and metamorphism, and were deformed locally by the late Algoman faulting (Sims, 1972).

Syenitic rocks that appear to be late syntectonic or post-tectonic intrude the Knife Lake Group in the eastern part of the district, and cut metavolcanic and metasedimentary rocks in the western part. The syenitic rocks form small, generally discordant plutons that range in composition from diorite to syenite. They appear to represent a family of syenitic rocks that were emplaced under a relatively shallow cover late in the Algoman orogeny, for the rocks contain strongly zoned plagioclase, local miarolitic cavities, and discordant contacts (Morey and Sims, 1972). Lamprophyres are spatially associated with some of the syenitic stocks and consequently may be related to this magmatic episode. The lamprophyres occur both as dikes and as crudely elliptical plutons.

The youngest of the Algoman intrusive rocks are the Linden and Icarus alkalic plutons. The two are similar in composition and structure and are interpreted as being post-tectonic (Sims, 1972).

The granodiorite stock in the Boulder Bay area has not been dated radiometrically. However, it is texturally similar to the late-syntectonic to post-tectonic syenitic intrusions and likewise has discordant contacts. It is probably related to the third magmatic episode.

METAVOLCANIC, METASEDIMENTARY,
AND METAGABBROIC ROCKS

Introduction

Quartz veins and eight major rock units were delineated in the Boulder Bay area (Plate 1). These units include basalt flows, gabbro sills or stocks, banded iron formations, muscovite phyllite, graywacke, rhyolite sills or bodies, a granodiorite stock and apophyses, and dacite dikes (Table 1). All rocks were metamorphosed under greenschist facies conditions and show varying degrees of cataclasis depending on their proximity to fault zones.

Metabasalt Flows

Metabasalt flows with a wide variety of textures are the dominant rocks in the Boulder Bay area (Plate 1) (Table 1) (Appendix II, Table 1). These flows are commonly massive, aphanitic to fine grained, light to dark green on fresh surfaces, and weather to lighter shades of green (Plates 4 and 5). Varying degrees of schistosity are developed depending on proximity to fault zones (Plate 6). Locally, the basalts are pillowed and have thin pillow rinds, 5 mm wide or less (Plate 7). Chert occurs as interpillow material where

TABLE 1. Boulder Bay Area Rock Types and Alterations With Petrographic Features

ROCK TYPE	PETROGRAPHIC FEATURES
Massive Metabasalt	Plagioclase phenocrysts; groundmass (70-90%) predominantly chlorite, epidote, amphibole; locally pyrite-bearing (10-15%).
Variolitic Metabasalt	Mineralogically similar to massive metabasalt except varioles comprise 10-15% of the rock and consist of ≤20% radiating plagioclase crystals and ≥80% clay minerals as alteration of pyroxene (?).
Fragmental Metabasalt	Mineralogically similar to massive flows except volcanic (basalt) rock fragments comprise ≤30% of the rock.
Magnetite-Rich Metabasalt	Mineralogically similar to massive flows, but contain 15-20% magnetite rimmed by hematite and goethite.
Sheared Metabasalt	Mineralogically similar to massive flows, but contain 20-30% carbonate and quartz; cataclastic textures are prevalent; rock is schistose.
Metabasalt in Contact Aureole	10-15 foot wide contact aureole around granodiorite stock; zone irregular and locally absent. Inner zone contains abundant quartz and calcite; outer zone contains abundant sericite and calcite and is gradational with inner zone and unaltered metabasalt.
Meta-Quartz Gabbro	Medium- to coarse-grained; consists predominantly of augite (40%) and saussuritized plagioclase (40%); hornblende (20%) rims augite as alteration product.
Banded Iron Formation	Alternating silica-rich layers (jasper and chert) and iron-rich layers (magnetite and hematite); locally pyrite-bearing (10-15%).

Muscovite Phyllite	Sheared and foliated. Muscovite (60-70%) and quartz (30-40%); either sedimentary or volcanic origin; evidence of two deformations.
Schistose Metagreywacke	Plagioclase and quartz grains (20-30%); rare rock fragments; groundmass of sericite, chlorite, carbonate, and quartz (70-80%); a recrystallized sediment or tuff.
Metarhyolite Intrusives	Plagioclase (An_{10}) phenocrysts in groundmass of feldspar, quartz and sericite; some shearing; foliated; evidence of 2 deformations.
Granodiorite	Plagioclase phenocrysts (An_{22}-An_{28}) (30-60%) in matrix of microcline (10-20%), quartz (10-15%), and hornblende (5-15%); locally sheared; altered near quartz veins; carries sulphide-bearing quartz veins.
Dacite Dikes	Plagioclase (20-30%), amphibole (5-15%) and microcline (5-15%) phenocrysts in groundmass (30-60%) of feldspar and quartz. Most abundant dike present and found cross-cutting all rock units in area except for stock. Locally sheared.
Quartz Latite Dikes	Plagioclase, microcline and amphibole microphenocrysts (5-15%) in groundmass (85-95%) of quartz and feldspar. Prevalent pink color due to hematite. Up to 5 cm wide. Occurs within stock and in immediately surrounding metabasalts.
Granite Dike	Medium-grained, pinkish, and relatively unaltered. Microcline and plagioclase crystals commonly intergrown with quartz. 2-3 cm wide. Rare occurrence, with one noted at depth in granodiorite.

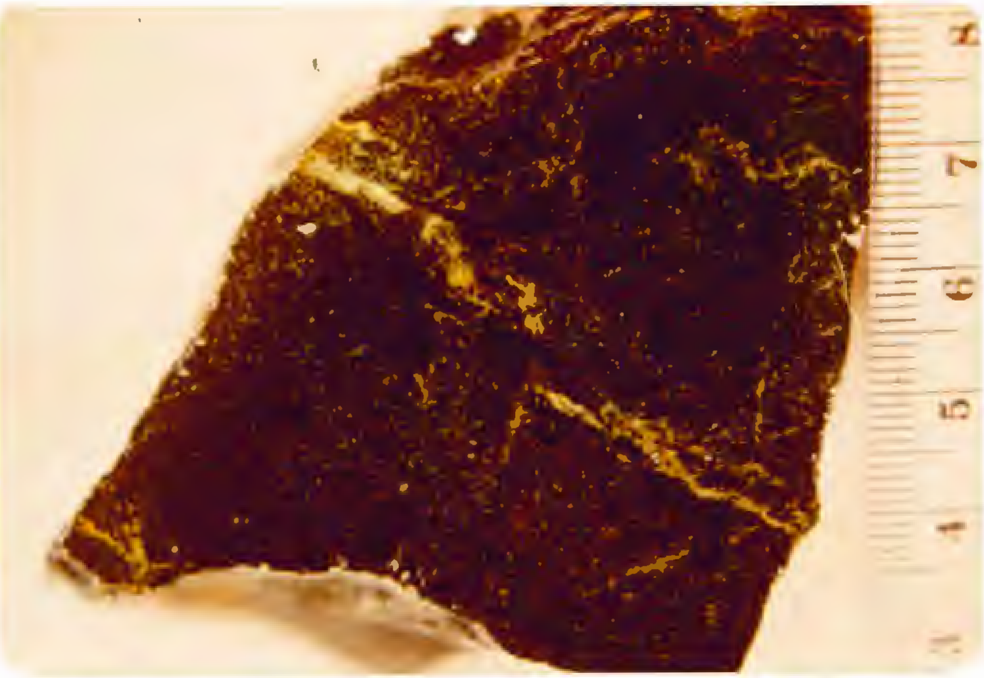


PLATE 4. Photograph of metabasalt with greenschist facies metamorphic assemblage of epidote, chlorite, amphibole, quartz, and plagioclase. Note irregular epidote veinlets. Scale in cm. Sample no. ALT-8E.

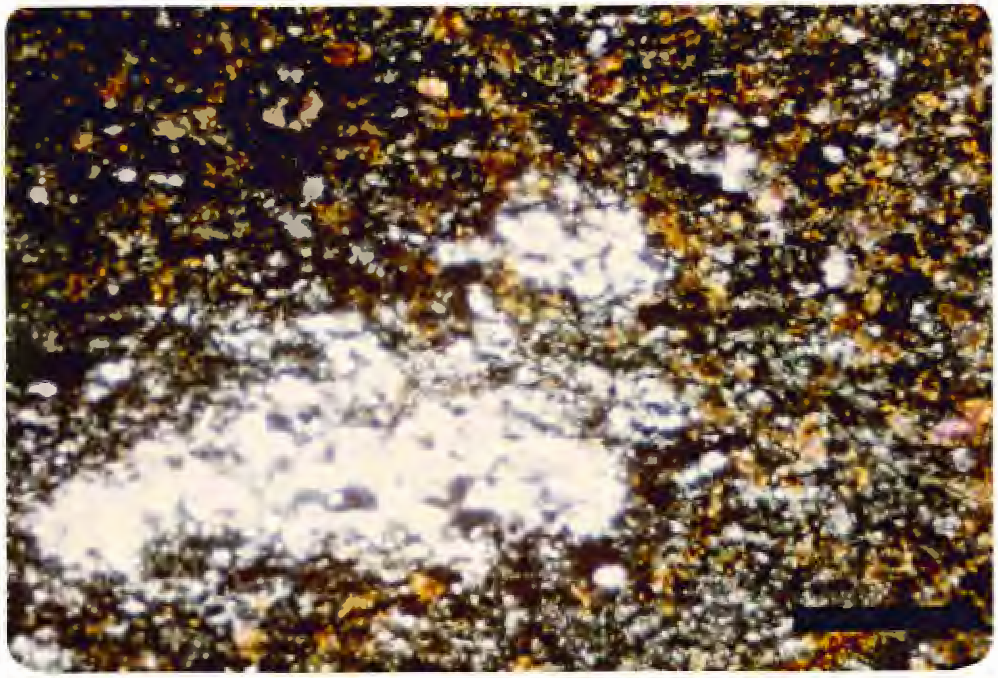


PLATE 5. Photomicrograph of metabasalt flow with greenschist facies metamorphic assemblage of epidote, chlorite, quartz, plagioclase, and opaques. Note stretched quartz amygdule. Crossed polars. Bar=0.5 mm. Sample no. ALT-31.

PLATE 6. Photograph of highly schistose metabasalt sample with crenulations in rock cleavage. Rock taken from fault zone. Scale in cm. Sample no. 10-3.

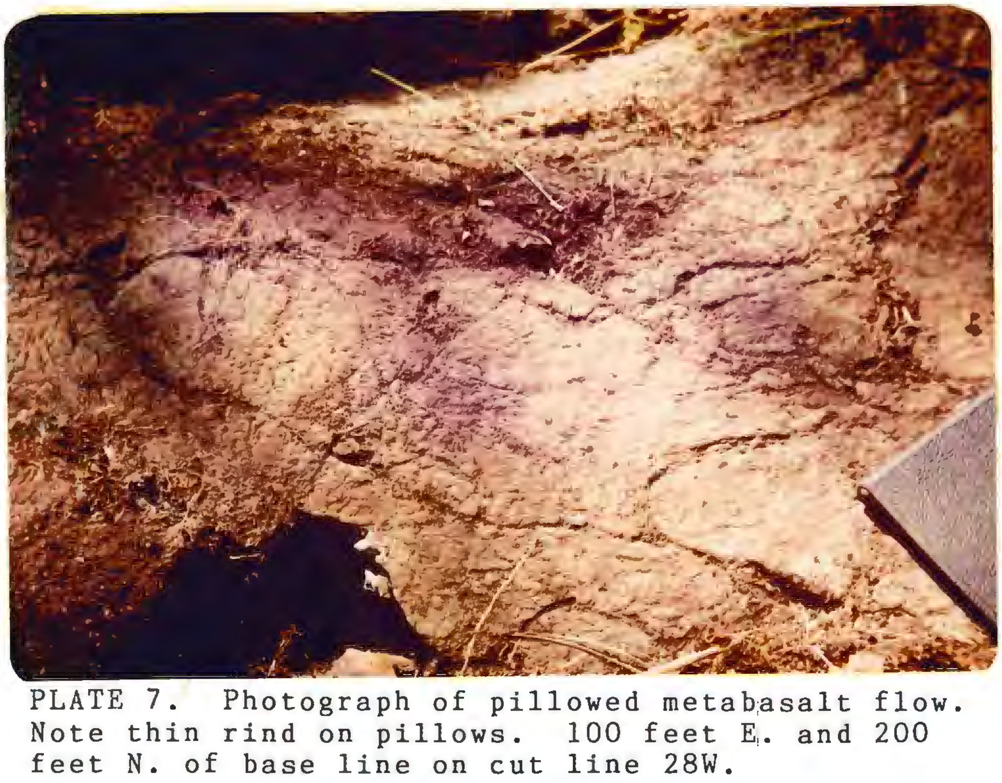


PLATE 7. Photograph of pillowed metabasalt flow. Note thin rind on pillows. 100 feet E. and 200 feet N. of base line on cut line 28W.

present. Variolitic flows (Plate 8) and pyroclastic rock containing small breccia fragments occur in units which in places reach a maximum thickness of 7 meters. Locally, the basalts are magnetic and contain fine euhedral magnetite crystals.

The presence of pillows in the flows indicate deposition in a subaqueous environment. The textural variations in the metabasalts probably reflect varying cooling rates with differing degrees of supercooling depending on location within the flow (Schulz, 1977).

Epidote occurs in small (1 to 2 cm wide) pods and irregular veinlets within the metabasalts. The relative abundance of epidote increases from the southwestern portion of the Boulder Bay area to the northeastern part. In the southwestern part of the study area, epidote may volumetrically occupy up to 2 percent of the rock, whereas in the northeastern portion the percentage increases to approximately 10 percent. Similarly, discontinuous and irregular dark grey chert horizons and pods up to 10 cm in thickness are present in the metabasalts. They increase in relative abundance to the northeast.

The metabasalts are hypidiomorphic. Chlorite, amphibole, and epidote together make up 70 to 90 percent of the rock, with the relative amount of each varying between samples (Plates 4, 5, and 6). Chlorite is moderately pleochroic, has anomalous interference

PLATE 8. Photograph of light green varioles in variolitic metabasalt. Sample from a localized thin horizon in more massive metabasalt flows. Scale in cm. Sample no. 44-20.

colors, and occurs as ragged patches and microcrystalline grains in the groundmass. The amphibole minerals present in the metabasalts include both actinolite and hornblende. Granular epidote is present as dusty-looking grains in the groundmass.

Variable amounts of quartz, carbonate minerals, opaques, sericite and relict plagioclase are present. Relict sericitized plagioclase crystals have Carlsbad and Albite twins and are rarely larger than 5 mm. Aphanitic to microcrystalline untwinned plagioclase and quartz is found in the groundmass. Quartz grains are strained and have an undulatory extinction. Fine-grained quartz-filled amygdules (2 mm) may be present and are commonly elongate. A network of fine quartz veinlets crosscut local portions of the metabasalts and are often associated with fine grained carbonate filled fractures. Pyrite occurs as euhedral grains in all of the basalts and makes up 10 to 15 percent of the rock in some instances. Many of the pyrite crystals have pressure shadows occupied by ribboned quartz, and more rarely, by chlorite.

Variolitic and fragmental metabasalts (Table 1) (Appendix II, Table 1) are uncommon and when present occur in thin units (7 meters wide) interbedded with massive metabasalts and are mineralogically similar to them. The varioles are light green on fresh surfaces and buff colored on weathered ones. They commonly weather to relief (Plate 8). They may form up to 10 to 15 percent of the rock, and are approximately 1 cm in size. Fine plagioclase crystals can be distinguished in the varioles under the microscope. Basaltic pyroclastic rocks contain volcanic rock fragments which are slightly finer grained and of the same composition as the matrix. These fragments can form up to 30 percent of these rocks. In one sample, elongated fragments are present and are approximately three times as long as they are wide.

Magnetite-bearing metabasalts (Table 1) (Appendix II, Table 1) occur as small discontinuous units interbedded with the non-magnetite-bearing flows. These rocks are commonly darker colored than the nonmagnetic flows and contain variable amounts of magnetite rimmed by hematite and goethite.

Sheared metabasalts (Table 1) (Appendix II, Table 1) are abundant in the southern portion of the Boulder Bay area, where the flows are faulted (Plate 1). Massive and sheared metabasalts are mineralogically similar although the latter commonly contain more quartz and carbonate, and are schistose (Plates 4 and 6). Small crenulations in the schistosity are common and cataclastic textures are prevalent. Relict quartz-filled amygdules exhibit mortar texture and the beginning of recrystallization. Sheared and foliated calcite and ankerite pods with discontinuous trails of fine-grained carbonate also indicate deformation of the rock.

Fault breccia (Appendix II, Table 1) is locally present within the metabasalts. These zones vary from several centimeters to 3 meters in width and are especially conspicuous in drill core. Fragments are commonly no larger than 2 centimeters in their longest dimension and are composed of silicified leucoxene-rich metabasalt and sheared vein quartz. The matrix is composed of coarse-grained calcite with deformed twin lamellae. Very fine chlorite veinlets cut across the breccia zones.

Metagabbro Intrusions

Two metamorphosed quartz gabbro intrusive bodies are exposed in the Boulder Bay area (Table 1) (Appendix II, Table 2). These rocks form some of the larger hills in the area and are thought to occur as sills, or possibly stocks, intrusive into the metabasalts. The rock is green to dark green and weathers to lighter shades of green. Locally, the intrusions are crosscut by epidote veinlets, or contain small (1 cm or less) epidote pods.

The quartz gabbro is medium to coarse-grained and contains subophitic clinopyroxene which weathers in relief (Table 1) (Appendix II, Table 2). Subophitic augite partially encloses randomly oriented highly saussuritized plagioclase laths (Plates 9 and 10).

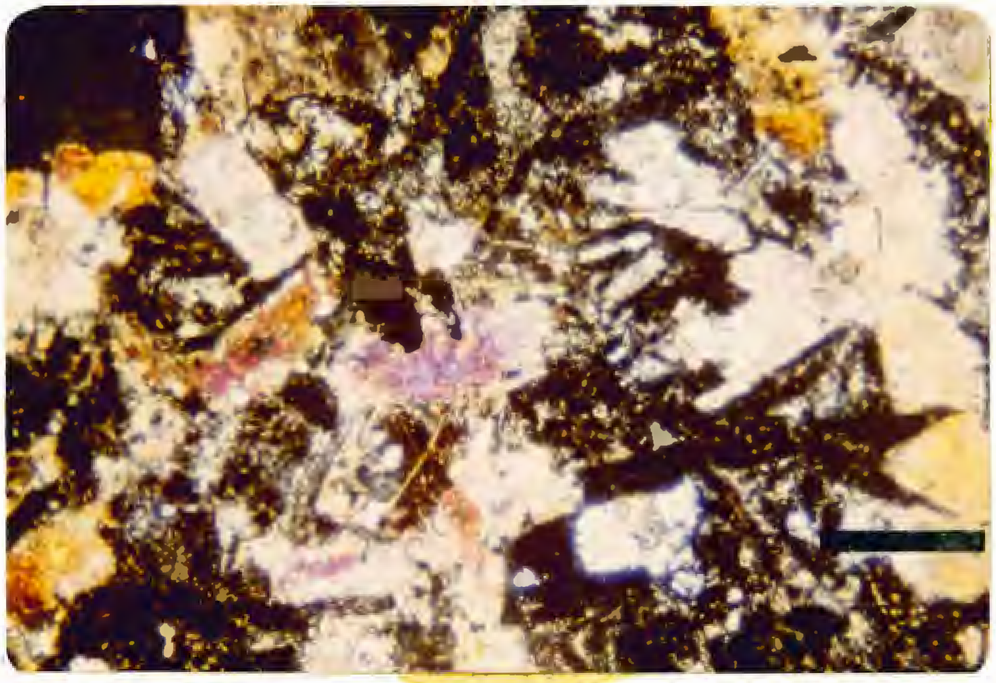


PLATE 9. Photomicrograph of quartz gabbro with subophitic augite, semiopaque plagioclase, interstitial quartz, and skeletal magnetite. Crossed polars. Bar=1 mm. Sample no. 48-21.

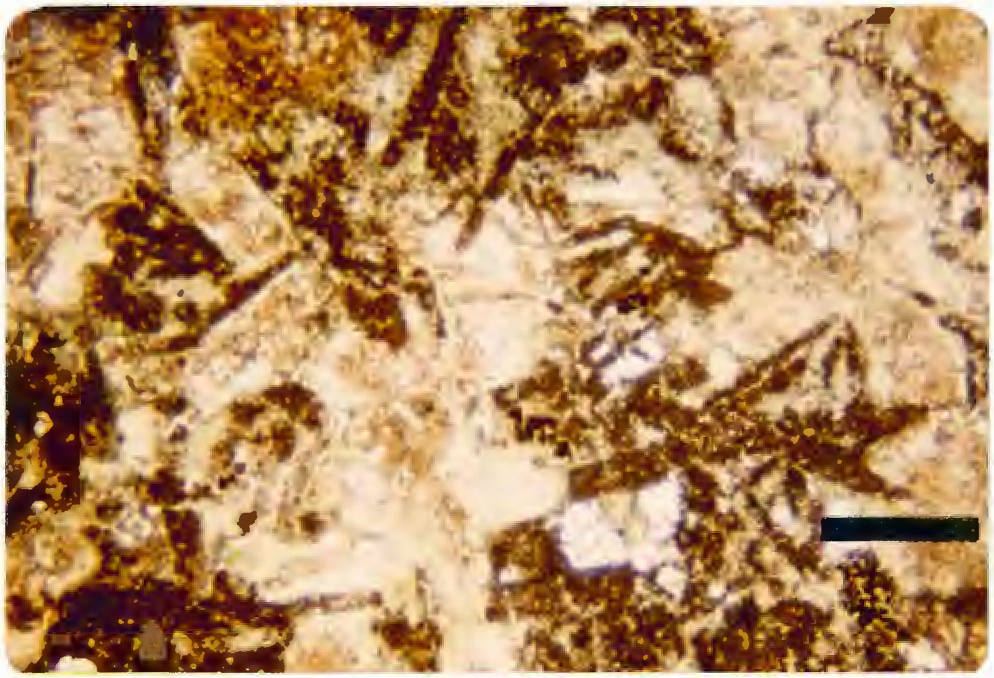


PLATE 10. Photomicrograph of quartz gabbro. Same as Plate 9, except uncrossed polars. Note pale green amphibole rims on clinopyroxene. Bar=1 mm. Sample no. 48-21.

Dusty augite crystals approximately 1 mm long make up 40 percent of the rock, and are altered to jade green-colored hornblende on rims and along fractures (20%). Plagioclase is semiopaque as a result of alteration to saussurite and makes up 40 percent of the rock. Trace amounts of unstrained quartz and orthoclase occur as fine grains interstitially.

The metagabbro bodies form sills or possibly stocks. Distinguishing metagabbro from metabasalt flows is often difficult in hand sample. Exposed contacts between the two are rare. Where such contacts are visible, no contact effects, such as chilled margins or alteration, are observed in either the metagabbro or the host rock. The compositional similarity and close spatial association of the metagabbro plutons to the metabasalt flows points to their being comagmatic (Schulz, 1977).

Banded Iron Formation

A number of banded iron formations occur in the Boulder Bay area as lensoidal bodies and pods, some beds being continuous for thousands of feet (Plate 1). The largest exposures are in the northern half of the area, with several scattered occurrences in the southern portion. Most of the iron formations are folded on both a large and small scale (Plates 1 and 11). A magnetometer survey was used to locate the iron formation across covered intervals between exposures. Exposed iron formation in the center of the Boulder Bay area

PLATE 11. Photograph of banded iron formation with minor folds parallel to hammer handle. 950 feet S. of baseline on cut grid line 12 W.

PLATE 12. Photograph of slightly sheared banded iron formation with 10 to 15 percent disseminated pyrite preferentially concentrated in iron-rich layers. The silica rich layers are white quartz. Scale in cm. Sample no. 40-2.

helps to delineate a large northeasterly plunging syncline with a 600 foot long northern limb and a southern limb at least 4,400 feet long.

Iron formation consists of alternating silica-rich and iron-rich layers, each of which is commonly up to a few centimeters thick (Table 1; Appendix II, Table 2). Purplish to red jasper and black to white chert are common. Magnetite and quartz or hematite and quartz form the iron-rich layers. Dark grey tuffaceous layers, less than 1 centimeter thick, are interbedded locally.

The iron formations are pyrite-bearing in the northwestern portion of the area. A maximum of 10 to 15 percent euhedral to subhedral fine-grained pyrite is preferentially concentrated in iron-rich layers (Plate 12).

Iron formation containing granular hematite without discrete silica-rich layers is located on the north end of cut line 48W (Plate 1). The rock is very fissile and is cut by a lattice-like network of many small silicified fractures.

Muscovite Phyllite

Muscovite phyllite is abundant in the northern half of the Boulder Bay area (Plate 1). The rock commonly forms small discontinuous knobs and rounded hills, or is found as small chips (5 cm diameter) in the soil with no topographic expression.

The rock is aphanitic, micaceous, and pale greenish grey in color on fresh surfaces and grey where weathered. Crenulations, 1 to 2 centimeters across, are commonly developed in the schistosity of the rock. Disseminated iron oxides and trace amounts of pyrite occur along foliation surfaces (Plate 13).

The phyllite has a well developed foliation defined by microcrystalline muscovite with a strong lattice preferred growth orientation (Plate 14) (Table 1; Appendix II, Table 2). A small amount of muscovite has recrystallized along and parallel to the axis of prevalent crenulations in the schistosity.

Quartz occurs in fine lamellae parallel to the foliation (Plate 14). Grains of quartz range in size from fine to microcrystalline ($\leq$.25 mm), are commonly strained, and are flattened. Fine grained pyrite is commonly altered to iron oxides. Some pyrite has pressure shadows containing quartz and is wrapped by the foliation.

Rocks mapped by Sims and Mudrey (1978) southwest of the Boulder Bay area are tuffaceous and locally agglomeratic and are thought to be continuous with the micaceous phyllite found in the Boulder Bay area.

Schistose Metagreywacke

A 10 foot wide exposure of metagreywacke was found 900 feet north of the base line on grid line 32W in the Boulder Bay area (Plate 1). In this exposure, the

PLATE 13. Photograph of muscovite phyllite sample. Note slight crenulations in schistosity, pale grey-green micaceous appearance, and iron oxides after pyrite along foliation planes. Scale is in cm. Sample no. 52-8.

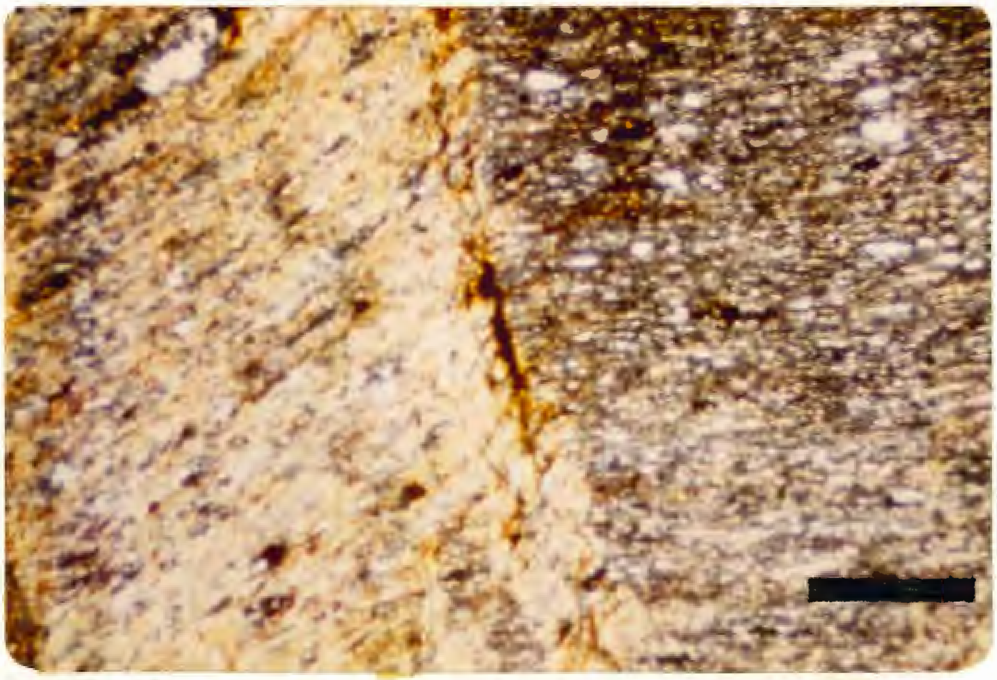


PLATE 14. Photomicrograph of muscovite phyllite. Note crenulation in foliation, abundance of muscovite with lattice preferred growth orientation, lenses of iron oxides, and fine grains of quartz. Crossed polars. Bar=1 mm. Sample no. 52-8.

rock is in contact with a small metarhyolite dike or sill, which separates it from a metabasalt flow. There is no evidence of alteration of the metagreywacke along the contact with the dike. Fine-grained flattened pyrite crystals are visible along small fractures which crosscut both units.

The metagreywacke (Table 1; Appendix II, Table 2) is pale green on fresh surfaces, green where weathered, finely schistose, and commonly is stained with iron oxides. No bedding was noted in outcrop. Fine-grained rock fragments and quartz and feldspar occur as clasts in the rock. A majority of the clasts are strained quartz which is locally ribboned and has undergone recrystallization. Mortar texture is locally developed. Sericitized fine-grained to aphanitic plagioclase grains are also present. The rock matrix is microcrystalline and consists of chlorite, sericite, quartz, and carbonate. Sericite, flattened plagioclase and quartz grains, and rock fragments delineate the foliation (Plates 15 and 16).

The presence of rock fragments and crystals in the metagreywacke indicates either an epiclastic or pyroclastic origin. Thus, the metagreywacke might be an andesitic or dacitic tuff (see whole rock analysis) since shearing and recrystallization have obscured original rock textures.

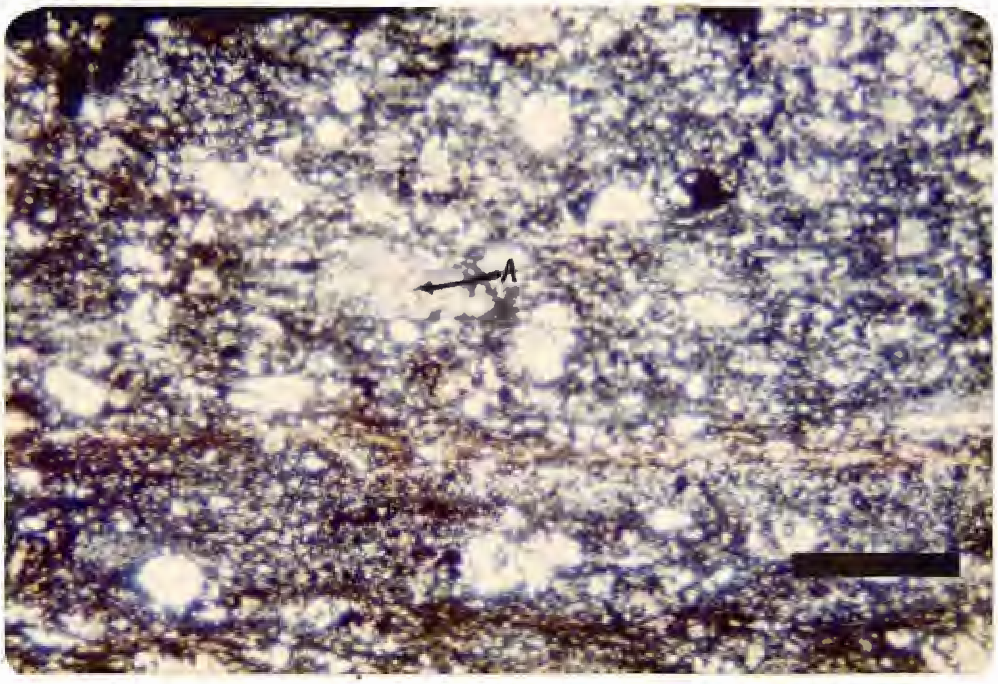


PLATE 15. Photomicrograph of schistose metagreywacke with abundant quartz crystals and rare rock fragments (A), in a microcrystalline matrix of chlorite, sericite, quartz, and carbonate. Note flattening of clasts parallel to foliation. Crossed polars. Bar=1 mm. Sample no. 32-9N.

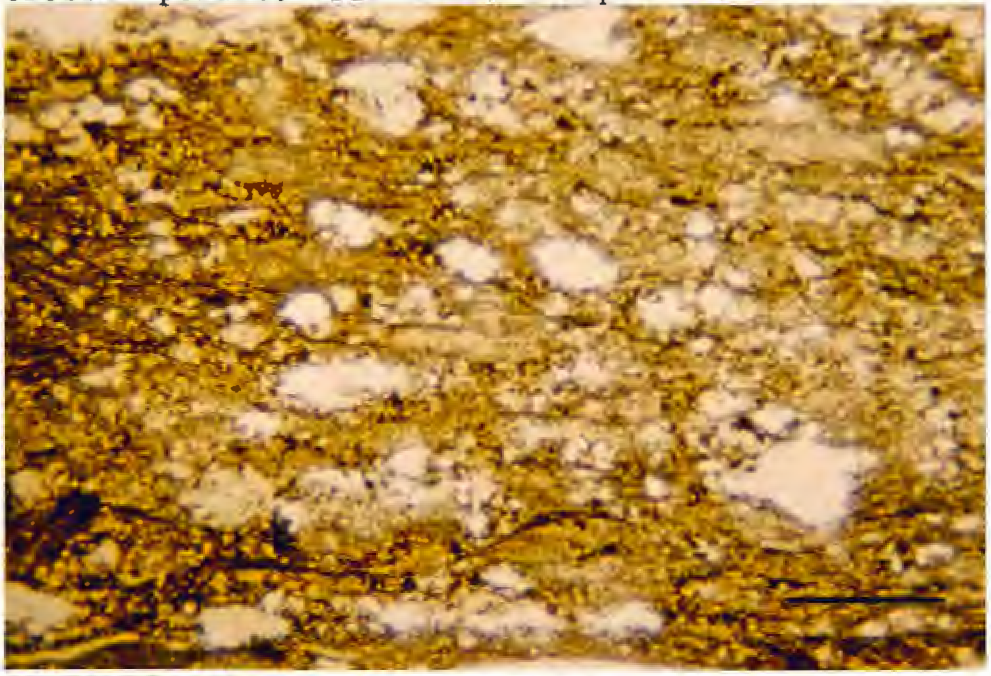


PLATE 16. Photomicrograph of schistose metagreywacke. Note flattened clasts and abundance of chlorite and sericite in this portion of the sample. Uncrossed polars. Bar=1 mm. Sample no. 32-9N.

Metarhyolite Intrusions

Metarhyolite occurs as lenticular sills or bodies, up to 400 feet long and 150 feet wide (Plate 1). These are in contact with iron formation, metagreywacke, and metabasalt flows. The contacts are sharp and lack chilled margins, and contain no visible evidence of assimilation, contact metamorphism, or cross-cutting relationships.

In hand sample the metarhyolite is aphanitic, tan colored on fresh surfaces, and white where weathered. Disseminated iron oxides occur in irregular fractures, with small pods and veinlets of carbonate.

The metarhyolite (Table 1; Appendix II, Table 3) contains broken microphenocrysts of fairly fresh plagioclase in a fine-grained to microcrystalline groundmass (Plate 17). Plagioclase grains are bimodal in size with a few 1 to 2 millimeters in length and the majority about 0.5 millimeters long. Many plagioclase crystals are strained, have an oscillatory extinction, and deformed twin lamellae, while other grains exhibit little evidence of deformation. Some crystals have twin lamellae offset by microfractures. Mortar texture is locally prominent.

The groundmass is dominantly microcrystalline, strained, and consists of quartz, feldspar, disseminated iron oxides, and sericite. The sericite delineates the spaced schistosity of the rock and has a

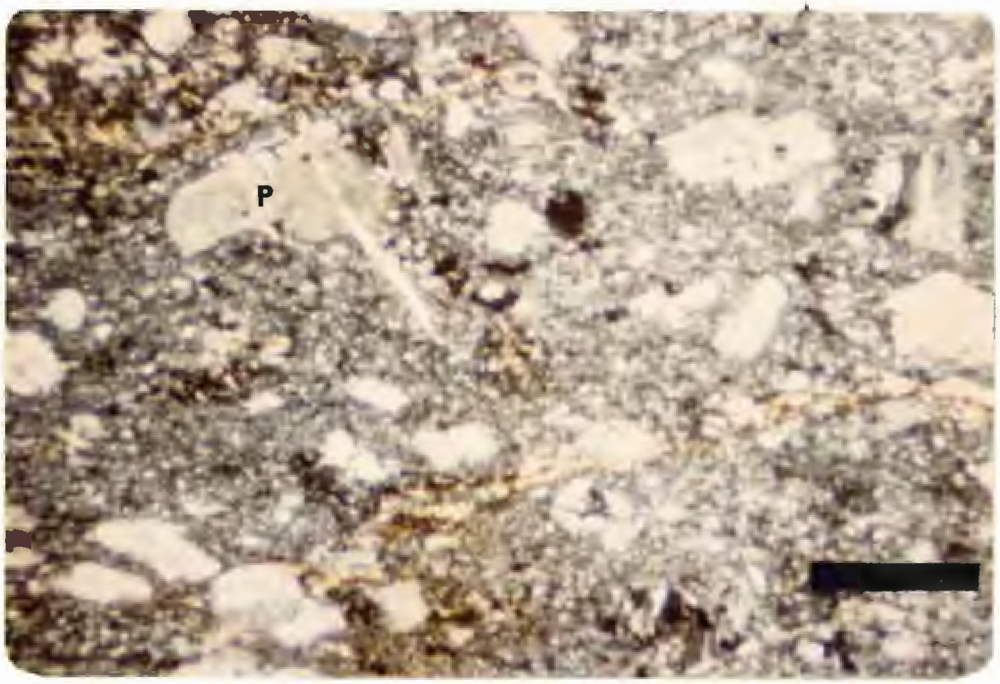


PLATE 17. Photomicrograph of metarhyolite sill with locally broken microphenocrysts of plagioclase in groundmass of microcrystalline quartz, feldspar, iron oxides, and sericite. Crossed polars. Bar=1 mm. Sample no. 44-31.

strong lattice-preferred growth orientation. Locally, some sericite is recrystallized at high angles to the foliation, indicating a second deformation.

Summary of Stratigraphy and Petrology

The dominant rock type present in the Boulder Bay area is metabasalt. The basalts exhibit a variety of textures, and with the interbedded metasediments are the oldest rocks in the area. They are intruded by granodioritic and gabbroic rocks. The basalts have been metamorphosed to greenschist facies with typical mineral assemblages consisting of chlorite-amphibole-epidote, chlorite-epidote-actinolite-albite, and chlorite-amphibole-epidote-albite-(calcite)-(quartz). The basalts include massive, pillowed, variolitic, and fragmental flows. They are all locally sheared.

Basalts in the Boulder Bay area were probably deposited in a subaqueous environment. The development of the variety of textures in the flows may reflect different cooling rates dependent on location within the flow. During the Algoman orogeny the basalts were metamorphosed under greenschist facies conditions, and locally deformed by faulting and folding.

Two quartz gabbro intrusions are exposed in the southwest portion of the Boulder Bay area. They appear to be either sills or stocks and are intrusive into the metabasalts. The close spatial association and compositional similarity of the metagabbro bodies to the metabasalt flows suggests the metagabbro is an intrusive equivalent of the metabasalt, and/or point to their being comagmatic.

Lensoidal bodies and pods of banded iron formations are interbedded with metabasalts in the northern half of the Boulder Bay area. Banded iron formation is thought to have been deposited in shallow basins during quiescent periods in volcanic activity. Fine grained tuffaceous layers locally interbedded with iron formation may have been deposited directly into basins as ash falls, or transported into the basins by water. The close association of iron formation and volcanic rocks throughout the Vermilion district suggests a volcanic source for the iron formations and possible deposition by volcanic exhalative processes (Sims, 1972; Goodwin, 1962). Local abundant sulphides with associated carbonate in iron formation may represent hydrothermal additions to the rock.

Abundant muscovite phyllite is present in the northern half of the Boulder Bay area. The unit has been intruded by rhyolite sills or stocks in the northwestern part of the area. A single small exposure of schistose metagreywacke was found in the north central Boulder Bay area. Both metasedimentary rock types have undergone deformation and recrystallization with primary textures virtually obliterated. The rocks originally may have been either volcanic or sedimentary.

Metarhyolite occurs as either sills or stocks in the northwestern Boulder Bay area. Some shearing of the rock has occurred, and a spaced schistosity and crenulation cleavage define two deformations.

The presence of metarhyolite, iron formation, and felsic tuffaceous metasediments in the dominantly metabasaltic terrain of the Boulder Bay area may indicate an interfingering between mafic units to the northeast and felsic to intermediate units to the southwest. Felsic and intermediate rocks mapped by Sims and Mudrey (1978) to the southwest as tuffaceous and locally agglomeratic units are thought to be the coarse-grained equivalent of the muscovite phyllite found in the Boulder Bay area. Siliceous marbles north of the Boulder Bay area (Sims and Mudrey, 1978) may also indicate an increase in felsic to intermediate rock types in the area. Green (1970) recognized compositionally similar felsic rock types, including siliceous marbles, in the northeastern end of the Newton Lake Formation where felsic and intermediate rocks interfinger with mafic rocks.

Chemistry of Metavolcanic, Metasedimentary, and Metagabbro Rocks

One representative sample each of massive metabasalt, sheared metabasalt, magnetite-rich metabasalt, metagabbro, metagreywacke, and muscovite phyllite from

from the Boulder Bay area were sent to X-Ray Labs, Don Mills, Ontario, for whole rock analysis by X-ray fluorescence (Table 2). Rock samples selected are typical of greenschist facies rock units, or are altered portions of the units from the alteration zone around the granodiorite stock. Locations of the rock samples are shown in Plate 1. The samples were analyzed to distinguish similarities and differences in chemistry between the Boulder Bay area rocks, rocks from other portions of the Vermilion district, and rocks from the Superior Province of the Canadian Shield.

These analyses are representative of rocks in the Boulder Bay area, but they are inadequate for determining systematic regional or stratigraphic chemical characteristics. The limited number of samples precludes the definition of a chemical trend in the rocks and can only suggest chemical affinities in a general sense. Metasomatic changes in rock chemistry can occur during metamorphism and/or burial even though a rock is not visibly altered.

The normative minerals and A-F-M ratios were calculated from analyses of the Boulder Bay rocks. The metagreywacke, basaltic, and gabbroic rocks are olivine and hypersthene normative. The phyllite has quartz and corundum in the norm.. It should be noted that analyses of sediments give only a rough approximation of their source rock chemistry, since weathering, transport and

Sample number used in Figures 4 and 5 this chapter.
Field sample number; Rock name; description.

1B	44-10; Basalt; Massive greenstone flow.
2B	28-16S; Basalt; Schistose greenstone from fault zone.
3B	48-17; Basalt; Magnetite-bearing massive greenstone flow.
4GO	12-7; Gabbro; Subophitic meta-quartz gabbro stock or sill.
5W	32-1; Schistose metagreywacke; Crystal-lithic tuffaceous metasediment.
6P	52-13N; Phyllite; with abundant muscovite.
7G	P-7; Granodiorite; Surface sample of the porphyritic stock.
8G	RZ-4-9; Granodiorite; Drill core sample of porphyritic stock 102.8 feet below surface.
9G	RZ-4-23; Granodiorite; Drill core sample of stock 242.5 feet below surface.
10AG	ALT-P; Granodiorite; Altered margin of porphyritic stock in contact with basaltic flows.
11AB	20-5; Basalt; Silicified, pyritic, carbonate rich greenstone flow in inner zone of contact metasomatic aureole around granodiorite stock.
12AB	16-9S; Basalt; Sericitized and carbonate-rich greenstone flow in outer zone of contact metasomatic aureole around granodiorite stock.

TABLE 2. Identification of Rocks Chemically Analyzed From the Boulder Bay Area.

deposition can considerably alter their original chemical composition.

Whole rock analyses from the Boulder Bay area are compiled in Tables 3 and 4. Average chemical compositions of Archean rocks in the Superior Province are shown in Table 5, whereas other analyses from the Vermilion district are shown in Tables 6 and 7.

Plots of the Boulder Bay samples, with the exception of the magnetite-rich basalts, show a subalkaline trend on an alkali versus silica diagram (Figure 4). Irvine and Baragar's (1971) line was used to divide the alkaline field from the subalkaline field. The magnetite-rich basalt falls in the alkaline field.

The Boulder Bay samples were also plotted on a calc-alkaline versus tholeiitic classification scheme to determine source rock chemistry (Figure 5). In the diagram, the metabasalts and metagabbro units plot within the tholeiitic field. These results suggest a similar chemical source for the gabbroic and basaltic rock units.

This limited sampling of rocks from the Boulder Bay area show some of the characteristic properties of Archean volcanic rocks such as low alkalis, especially K_2O (Goodwin, 1968; Tables 5 and 6). Boulder Bay rocks are similar to rocks in other portions of the Vermilion district since they compare favorably with Green's (1970) samples from the Newton Lake Formation (Table 7, Figures 4 and 5).

	44-10	28-16S	48-17	12-7	32-1	52-13N	P-7	RZ-4-9	RZ-4-23	ALT-P	20-5	16-9S
SiO_2	47.50	47.30	52.70	44.60	64.80	63.80	62.30	62.40	59.40	76.00	42.10	52.80
TiO_2	0.84	1.90	1.56	0.50	0.79	0.48	0.35	0.37	0.36	0.09	1.60	2.15
Al_2O_3	14.20	15.30	13.70	13.40	15.30	17.10	16.60	16.80	17.80	12.70	11.30	20.30
Fe_2O_3	1.24	1.49	1.12	1.09	0.99	0.78	0.29	0.31	0.32	0.07	1.23	0.34
FeO	10.08	12.06	9.09	8.81	8.00	6.34	2.38	2.53	2.56	0.57	9.99	2.79
MnO	0.19	0.24	0.19	0.15	0.13	0.05	0.03	0.05	0.06	0.02	0.27	0.10
MgO	7.69	5.52	4.40	13.00	2.56	2.30	2.00	2.20	2.29	0.16	2.45	1.09
CaO	11.70	5.65	5.03	9.62	0.59	0.28	2.79	3.60	4.25	1.46	8.17	8.44
Na_2O	1.52	2.59	5.77	0.99	2.59	1.77	5.24	5.74	6.11	6.62	4.58	5.33
K_2O	0.29	0.17	1.42	0.52	1.51	1.80	2.53	2.41	2.39	0.45	1.00	1.13
P_2O_5	0.07	0.27	0.25	0.12	0.14	0.08	0.24	0.22	0.25	0.04	0.24	0.33
CO_2 & H_2O (L.O.I.)	1.77	7.15	2.08	3.69	3.31	3.85	2.62	1.62	1.23	1.31	8.92	2.54
TOTAL	97.09	99.64	97.31	96.49	100.67	98.63	97.38	98.25	97.02	99.49	91.85	97.34

TABLE 3. CHEMICAL ANALYSES OF ROCKS FROM THE BOULDER BAY AREA.

	44-10	28-16S	48-17	12-7	32-1	52-13N	P-7	RZ-4-9	RZ-4-23	ALT-P	20-5	16-9S
Quartz	0.84	5.32	0	0	34.74	38.99	12.47	8.72	2.57	32.92	0	.481
Orthoclase	1.71	1.00	8.39	3.07	8.92	10.64	14.95	14.24	14.12	2.66	5.91	6.68
Albite	12.86	21.92	47.90	8.38	21.58	14.98	44.34	48.57	51.70	56.02	24.74	46.15
Anorthite	31.07	26.44	7.29	30.59	2.10	0.92	12.43	12.96	14.09	3.61	7.32	27.82
Corundum	0	1.16	0	0	8.70	11.90	0.69	0	0	0	0	0
Nepheline	0	0	0.50	0	0	0	0	0	0	0	7.59	5.40
Diopside	21.72	0	13.39	13.20	0	0	0	2.93	4.49	2.17	26.92	8.78
EN	6.26	0	3.35	4.62	0	0	0	0.91	1.40	0.40	4.57	6.06
FS	4.37	0	3.28	1.72	0	0	0	0.51	0.78	0.70	9.08	0.74
WO	11.09	0	6.76	6.86	0	0	0	1.51	2.31	1.08	13.28	1.98
Hypersthene	21.88	28.28	0	21.04	16.74	14.08	7.86	7.15	6.70	0	0	0
EN	12.89	13.75	0	15.33	6.38	5.73	4.98	4.57	4.30	0	0	0
FS	8.99	14.53	0	5.70	10.36	8.35	2.88	2.58	2.40	0	0	0
Olivine	0	0	11.11	12.27	0	0	0	0	0	0	3.43	0
FO	0	0	5.33	8.70	0	0	0	0	0	0	1.08	0
FA	0	0	5.77	3.57	0	0	0	0	0	0	2.36	0
Magnetite	3.61	4.32	3.25	3.16	2.86	2.27	0.85	0.91	0.92	0.20	3.58	0.93
Ilmenite	1.60	3.61	2.96	0.95	1.50	0.91	0.66	0.70	0.68	0.17	3.04	4.25
Apatite	0.15	0.59	0.55	0.26	0.31	0.17	0.52	0.48	0.55	0.09	0.52	0.67
Acmite	0	0	0	0	0	0	0	0	0	0	0	1.85
TOTAL	95.45	92.64	95.35	92.91	97.46	94.86	94.79	96.66	95.82	98.18	83.06	102.99

TABLE 4. NORMS OF ROCKS FROM THE BOULDER BAY AREA

	Basalt	Andesite	Dacite	Rhyodacite	Rhyolite
SiO_2	48.90	54.70	61.50	67.30	74.30
Al_2O_3	14.30	15.00	15.70	14.80	12.90
Fe_2O_3	2.14	2.00	1.83	1.17	0.74
FeO	9.03	7.64	4.49	3.44	2.22
MgO	6.27	4.50	2.38	1.55	0.85
CaO	8.74	6.39	4.41	3.13	1.48
Na_2O	2.51	2.79	3.15	3.07	2.47
K_2O	0.45	0.55	1.16	1.40	2.10
H_2O	3.34	2.92	2.27	1.56	1.17
CO_2	1.93	1.93	2.18	0.98	0.86
TiO_2	1.06	0.99	0.63	0.51	0.26
MnO	0.21	0.28	0.16	0.08	0.10
P_2O_5	0.07	0.12	0.12	0.07	0.07
TOTAL	98.95	99.81	99.98	99.06	99.52

TABLE 5. AVERAGE CHEMICAL COMPOSITIONS OF ARCHEAN VOLCANIC ROCKS IN THE SUPERIOR PROVINCE OF THE CANADIAN SHIELD (After Goodwin, 1968).

	M-7251	EG-17	M-7441	M-7112	M-7509
SiO_2	51.06	50.90	63.61	66.75	69.55
TiO_2	1.44	1.33	0.61	0.28	0.37
Al_2O_3	13.85	16.05	13.91	15.56	17.05
Fe_2O_3	1.79	2.33	1.64	1.42	0.62
FeO	10.86	8.66	3.90	1.20	0.44
MnO	0.22	0.18	0.09	0.03	0.01
MgO	5.31	6.15	4.00	0.92	0.68
CaO	10.66	9.30	4.27	3.18	1.77
Na_2O	2.49	2.06	5.23	5.60	5.84
K_2O	0.25	0.76	0.43	1.73	1.72
H_2O+	1.83	1.74	2.27	1.42	1.81
H_2O-	0.06	n.d.	0.11	n.d.	0.18
CO_2	0.33	0.00	0.53	1.62	0.58
P_2O_5	0.13	0.20	0.14	0.07	0.09
TOTAL	100.28	99.66	100.77	99.78	100.72

TABLE 6. CHEMICAL COMPOSITION OF ARCHEAN VOLCANIC ROCKS FROM THE VERMILION DISTRICT (After Green, 1970).

Sample no., normative name, descriptive name.

M-7251	Basalt, pillowed greenstone.
EG-17	Basalt, subdiabasic basalt.
M-7441	Intermediate dacite, pillowed metavolcanic.
M-7112	Rhyodacite, sheared porphyry.
M-7509	Rhyodacite, trachytic felsite.

	M-7527	M-7152	M-7194	M-7441	M-7548	M-7560
SiO_2	51.45	57.83	58.79	63.61	60.55	54.72
TiO_2	0.98	0.79	0.67	0.61	0.53	0.76
Al_2O_3	11.60	13.39	15.81	13.91	15.99	14.77
Fe_2O_3	3.24	2.44	3.70	1.64	2.44	2.37
FeO	8.24	5.07	4.09	3.90	3.13	4.92
MnO	0.19	0.20	0.10	0.09	0.08	0.11
MgO	7.73	2.69	4.44	4.00	3.50	3.77
CaO	11.09	7.16	2.86	4.27	6.95	7.94
Na_2O	2.62	3.84	5.59	5.23	4.14	3.29
K_2O	0.08	0.23	0.20	0.43	0.86	0.68
H_2O+	2.44	3.44	3.33	2.27	2.17	3.16
H_2O-	n.d.	0.14	0.16	0.11	0.06	0.23
CO_2	0.00	2.87	0.53	0.53	0.10	3.06
P_2O_5	0.22	0.24	0.14	0.14	0.11	0.17
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
S	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
TOTAL	99.88	100.33	100.41	100.77	100.61	99.95

TABLE 7. CHEMICAL COMPOSITION OF NEWTON LAKE FORMATION ROCKS FROM THE GABBRO LAKE QUADRANGLE (After Green, 1970).

Sample no.,	normative name, descriptive name.
M-7527	Quartz tholeiite, variolitic pillowed greenstone.
M-7152	Dacite, amygdaloidal subtrachytoid greenstone.
M-7194	Andesite, massive greenstone.
M-7441	Andesite, porphyritic bulbous-pillowed metavolcanic flow.
M-7548	Andesite, unwelded tuff-breccia.
M-7560	Quartz basalt, tuff-breccia.

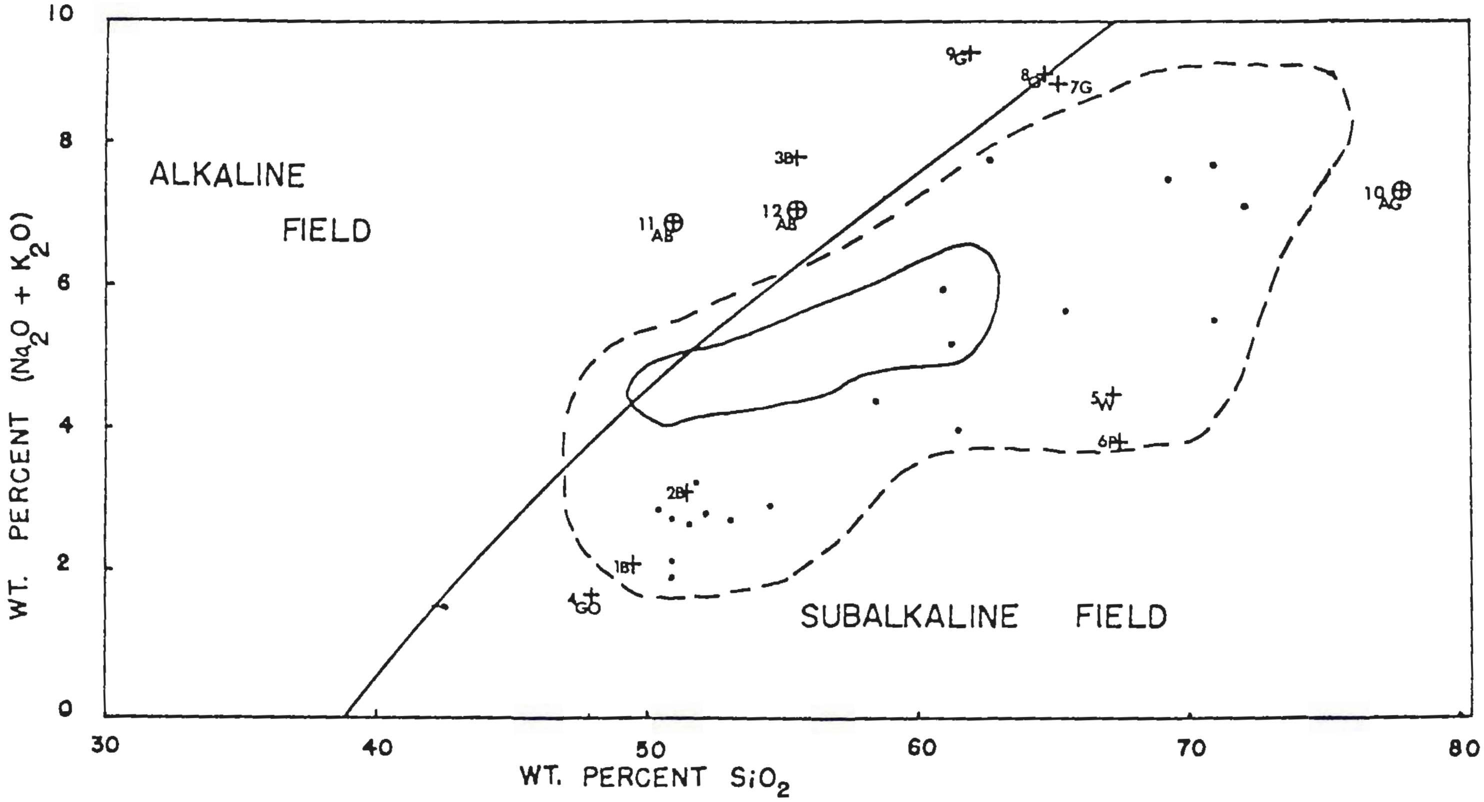


FIGURE 4 - ALKALI-SILICA PLOT, IN WEIGHT PERCENT. The dividing line is after Irvine and Baragar (1971). B-Basalt; GO-Gabbro; W-Greywacke; P-Phyllite; G-Granodiorite; A-Altered. See Table 2 for Sample Identification.

+ Unaltered Boulder Bay samples

⊕ Altered Boulder Bay samples

• Vermilion District samples (After Green, 1970)

– – – Aleution Samples (After Irvine and Baragar, 1971)

—— Paricutin Region Samples (After Irvine and Baragar, 1971)

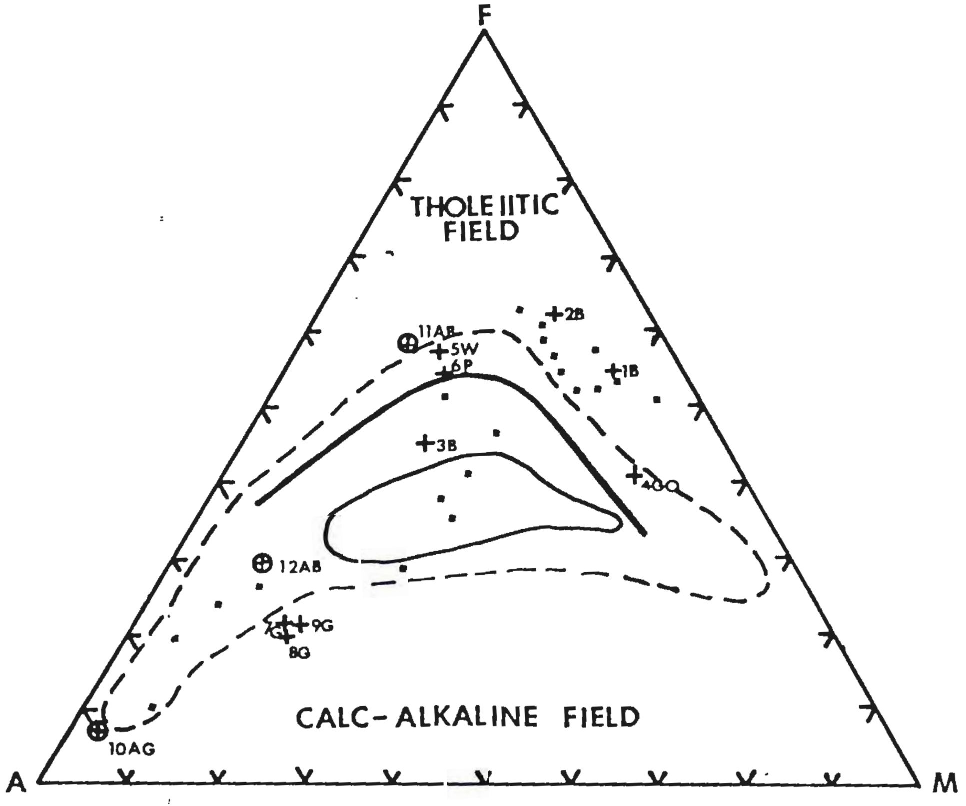


FIGURE 5' - PLOT OF ALKALIS, TOTAL FE OXIDES, AND MgO. Line separates tholeiitic field from calc-alkaline field. B=Basalt; GO=Gabbro; W=Greywacke; P=Phyllite; G=Granodiorite; A=Altered (Table 2).

+ Unaltered Boulder Bay Samples

⊕ Altered Boulder Bay Samples

• Vermilion District Samples (after Green, 1970)

- - - Aleution Samples (after Irvine and Baragar, 1971)

—— Paricutin Region Samples (after Irvine and Baragar, 1971)

Schulz (1977) concluded from detailed sampling and trace element analyses of magnesian rich mafic members of the Newton Lake Formation that the members studied consist of at least two chemically distinct types of komatiitic flows. The basis for this conclusion was a large number of trace element analyses taken of the Newton Lake Formation, which were not done on samples taken for this study. Trace element determinations are a valuable method for distinguishing between komatiitic and tholeiitic rock chemistries.

Green's (1970) analyses of less magnesian rocks of the Newton Lake mafic members clearly indicated a calc-alkaline trend. Although no felsic volcanic rock types were analyzed in this study, Schulz and Green both concluded that the felsic member of the Newton Lake Formation is calc-alkaline.

The similarities of Boulder Bay rock chemistry to rock analyses from the Superior Province given by Goodwin (1968) and Green (1970) suggest that these rocks are similar to other rocks of the Superior Province and may have a continental orogenic, or island arc, origin as suggested by Wilson et al (1965), Schulz (1977), and others.

GRANODIORITE INTRUSION

Introduction

A granodiorite stock intrudes metabasalt flows in the central portion of the Boulder Bay area (Plate 1). The stock is approximately 1,100 feet in diameter, roughly circular in outline, and plunges to the northwest at a high angle (Plate 2). The stock contains mineralized quartz veins and local zones of alteration. The contact between the granodiorite and metabasalts is somewhat irregular, nearly vertical, and commonly sheared. The stock and associated granodiorite apophyses are interpreted by the author to be epizonal and syntectonic (Algoman orogeny, 2.7 b.y.).

Petrography

The granodiorite is weakly porphyritic and contains medium- to coarse-grained plagioclase phenocrysts in a finer-grained matrix of amphibole, quartz, and potassium feldspar (Plate 18) (Table 1; Appendix II, Table 3). Oligoclase phenocrysts exhibit strong oscillatory zoning. The phenocrysts contain finely disseminated hematite which stains the crystals a reddish color (Plates 20 and 21). The euhedral greenish hornblende occurs as fine to medium-grained crystals and is locally altered to biotite, chlorite, and opaques. Subhedral

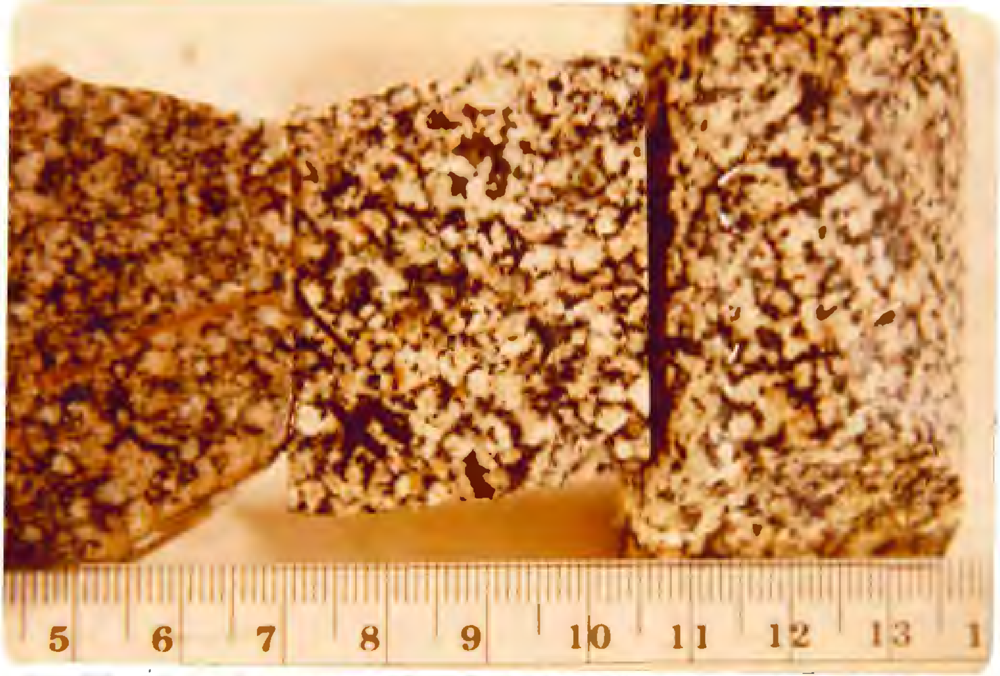


PLATE 18. Photograph of granodiorite with hornblende, microcline, zoned plagioclase phenocrysts, and late interstitial quartz. Note quartz latite dikelet and reddening of plagioclase by disseminated hematite. Scale in cm. From left, Sample nos. RZ-1-12C, RZ-4-2, RZ-4-19.

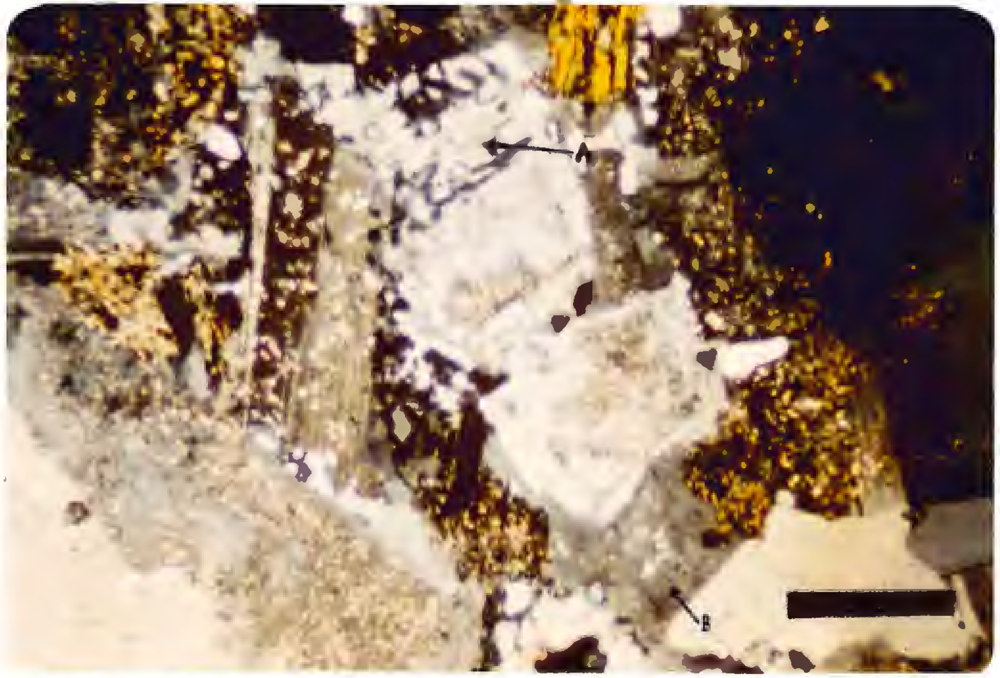


PLATE 19. Photomicrograph of granodiorite with micrographic rims on plagioclase phenocrysts (A) and microcline (B). Crossed polars. Bar=1 mm. Sample no. P-11.

microperthitic microcline occurs as fine grains and is poikilitic and locally graphic in texture (Plate 19). Quartz is fine-grained and strained, and is intergrown with microcline and plagioclase phenocrysts (Plate 20). Fine to aphanitic plagioclase and potassium feldspar are present in the groundmass.

The granodiorite stock is locally visibly altered near quartz veins and veinlets. The alteration is zoned around the veins and is discussed in a later section of this chapter. Texturally and mineralogically little vertical change is noted in the granodiorite to depths of 280 feet, as indicated by drill hole samples.

The granodiorite is locally cut by faults which vary in size from small fractures, visible only in thin section, to 2 foot wide zones of brecciation. Faulting and fracturing appear to be randomly oriented and form no visible pattern. One of the larger brecciated fault zones is found at the surface in a pit between two large quartz veins (Plate 22). Here, angular fragments of granodiorite up to several centimeters across occur in a fine-grained to aphanitic matrix composed of granodiorite debris, and abundant chlorite and carbonate (Plates 22 and 23).

Chemistry of the Granodiorite Intrusion

Three representative, unaltered samples from the granodiorite stock were selected for whole rock analysis.

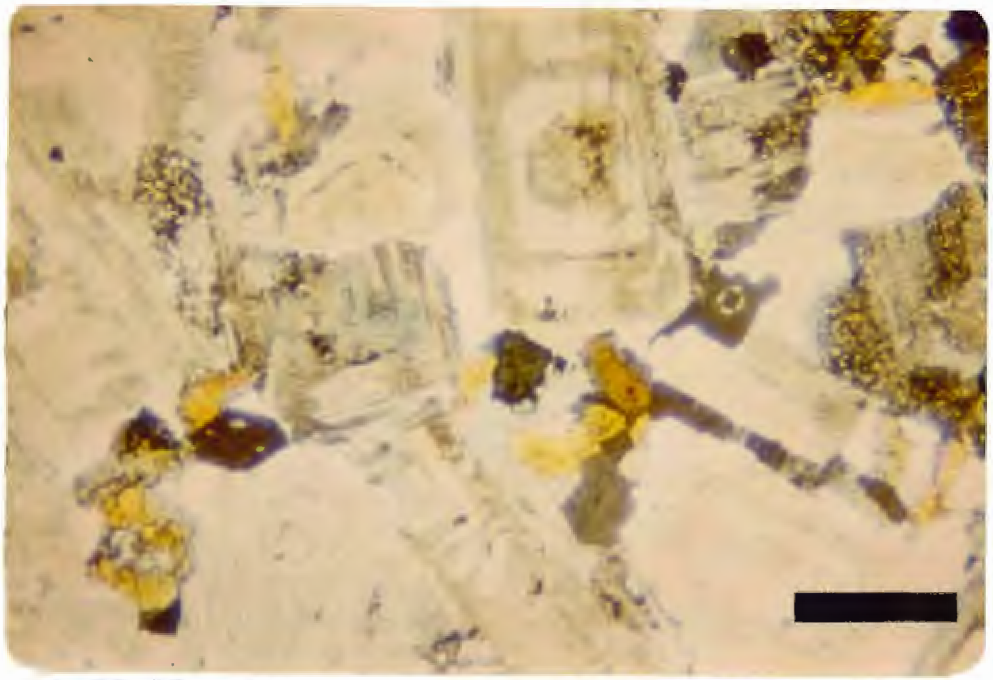


PLATE 20. Photomicrograph of granodiorite with plagioclase phenocrysts exhibiting oscillatory zoning. Interstitial feldspar, euhedral hornblende, and quartz also present. Crossed polars. Bar=1 mm. Sample no. P-11.

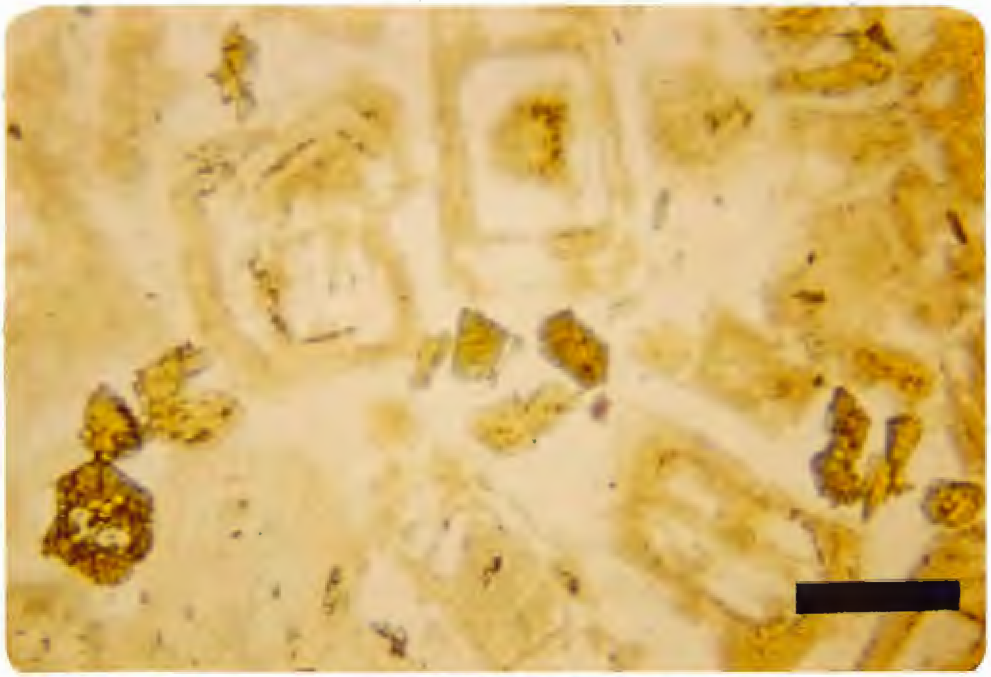


PLATE 21. Photomicrograph of granodiorite. Same as Plate 20, except uncrossed polars. Note zoned alteration of plagioclase phenocrysts. Bar=1 mm. Sample no. P-11.

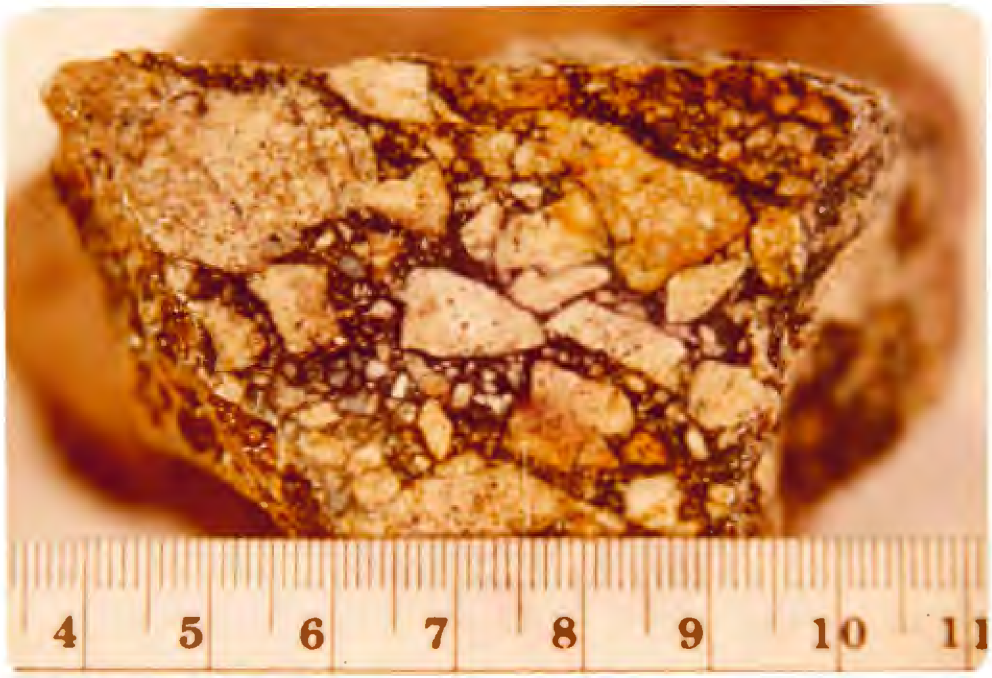


PLATE 22. Photograph of fault breccia from pit in granodiorite stock at surface. Scale in cm. Sample no. MNER-82.

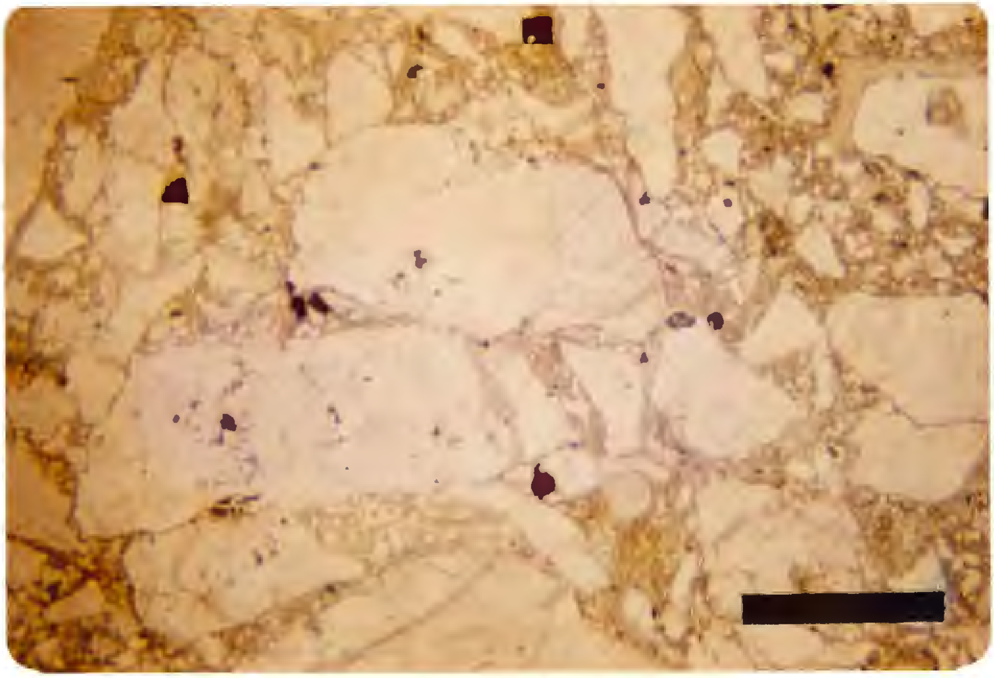


PLATE 23. Photomicrograph of fault breccia from pit in granodiorite stock at surface. Matrix is chlorite, carbonate, and fine rock fragments. Uncrossed polars. Bar=0.5 mm. Sample no. MNER-82.

Sample P-7 was taken from the surface towards the center of the stock (Plate 1), sample RZ-4-9 is from drill core at 102.8 feet below the surface, and sample RZ-4-23 is from drill core at a depth of 242.5 feet (Table 2).

The granodiorite (sample numbers 7G, 8G, and 9G) is chemically calc-alkaline, as shown in Figure 5. The rock is quartz, diopside, and hypersthene normative.

Little chemical variation is observed in the three samples of the granodiorite stock. Figure 6 is a plot of major oxides from whole rock analyses versus depth in feet within the pluton. Volatiles (L.O.I.), K_2O, and SiO_2 decrease with depth; Na_2O, CaO, MgO, MnO, FeO (total), and Al_2O_3 increase with depth; and P_2O_5 and TiO_2 are variable.

Whole rock analyses of the granodiorite compare favorably with analyses of Archean extrusive intermediate rocks in the Superior Province of the Canadian Shield, as tabulated by Goodwin (1968) (Table 3). The granodiorite stock also shows similarities with the compositions, textures, and mineralogies of intrusive dacite porphyries in the Ely Greenstone (Green, 1970) (Table 4), and with extrusive dacites from other portions of the Newton Lake Formation (Green, 1970) (Table 5). These rock types are also typically calc-alkaline.

Porphyritic intrusions having compositions ranging from rhyodacite to andesite are found in the Ely

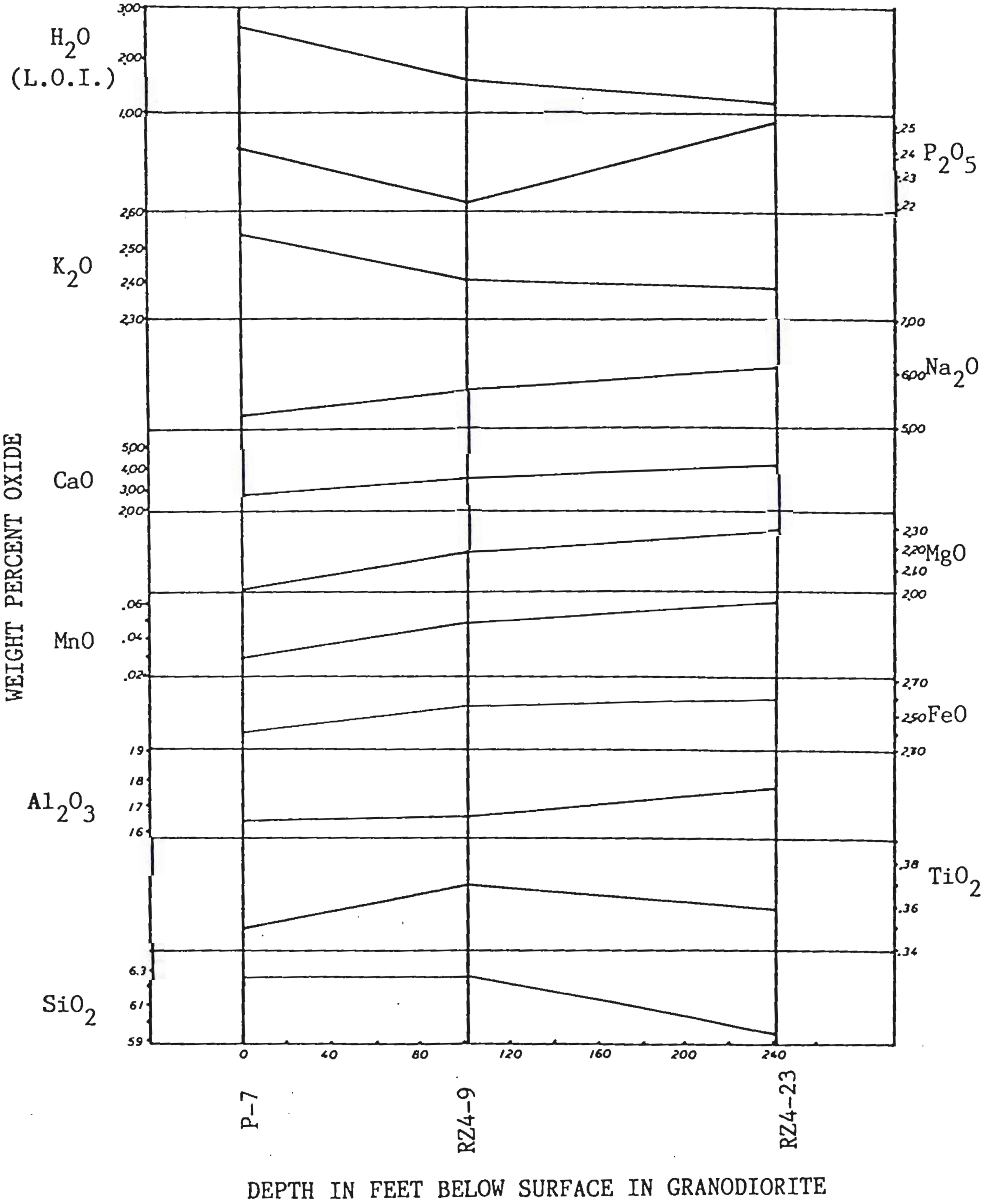


FIGURE 6 - PLOT OF WEIGHT PERCENT OXIDE AND DEPTH IN FEET BELOW THE SURFACE IN THE GRANODIORITE STOCK.

Greenstone, the Knife Lake Group, and the Lake Vermilion Formation. As in the granodiorite stock, plagioclase is the most abundant phenocryst in these intrusions, and often occurs as blocky zoned crystals which are slightly to strongly altered. Other similarities between these intrusions and the granodiorite include quartz, which is nearly ubiquitous, although less abundant than plagioclase; hornblende phenocrysts which show alteration to carbonate, chlorite and epidote; and a microcrystalline groundmass of quartz, plagioclase, and occasional potassic feldspar.

Dikes

Three compositional types of dikes are present in the Boulder Bay area: dacite, quartz latite, and granite (Table 1) (Appendix II, Table 3). Dacite dikes are the most abundant and are found crosscutting all of the rock units in the area except the granodiorite stock. Quartz latite dikes occur within the stock and in the surrounding metabasalt flows, but have not been observed further from the stock than approximately 25 feet. Granite dikes are rare, with one present in the granodiorite at the bottom of drill hole RZ-4 (Plate 1). The quartz latite and granite dikes and veins are among the most felsic rock types present in the area.

Dacite dikes, typically 2 to 5 feet wide, commonly cut the east-northeast trend of rock cleavage at a 5 to 10 degree angle, both clockwise and counter-clockwise to cleavage. The dacite is composed of plagioclase, amphibole, and microcline phenocrysts in a groundmass of feldspar and quartz. The feldspars are weakly altered to sericite and clays, and the plagioclase phenocrysts are commonly reddened by disseminated hematite. Local cataclasis in the dacite dikes is apparent from plagioclase lamellae which are deformed and offset by microfracturing. Fine to medium-grained hornblende phenocrysts are pseudomorphed by chlorite, biotite, and opaques. The groundmass of the dacite is aphanitic to microcrystalline, and consists of anhedral to subhedral feldspars and quartz (Plates 24 and 25).

Quartz latite dikes, the second most common type of dike present in the area, are more prevalent in the granodiorite stock than in the metabasalts surrounding the stock. These dikes have irregular strikes and no visible consistent structural pattern. They have a maximum width of 5 centimeters, but many are no more than 1 centimeter wide. The quartz latite dikes are fine-grained to microcrystalline and are commonly pinkish-red in color, although buff-colored varieties occur as well (Plates 18 and 36).

The quartz latite dikes are composed of plagioclase, microcline, and hornblende microphenocrysts in a microcrystalline groundmass of quartz and feldspar. The feldspar microphenocrysts include euhedral to subhedral unzoned plagioclase crystals and slightly smaller

PLATE 24. Photograph of dacite dike with feldspar, amphibole, and quartz in a fine-grained to microcrystalline groundmass of feldspar and quartz. Scale in cm. Sample no. 12-4.

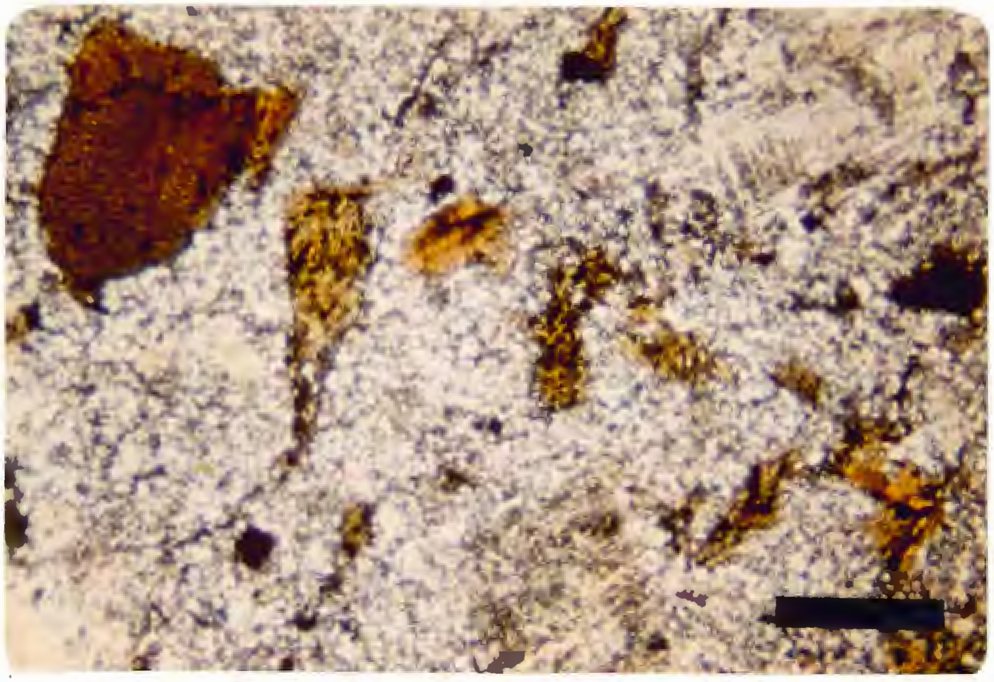


PLATE 25. Photomicrograph of dacite dike with zoned plagioclase phenocrysts in a fine-grained to microcrystalline groundmass of feldspar and quartz. Note large hydrothermal biotites and smaller ones with opaques after hornblende. Crossed polars. Bar=1 mm. Sample no. 36-1.

subhedral microperthitic microcline crystals. (The latter were identified by thin section staining.) The feldspars are slightly altered to sericite and clays. Hornblende occurs in trace amounts as 0.3 mm subhedral to euhedral microphenocrysts. They are largely altered to biotite, chlorite, and opaques. The prevalent pinkish-red color of the quartz latite dikes is due to finely disseminated hematite occurring interstitially to, and within, constituent grains of the dikes. In some samples, the dikes are offset along carbonate-filled microfractures (Plate 26).

Granite dikes, the third and rarest compositional type of dike in the area, were observed in only one drill hole core and were not observed at the surface. The dikes are medium-grained, pinkish in color, and 2 to 3 centimeters wide. The rock consists of microperthitic microcline, anhedral to subhedral plagioclase, and strained quartz, which occurs interstitially to the feldspar crystals. The feldspars are fresh and only locally altered to sericite and clays. The quartz commonly forms graphic and myrmekitic textures with the feldspars.

The mineralogical and textural similarity and spatial association of the dacite dikes to the granodiorite stock suggests that the dikes were injected about the same time the stock was intruded. The dikes represent more rapidly cooled hypabyssal equivalents of

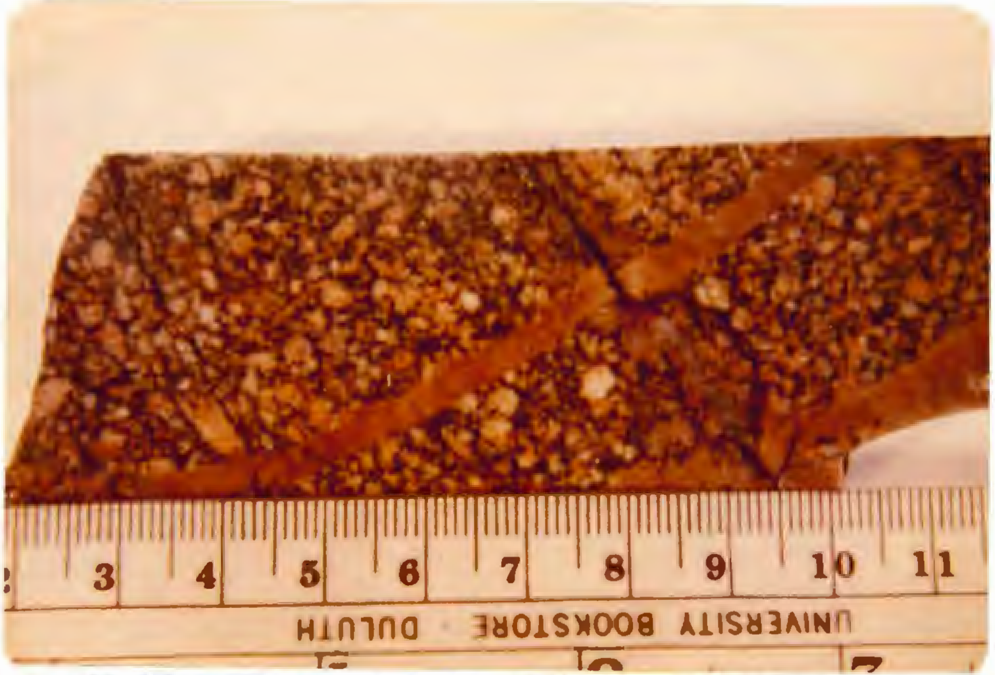


PLATE 26. Photograph of pinkish-red colored quartz latite dikes crosscutting the granodiorite stock in drill core. Dikes are offset along a small fracture. Scale in cm. Sample no. RZ-3-44.

the stock. The quartz latite and granite veins intrude both the stock and the surrounding rocks, thus post-dating the granodiorite.

Quartz Veins

Two types of quartz veins are present in the granodiorite stock: large, subhorizontal mineralized veins and small, irregular veinlets with a wide range in orientation.

Large, white quartz veins are most abundant in the granodiorite stock (Plate 1). Trace amounts of gold and silver mineralization occur in the large quartz veins. The majority of the quartz veins exposed at the surface dip to the south at 5 to 10 degrees, strike in an east-northeast direction, and range in thickness from 1 to 3 feet. Only one vertically oriented vein was found. Quartz veins in drill core may also dip at shallow angles, although the orientation of the veins is difficult to determine in holes drilled at an angle of 45 degrees. It is apparent from crosscutting relationships in drill core that several ages of quartz veins are present. The relationship of quartz veins at the surface with veins at depth in the stock is difficult to determine since many exposures are separated by several hundred feet of granodiorite and veins are only rarely intersected in drill holes.

Quartz veins are best exposed in the single accessible shaft. Here, two quartz veins parallel to one another are separated by 10 to 15 feet of granodiorite which is locally sheared. The veins pinch and swell, ranging in thickness from 6 inches to several feet. The upper quartz vein is monomineralic and barren of mineralization. The lower quartz vein contains abundant small fracture fillings and pods, several inches across, of argentiferous tetrahedrite, galena, chalcopyrite, sphalerite, potassium feldspar, and carbonate.

All of the quartz veins and some of the veinlets are highly sheared. Quartz is commonly deformed and elongate parallel to vein walls, producing ribboned quartz. Incipient recrystallization is common along grain boundaries. Granodiorite is also commonly sheared where close to the veins. Plagioclase phenocrysts are deformed and microfractured up to several inches away from vein contacts (Plate 27).

The subhorizontal orientation of the large quartz veins may be explained by deposition from solutions preferentially channeled along low angle faults or tension cracks. The irregular quartz veinlets may occupy fractures in the stock generated during its cooling. The quartz in the veins and veinlets may represent a late stage hydrothermal phase of the cooling granodiorite magma, a similar phase of a separate felsic magma, or be an early stage of mineralization. The

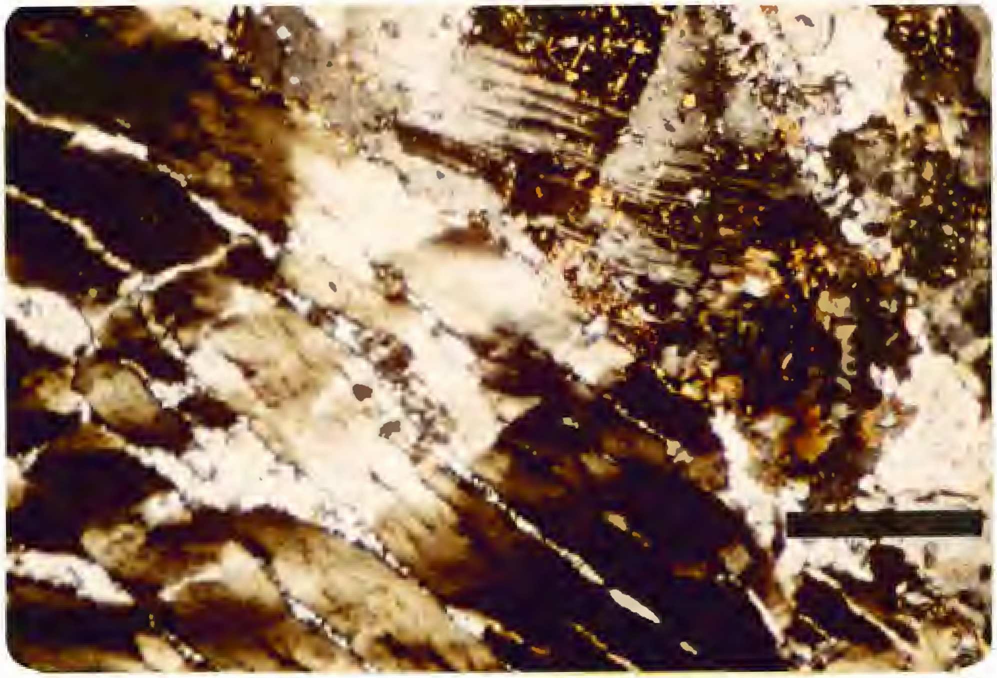


PLATE 27. Photomicrograph of highly ribboned quartz vein (lower left) and cataclastic granodiorite (upper right). Note shearing and fracturing parallel to contact and deformed and fractured plagioclase lamellae near contact. Crossed polars. Bar=0.5 mm. Sample no. 29-9.

presence of ribboned quartz indicates shearing occurred parallel to the vein walls following the deposition of quartz.

Boyle (1978) suggests that large quartz veins in many gold-quartz deposits in the Canadian Shield may have been deposited from metamorphic solutions, rather than solutions derived directly from a magmatic source. Rare earth and trace element studies of ore and gangue minerals from these deposits indicate a more mafic or felsic source for the solutions than the mineralized rock itself. Sulfides and much of the quartz in these deposits appear to have been derived from the alteration of large volumes of rock at depth. The common occurrence of large volumes of altered rock in drill holes near known deposits is cited as evidence.

Contact Metamorphism by the Granodiorite Intrusion

A 10 to 15 foot wide contact metasomatic aureole is developed in the metabasalt flows surrounding the granodiorite stock. The aureole is irregular and may be absent in some areas. Two mineralogic zones are present in the aureole: an inner zone containing abundant quartz and carbonate, and an outer zone with abundant sericite and carbonate (Table 1; Appendix II, Table 1).

Metabasalts of the inner alteration zone are progressively more quartzose and contain increasingly abundant light-colored patches of carbonate as the contact with the granodiorite is approached. At the contact, the metabasalt has a mottled grey-green color with a prevalent rust-colored weathering rind, is strongly silicified, and commonly contains a network of irregular quartz veinlets (Plate 28). In the inner alteration zone the metabasalt consists of quartz, calcite, pyrite, and sericite (Plate 29). Quartz is commonly polygonal and occurs as strain-free, microcrystalline grains. In contrast, quartz in the granodiorite is fine-grained, strained, and occurs in intergrowths with plagioclase and microcline phenocrysts. Calcite in the inner alteration zone occurs as subhedral to anhedral, microcrystalline grains and as small clots of grains. Euhedral to subhedral, fine-grained pyrite is especially abundant at the contact with the granodiorite. Fine-grained anhedral magnetite and ilmenite are present in increasing amounts away from the contact. No chlorite or epidote is present in the rock, although these are common greenschist facies minerals elsewhere in the Boulder Bay area.

The outer metamorphic zone is developed at distances of 5 to 10 feet from the contact with the granodiorite stock and is gradational with the inner zone. Metabasalt in the outer zone is microcrystalline, less quartzose than the inner zone, commonly a greenish color, and contains abundant buff-colored patches with large amounts of sericite. Plate 30 shows a sample in

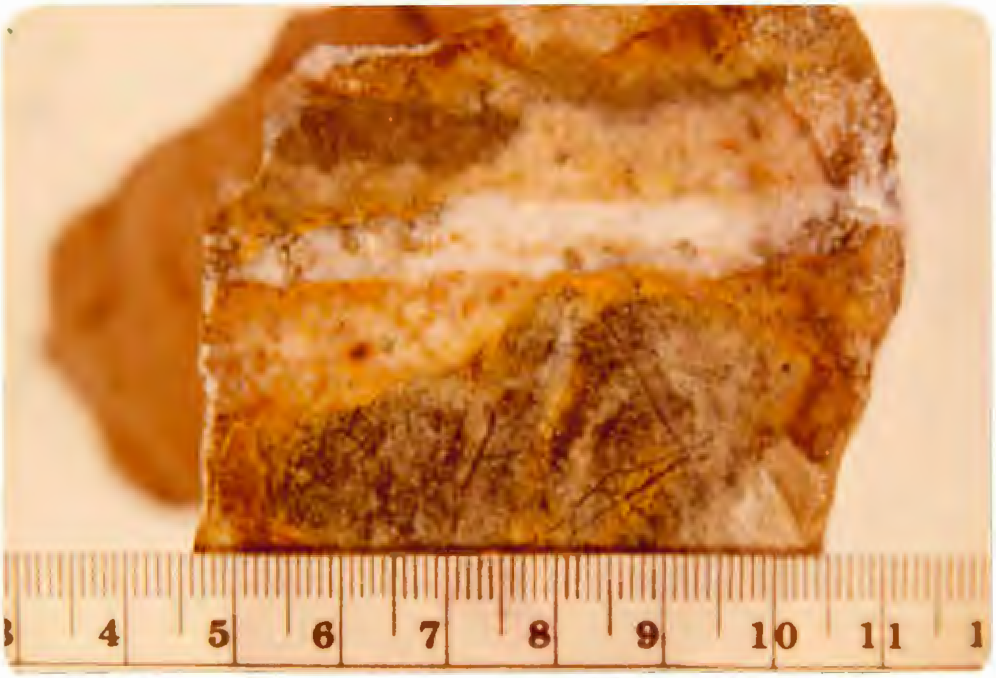


PLATE 28. Photograph of altered basalt from inner zone of contact metasomatic aureole around granodiorite stock. Note "bleached" appearance and crosscutting quartz veinlets. Scale in cm. Sample no. 20-5.

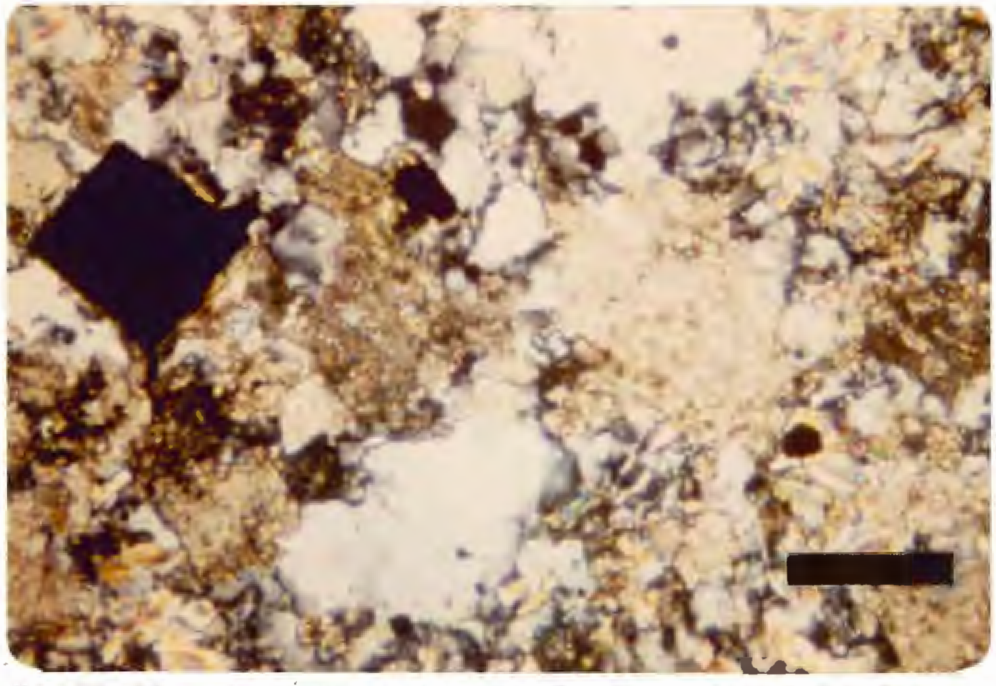


PLATE 29. Photomicrograph of altered basalt from inner zone of contact metasomatic aureole around granodiorite stock showing abundant quartz, carbonate, and pyrite. Crossed polars. Bar=1 mm. Sample no. ALT-1E.

PLATE 30. Photograph of altered basalt from outer zone of contact metasomatic aureole around granodiorite stock. Fine-grained to microcrystalline buff colored alteration assemblage is well developed. Scale in cm. Sample no. 16-9S.

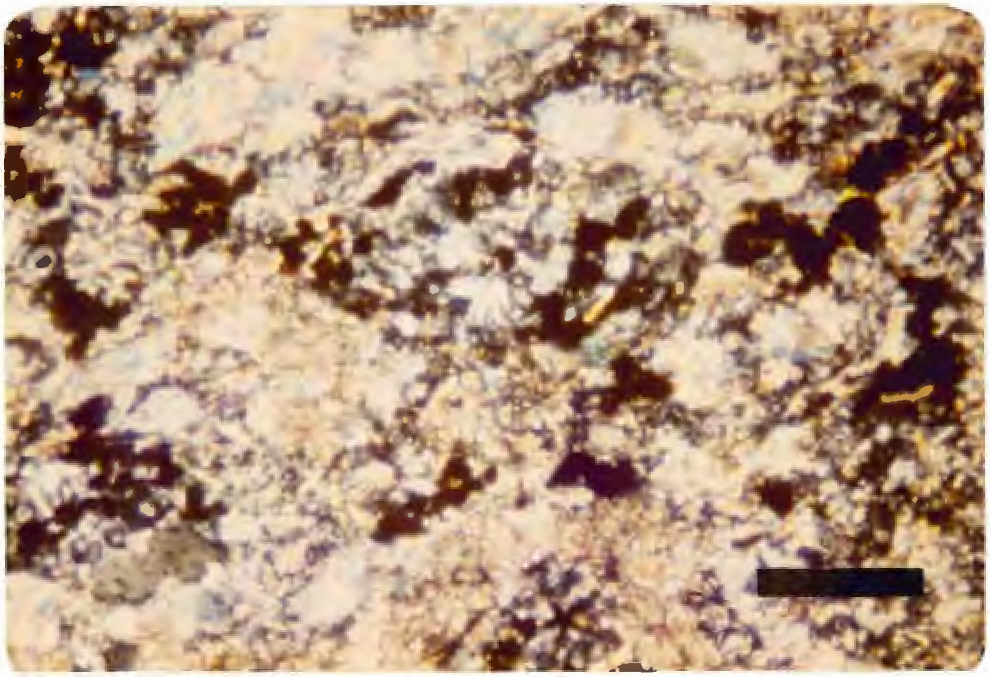


PLATE 31. Photomicrograph of altered basalt from outer zone of contact metasomatic aureole around granodiorite stock with abundant sericite, quartz, carbonate, magnetite, ilmenite, and trace epidote and chlorite. Crossed polars. Bar=0.1 mm. Sample no. ALT-2E.

which the buff colored alteration assemblage is predominant. Sericite, carbonate, and locally, sericitized plagioclase crystals make up the majority of the rock. Strained microcrystalline quartz occurs in small aggregates of grains (Plate 31). The outer zone is gradational with metabasalts that have not undergone alteration. Minerals typical of regionally metamorphosed greenschist facies basalts are present at distances of 15 to 20 feet from the contact with the granodiorite stock.

The granodiorite is locally altered at the contact with the metabasalt flows. Deformed and microfractured plagioclase twin lamellae indicate that the rock has been deformed. A study of drill core shows a change in the granodiorite over distances ranging from several inches to several feet from its contact with metabasalt. There it takes on a buff color and is moderately silicified. The most abundant minerals in this altered zone are sericite and calcite. The groundmass of the granodiorite in this contact zone is fine-grained and commonly contains irregular veinlets of chlorite. The plagioclase phenocrysts are fine-grained (0.5 to 1 mm) and moderately to highly sericitized. Small ($\leq$.05 mm) microperthitic microcline crystals are common. Strained quartz occurs as microcrystalline aggregates. No amphibole is present, and opaques are rare. Calcite is found as fracture fillings and small pods throughout the rock.

Chemistry of the Contact Alteration

Three samples of altered rock were selected for whole rock analysis: one each from the altered margin of the granodiorite (ALT-P), the inner alteration zone (20-5), and the outer zone of the contact aureole (16-9S). Chemical changes in rocks from the contact zones are shown by comparing the whole rock analyses of these rocks with analyses of "unaltered" granodiorite and metabasalt (Tables 3 and 4). Although this represents very limited sampling, it is believed that the trends shown are real since they are consistent with the petrographic evidence from many samples.

The major oxides present in samples from the unaltered granodiorite, the contact aureole, and the metabasalt are shown in Figure 7.

Metabasalt from the inner zone of the contact aureole is quartzose, carbonatized, and pyritized. SiO_2 only increases slightly in comparison to unaltered metabasalt, which suggests that quartz was formed by the breakdown of silicate minerals. Depletions in Al_2O_3 (2.9 wt. %), MgO (5.2), and CaO (3.5) indicate the removal of these species in the inner zone. The abundance of carbonate minerals and the increase in volatile content (7.2) in the zone indicate additions of CO_2 to the rock. CO_2 may have reacted with calcium, magnesium, and iron in the metabasalts to form calcium carbonate and ankerite. Addition of sulphur to the

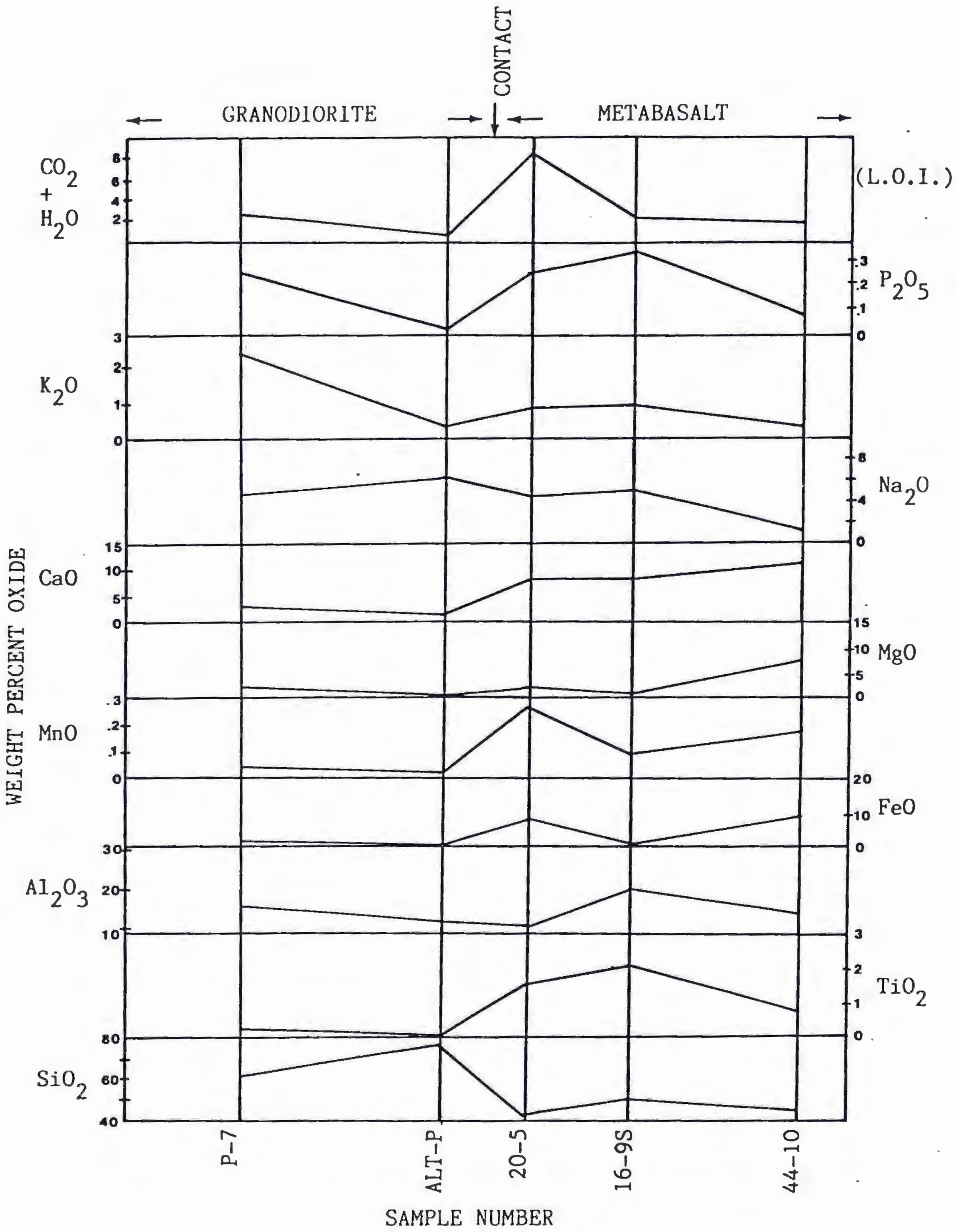


FIGURE 7 - PLOT OF WEIGHT PERCENT OXIDE AND SAMPLES FROM CONTACT AUREOLE AND UNALTERED GRANODIORITE AND METABASALT. The samples were taken from throughout the study area and are considered representative of the rock units. For exact locations see PLATE 1.

rock is suggested by the presence of abundant pyrite. A small amount of potassium (0.7) and sodium (3.1) appears to have accompanied additions of the carbonate and sulphur in the inner zone, as indicated by increases in these components.

The outer zone of the contact aureole contains small amounts of carbonate, quartz, relict plagioclase, magnetite, ilmenite, and abundant sericite. Addition of Al_2O_3 (6.1) to the rock is expressed by the sericite. Sericite growth may have been enhanced by a small amount of potassium (0.7) metasomatism, as suggested by the oxide plots. Sodium (3.8 increase) was probably also added to the rock, and Fe (7.3 FeO), Mg (6.6 MgO), and Mn (0.1 MnO) were removed with the breakdown of silicate minerals. The absence of pyrite in the outer zone shows that sulphur metasomatism was less intense than in the inner zone of the aureole. The slight increase in volatile content (0.8) and the presence of carbonate minerals in the outer zone indicate additions of CO_2.

Granodiorite in contact with metabasalt flows is more quartz-rich than the rest of the stock and contains no amphibole. Hornblende in unaltered granodiorite forms 5 to 10 percent of the rock. The quartzose nature of the rock is suggested by an increase in SiO_2 (15 wt. %). The removal of Al (3.9%), Fe (1.8%), Mg (1.8%), Ca (1.3%), and K (21%) from margins of the granodiorite stock might generate quartz through the alteration of silicate minerals, such as the feldspars, or amphibole which is notably absent. Migration of a small amount of K out of the stock may have resulted in the potassium metasomatism (0.7 and 0.8) in both zones of the contact aureole. Relict feldspars and inequigranular textures in altered margins of the granodiorite may indicate no change in volume during alteration reactions.

STRUCTURE

Introduction

The Boulder Bay area is located in the east-central portion of the Vermilion district. Rocks of the district comprise an eastward-trending, nearly linear belt of steeply dipping and complexly folded and faulted metavolcanic and metasedimentary units. The supracrustal rocks of the district were metamorphosed and deformed approximately synchronously with emplacement of adjacent batholithic rocks during the Algoman orogeny, 2.7 b.y. ago. Regional strike-slip faulting followed emplacement of the batholiths. This faulting marked the transition from an unstable crust dominated by vertical tectonic movements and high heat flow, to a more stable crust capable of sustaining regional fractures (Sims, 1976).

Rock Cleavage

Rock cleavage or schistosity is the most prevalent penetrative structure in the Boulder Bay area. All rocks within the area are sheared to some degree, and every rock unit, except for the banded iron formation, granodiorite, and the metagabbro, is at least locally schistose. The phyllite is more schistose than any other rock type, and abundant microcrystalline muscovite delineates the schistosity. The volcanogenic greywacke is also schistose, although to a lesser degree. Here, sericite, rock fragments, and oriented crystals delineate the schistosity.

A plot of 78 poles to cleavage, contoured on a Schmidt equal area net, indicates a strong east-northeast strike (average N65°E) of rock cleavage (Figure 8). The cleavage dips 75-90° to the southeast. Local steep northwest dips due to faulting occur in the southern portions of the area (Plate 1).

S-shaped crenulations (2 centimeters wide or less) in rock cleavage are abundant in portions of the phyllite and in some schistose metabasalts (Plate 1). The crenulations occur in the plane of the rock cleavage and perpendicular to the axial planes. These crenulations are evidence for a strong period of deformation whose principal axis of stress lies roughly at right angles to the east-northeast structural trend present in rocks of the Boulder Bay area.

The orientation of cleavage in the Boulder Bay area corresponds to the general trend of those observed elsewhere in the Vermilion district. Within the eastern Vermilion district, Gruner (1941) observed that cleavage is poorly developed, but wherever found, generally strikes about N60°E to 90°E with steep dips.

FIGURE 8 - STEREOGRAPHIC PROJECTION OF 78 POLES TO CLEAVAGE COUNTED ON A KALSBEEK COUNTING NET AND CONTOURED AT 3, 8, 13, 18, AND 23 PERCENT OF TOTAL DATA PER 1 PERCENT AREA.

Bedding

Primary sedimentary bedding is found only in banded iron formation and in the thin tuffaceous layers interbedded with them. Primary bedding is not evident in either the phyllite or volcanogenic metagreywacke, probably because of the moderate to well developed schistosity of these rocks. None of the rock units in the area contain graded bedding or cross bedding.

Figure 9 is a plot of 17 poles to bedding taken from banded iron formations throughout the area. The figure shows an east-northeast trend to bedding similar to that delineated by rock cleavage. Bedding commonly dips to the southeast at 75° or more.

Pillowed basalts were observed at three localities in the Boulder Bay area (Plate 1). Two of these localities are near one another and are located approximately 200 feet north of the granodiorite stock, and about the same distance south of the folded banded iron formation. Here, the basalts dip to the south and top to the north, indicating they have been overturned. The overturned basalts occur on the south limb of a large, overturned, isoclinal syncline (see below). At the third locality, approximately 400 feet southeast of the granodiorite stock in the southeast portion of the study area, the basalts show a topping direction to the south, while dipping south. This indicates the basalts here have been inclined to the south, at a dip of up to 85°, but have not been overturned.

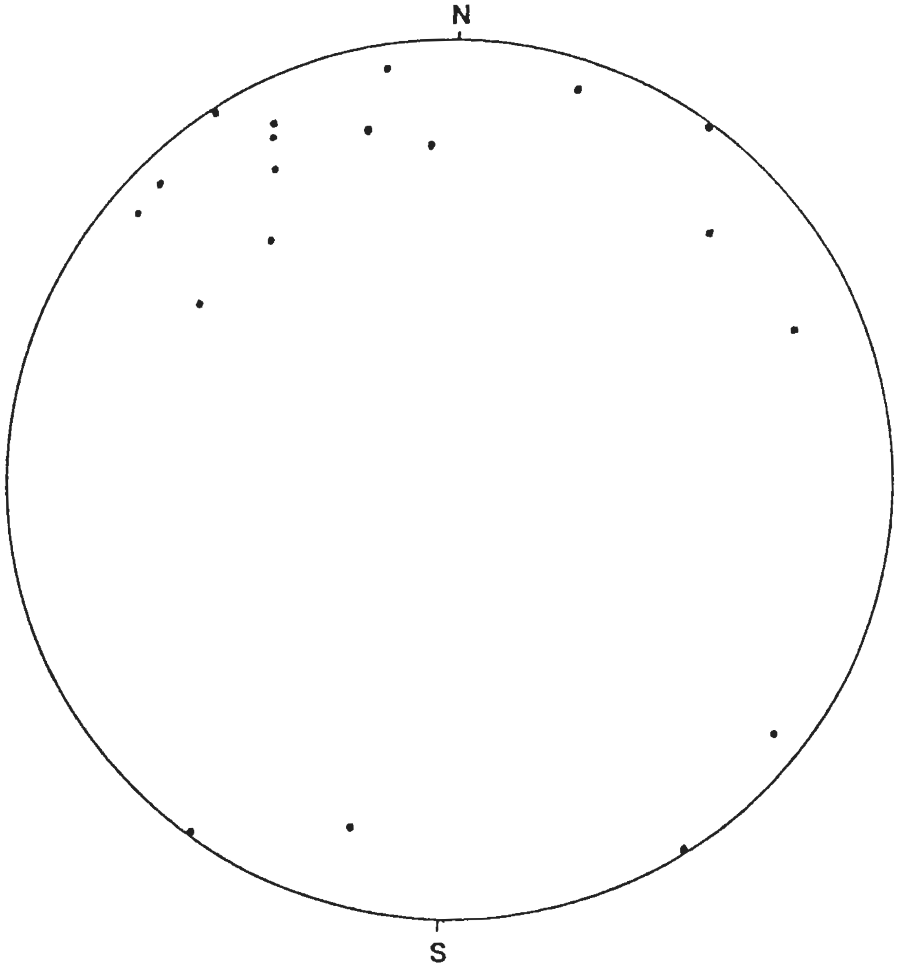


FIGURE 9 - STEREOGRAPHIC PROJECTION OF 17 POLES TO BEDDING TAKEN FROM BANDED IRON FORMATIONS IN THE BOULDER BAY AREA.

Lineations

A variety of lineations are present in the supracrustal rocks, formed by the intersection of two planes. These include lineations formed by the intersection of crenulation cleavage with rock cleavage, the intersection of a bedding surface with an axial plane (i.e., fold axes), and the intersection of joint surfaces with cleavage planes.

Thirteen lineations from the Boulder Bay area were plotted on a Schmidt equal area net (Figure 10). The figure shows there is no consistent orientation of the lineations. A more complete study of lineations is needed before any conclusion can be reached. It is commonplace for even a single deformation to give rise to lineations of more than one orientation (Hobbs, Means, and Williams, 1976). The varied orientations are also likely to be the result of their different origins. That is, a lineation formed by the intersection of crenulation cleavage with rock cleavage would give a different attitude than one formed by the intersection of a bedding surface with an axial surface, or of joint surfaces with cleavage planes.

Folds

In the Boulder Bay area one major fold and at least one minor fold are present in the steeply dipping metavolcanic-metasedimentary sequence. The folds are best seen in banded iron formation and were clearly delineated by flux gate magnetometer survey (Plate 2).

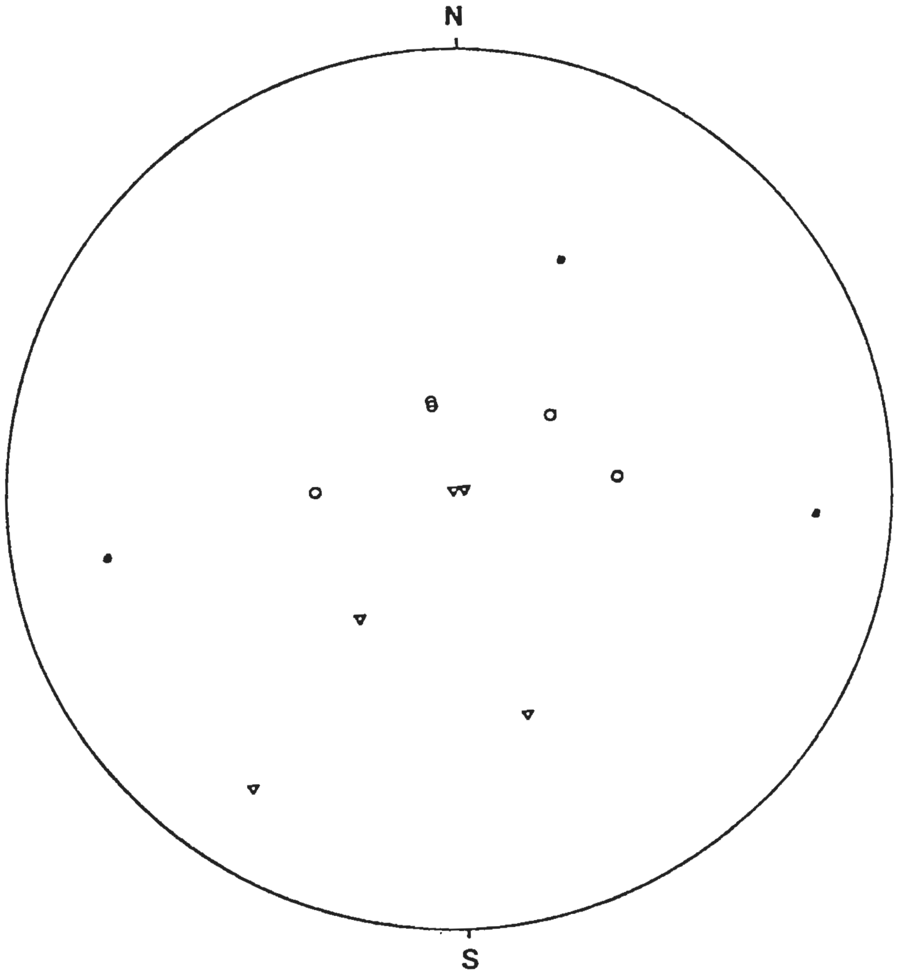


FIGURE 10 - STEREOGRAPHIC PROJECTION OF 13 AXES OF LINEATIONS. SOLID CIRCLES: CRENULATION AXES/CLEAVAGE INTERSECTION; OPEN CIRCLES: MINOR FOLD AXES/BEDDING INTERSECTION; TRIANGLES: JOINT/CLEAVAGE INTERSECTIONS.

The major fold in the area is an overturned isoclinal syncline, located approximately 300 feet north of the granodiorite stock (Plate 1). The syncline has an overturned southern limb at least 4,200 feet long, and a northern limb at least 1,800 feet long. Over-turning of the fold is indicated by nearby pillow basalts which crop out on the southern limb of the fold. The basalts dip to the south at 72° or more, but top to the north, indicating they have been overturned. The orientation of the fold axis is difficult to determine since banded iron formation does not crop out in the nose of the fold. However, anomalies obtained from the magnetometer survey correspond almost exactly to the width of iron formation surface exposures. This makes it possible to extrapolate information about the orientation of the fold from the portions of the iron formation under alluvium. It appears that the fold plunges nearly vertically and probably in the southerly direction, common to other structures in the area. The fold axis trends about east-northeast.

A smaller overturned fold is located in the far northwestern part of the area in banded iron formation (along the north ends of lines 32-48W, Plate 1). The southern limb of the fold is approximately 400 feet long, whereas the northern limb is about 200 feet in length. The fold strikes east-northeast, and has a similar near-vertical plunge and axial-plane orientation as the overturned syncline. Whether the fold is an anticline or a syncline cannot be determined because of an absence of top indicators.

Open folds are indicated by magnetic anomalies in the limbs of the major synclinal fold (Plate 1). The wave lengths of these folds range from 800 to 1200 feet, they strike in a west-northwesterly direction, and appear to have vertical axes. Similar smaller, open folds having a wave length of approximately 1 meter occur locally in the bedding of the banded iron formation. These folds indicate a second period of deformation which occurred approximately at right angles to the first deformation.

A structural study by Hooper and Ojakangas (1971) of folded Archean rocks in the western portion of the Vermilion district demonstrated that two significant deformations affected that area. According to this study, the first deformation produced isoclinal folds with gently plunging axes and vertical axial planes trending west-northwest, and a second deformation which produced open to close folds with steep axes and vertical axial planes trending east-west. The dissimilarity between folds in the Boulder Bay area (the east-central portion of the Vermilion district) with folds in the western portion of the district may largely be a function of local deformation and the geographic distance between the two areas, as well as a function of the physical characteristics of the rocks involved.

Faults

Six major east-northeast trending faults are inferred to cut the supracrustal rocks in the Boulder Bay area. Four of these faults are over 1,000 feet in length and form large continuous features. Other minor faults, up to 700 feet in length, cut all the rocks in the area, including the granodiorite stock. The largest fault in the area is the Shagawa Lake Fault (Plate 1). This fault is a right-lateral strike-slip fault which splits into four separate planes of movement in the northeastern portion of the study area. The east-northeast trend of the faults in the Boulder Bay area roughly parallels the trend of other major structural features present, including folds and rock cleavage.

Faults are indicated in the area by linear depressions evident in the field and from aerial photographs. In the few places exposed, fault zones are more than 200 feet wide. Most fault zones are indicated by zones of cataclastic and altered rocks, and by a gradual increase in schistosity of the rock as the locus of movement is approached. Associated with this increased fissility is the gradual eradication of primary features, such as lava pillows and pyroclastic textures. Fault planes, where observed, and schistosity dip to the south at steep angles (75° or more) and trend in an east-northeast direction.

Metabasalts cut by faults are schistose and exhibit abundant cataclastic textures. Common textures include sheared and foliated calcite and ankerite pods with discontinuous trails of fine-grained carbonate, and flattened quartz-filled amygdules exhibiting mortar texture. Fragmental basalts observed near fault zones commonly contain flattened rock fragments which are elongate parallel to the fault plane. Lava pillows may be elongated near faults as well.

Cataclastic textures are also present in metarhyolite sills and in portions of the granodiorite stock, especially adjacent to the large quartz veins. Common textures here include microfractured grains, deformed plagioclase twin lamellae, and strained quartz crystals.

Comparisons with movements on larger faults in and adjacent to the Boulder Bay area, such as the Shagawa Lake fault, suggest that most movement on fault planes contains a strong strike-slip component. Relative displacements on the faults in the Boulder Bay area cannot be determined because of the lack of lineations in rocks and the difficulty of correlating rock units across fault zones.

The easterly trend of Boulder Bay area faults is similar in orientation to regional faults, such as the Vermilion and Kawishiwi faults, in the central and western portions of the Vermilion district. Movement along these faults is thought to have occurred during and at the close of the Algoman orogeny (Sims, 1972).

ECONOMIC GEOLOGY

Introduction

Small amounts of gold were discovered in the Vermilion district as early as 1860 when several small prospect shafts were dug near Lake Vermilion. Host rocks of this mineralization included several types of greenstones and dacite porphyries. Gold was found in narrow quartz veins which contained pyrite, ankerite, chalcopyrite, and small amounts of silver, rutile, and tourmaline. The discovery of gold ore in northern Minnesota led to a small-scale gold rush which resulted in the discovery of the more profitable Precambrian iron ores (Grout, 1937).

Gold-bearing quartz veins in the Boulder Bay area occur in the granodiorite stock which intrudes metabasalt flows in the central portion of the area (Plate 1). The stock is thought to be an epizonal syntectonic intrusion of the Algoman orogeny (2.7 b.y.).

Five mineralized quartz veins are present in surface exposures of the granodiorite stock and at least five other veins were intersected at depth by diamond drilling. The quartz veins at the surface range from 1 to 3 feet in thickness, while those at depth are from 1 inch to 2 feet thick. The veins strike in an east-southeast direction and show a range of dip orientations. Veins exposed in the workings on the west side of the stock are subhorizontal, whereas those in the eastern portions range from subhorizontal to vertical. A southerly dip is common to all veins except for a single vein in the northcentral portion of the stock which dips to the north at 74° (Plate 1).

Four unmineralized quartz veins are exposed in rocks other than those of the main granodiorite stock. Two of these veins occur in one of the small granodiorite bodies west of the stock. One vein strikes to the east and is vertical, and the other strikes to the northeast and dips to the southeast at 76°. Two other quartz veins are exposed in metabasalt flows south of the smaller granodiorite body. One of these strikes northeast and dips to the southeast at 15°, and the other strikes northwest and dips northeast at 5°. Although these four veins are texturally similar to those veins occurring within the stock, polished section examination revealed no sulphides. No quartz veins were observed in the zone of alteration around the granodiorite intrusive. This could be due to poor rock exposure or to an absence of veins.

All quartz veins are highly cataclastic, regardless of the rock they are found in. Zoned alteration occurs around many of the larger quartz veins found within the granodiorite stock, although no alteration was noted around veins outside of the stock. Cataclastic textures and zoned alteration are also locally well developed in the myriad of quartz veinlets in the stock and surrounding altered greenstones.

Small amounts of gold, argentiferous tetrahedrite, pyrite, chalcopyrite, and sphalerite occur as fracture fillings in the mineralized quartz veins (Plate 32). Ore minerals are most abundant in fractures paralleling the contacts between granodiorite and quartz veins. Mineralization introduced along microfractures commonly infills around individual grains.

Ore Petrology

Pyrite

Pyrite occurs in quartz vein fractures as anhedral embayed grains where it forms trace amounts of the mineralization, and as euhedral grains where it locally forms 100 percent of the opaques. Embayed grains range in size from microcrystalline to ≤1 mm. Euhedral pyrite is commonly 0.25 to 4 mm in diameter. Chalcopyrite commonly surrounds and embays pyrite. Pyrite is also locally embayed by galena and argentiferous tetrahedrite. Many pyrite grains are broken and

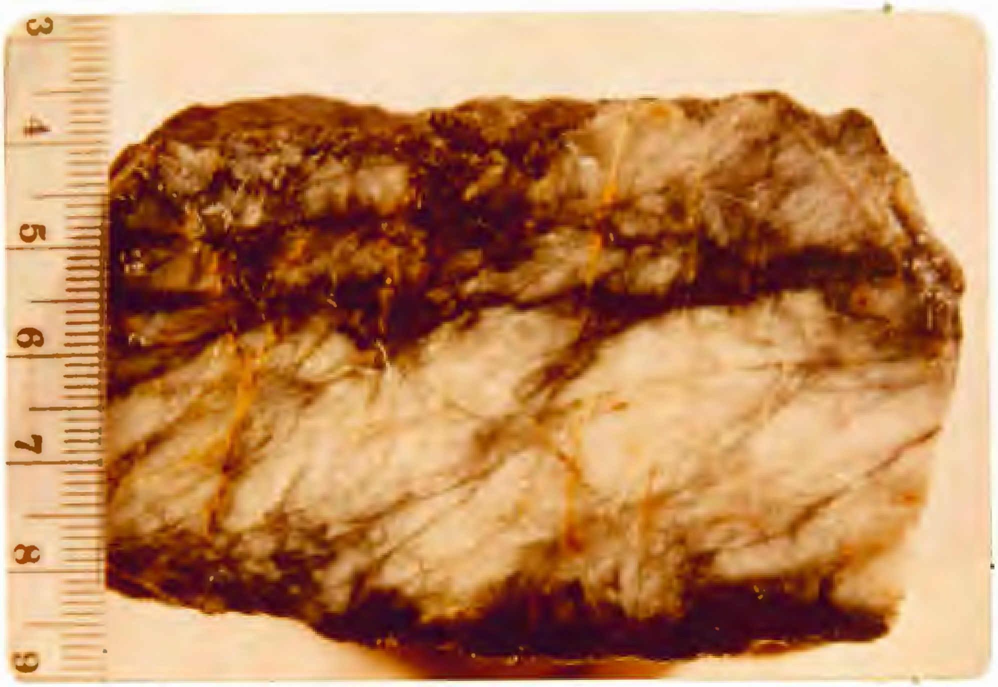


PLATE 32. Photograph of quartz vein with sulfide mineralization (black and grey) controlled by fracturing within the veins. Scale in cm. Sample no. ADIT-1.

fractured. Grains were probably fractured in situ, since fragments of a single crystal commonly are found close to one another.

Massive pyrite float is present next to the road and under the powerline in the northern half of the area (Plate 1). It occurs over a 10 by 20 foot area. The rock is bimineralic, consisting of pyrite and cryptocrystalline quartz. Highly fractured and broken subhedral to euhedral pyrite forms 85 percent or more of the rock, with chert making up the remaining 15 percent. No base or precious metals are present. Pyrite grains range in size from microcrystalline to less than 5 mm. Locally, quartz has recrystallized in pressure shadows around pyrite grains. In many instances pyrite shows size gradation across 3 cm-wide bands in the rock, interpreted as graded bedding (Plate 33). Graded bedding, the close association of pyrite and chert, the abundance of pyrite, and the presence of this massive sulphide in a metabasalt terrain, suggests the rock formed by exhalative processes (Boyle, 1979).

Gold

Visible gold was found in only one sample collected in the Boulder Bay area. It was found in trace amounts in a quartz vein of the granodiorite stock where it occurs as microcrystalline anhedral grains next to a microcrystalline anhedral pyrite grain.

PLATE 33. Photograph of massive sulfide rock composed of pyrite and silica. Two beds and part of a third with graded bedding (Top to Top of Photo) are indicated. Scale in cm. Sample no. MNER-213.

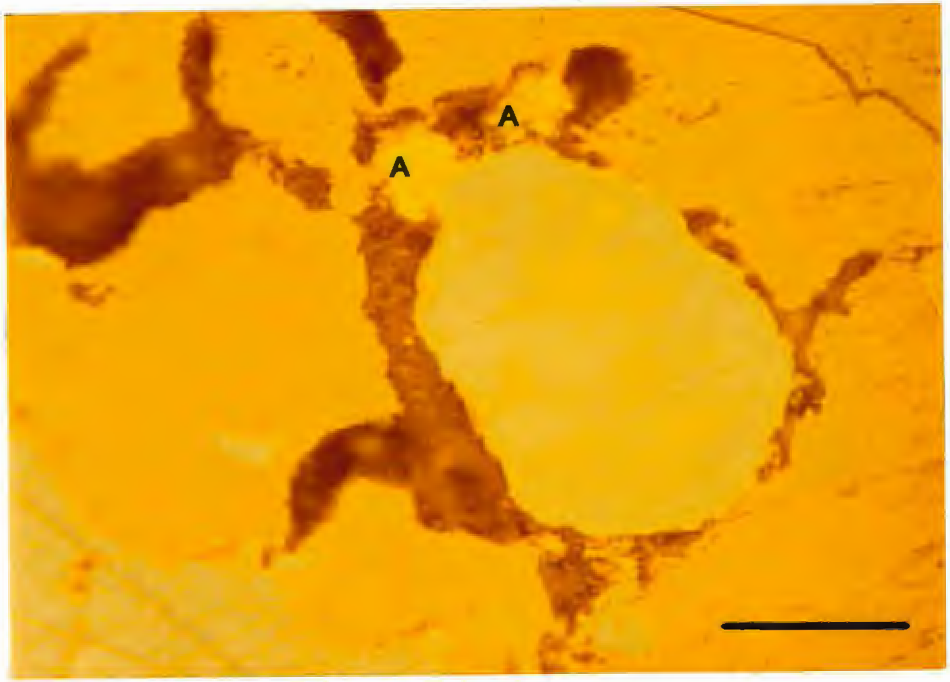


PLATE 34. Photomicrograph of microcrystalline grains of gold (A) adjacent to pyrite. Reflected light. Uncrossed polars. Bar=0.3 mm. Sample no. 20-22-2.

Both pyrite and gold occur along microfractures in a groundmass of quartz (Plate 34). Gold is commonly associated with pyrite as inclusions within the grain or as separate grains in close proximity to pyrite (Boyle, 1979). Although no gold was found as inclusions in pyrite in this study, this extremely fine-grained gold could easily have been overlooked in the samples studied. Very little visible gold was found even in those few samples from the area assaying from 0.50 to 20.0 oz/T gold.

Sphalerite

Polished section examination revealed that sphalerite is present in trace amounts. Anhedral, microcrystalline grains of sphalerite occur in chalcopyrite (Plate 35) and infrequently in galena. Sphalerite grains have no internal reflection, nor do they contain exsolved chalcopyrite.

Chalcopyrite

Anhedral, fine-grained to microcrystalline chalcopyrite commonly forms no more than 2 to 3 percent of the opaque minerals. Locally, it forms 10 to 15 percent of the sulphides, especially where tetrahedrite and galena form over 70 percent of the ore minerals. Chalcopyrite embays pyrite and sphalerite grains, and is itself embayed by galena and tetrahedrite (Plates 35 and 36). Fractured pyrite crystals are infilled by chalcopyrite.

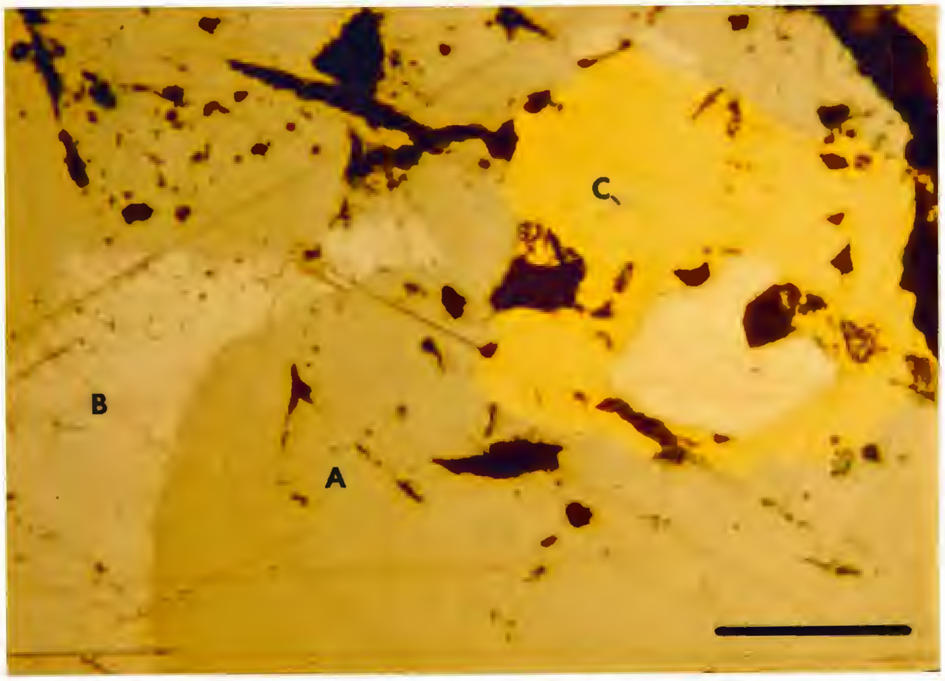


PLATE 35. Photomicrograph of argentiferous tetrahedrite (A) embaying galena (B), which embays chalcopyrite, which in turn embays pyrite and sphalerite (C). Reflected light. Uncrossed polars. Bar=0.48 mm. Sample no. ADIT-1.

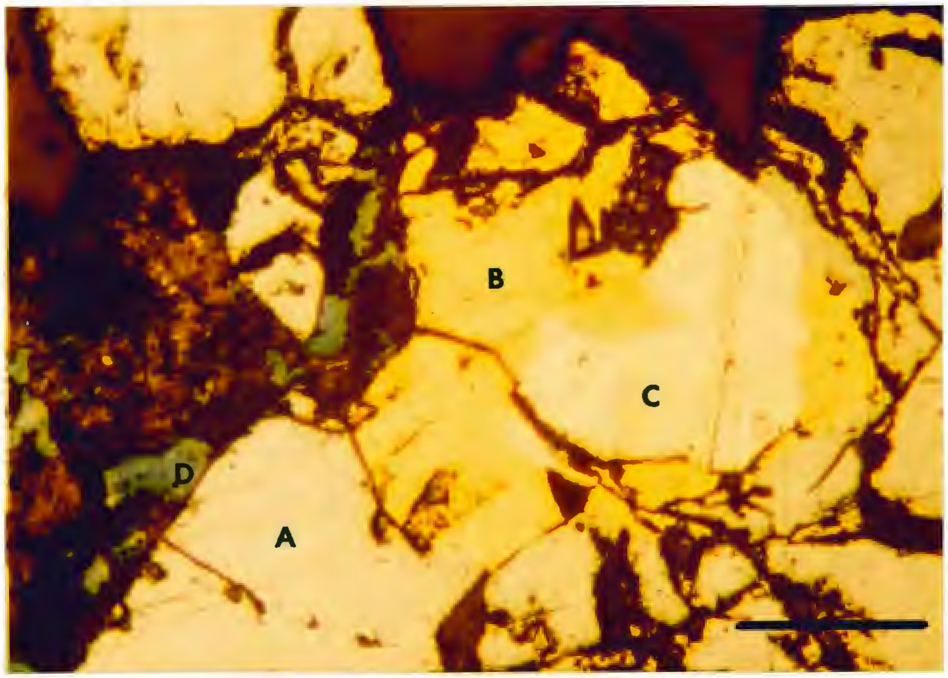


PLATE 36. Photomicrograph of argentiferous tetrahedrite (A), replacing chalcopyrite (B), which in turn replaces pyrite (C). Small amount of supergene covellite (D). Reflected light. Uncrossed polars. Bar=0.2 mm. Sample no. ADIT-1-2.

Galena

Anhedral to subhedral galena occurs as fine grains and commonly forms 20 to 30 percent of a fracture filling. Locally, galena forms 80 percent of the ore minerals where tetrahedrite is absent. Galena embays pyrite and chalcopyrite and can be found filling fractures in pyrite. Tetrahedrite embays galena (Plate 35) and is embayed by it in an approximately equal number of occurrences.

Tetrahedrite

Tetrahedrite commonly forms 50 to 60 percent of the sulphide mineralization, with galena forming 35 to 40 percent. The tetrahedrite is argentiferous. Samples assayed contained up to 4.0 oz. of silver per ton. Tetrahedrite and pyrite have an inverse abundance relationship: where tetrahedrite is abundant, pyrite is present in trace amounts; where tetrahedrite is absent, pyrite may form up to 100 percent of the opaques. Tetrahedrite occurs as anhedral, fine- to medium-sized grains, and embays galena, chalcopyrite (Plate 35), and pyrite. Galena embays tetrahedrite as commonly as the latter embays the former. In some samples, rounded grains of tetrahedrite are infilled along fractures by galena (Plate 37).

Telluride

Trace amounts of an unknown, creamy yellow, isotropic, soft mineral occur as microcrystalline subhedral

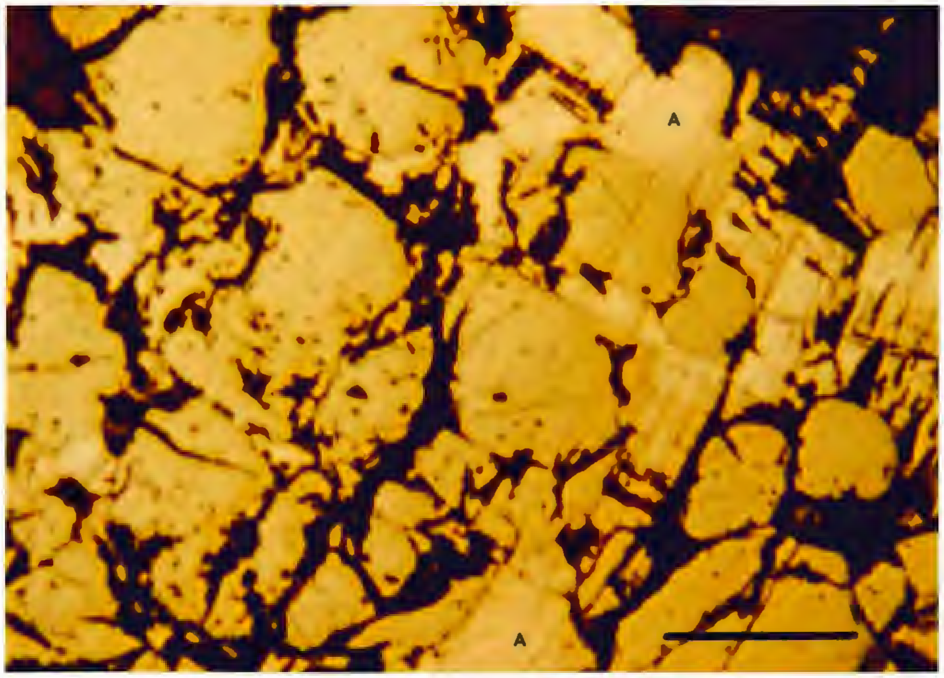


PLATE 37. Photomicrograph of rounded and fractured grains of argentiferous tetrahedrite infilled by galena (A). Reflected light. Uncrossed polars. Bar=0.2 mm. Sample no. ADIT-1-2.

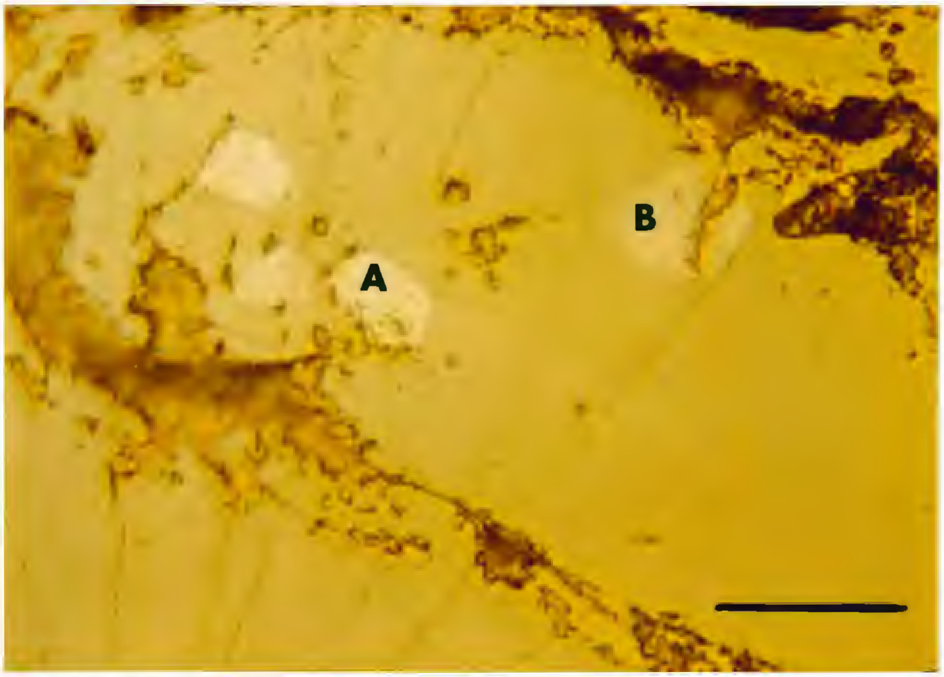


PLATE 38. Photomicrograph of telluride (A) and galena (B) in argentiferous tetrahedrite. Telluride possibly calaverite or petzite. Reflected light. Uncrossed polars. Bar=0.3 mm. Sample no. ADIT-1-2.

grains in tetrahedrite. This mineral is embayed by tetrahedrite (Plate 38) and was found in only one sample (ADIT-1-2) from the lower mineralized quartz vein in the only accessible shaft on the property. The color, hardness and isotropy of this mineral suggest it is a telluride, possibly calaverite ($AuTe_2$), a common telluride in Precambrian gold-quartz deposits (Boyle, 1979), or petzite (Ag_3AuTe_2).

Pyrostilpnite

Microcrystalline grains of a soft granular mineral, possibly pyrostilpnite (Ag_3SbS_3), form rims and fracture fillings on galena and pyrite grains along microfractures in quartz veins. It is most abundant in samples collected from the shaft and adit. In some samples, pyrostilpnite occurs as euhedral to subhedral tabular crystals (Plate 39). The mineral commonly exhibits a brownish red internal reflection and forms no more than 1 percent of the ore minerals. The habit, mineral association, and internal reflection suggests the mineral is pyrostilpnite.

Malachite

Fine-grained to microcrystalline, anhedral malachite occurs in trace amounts along fractures in mineralized quartz veins at the surface. It is most abundant in quartz veins exposed in and near the shaft and adit. Malachite replaces chalcopyrite along grain boundaries and microfractures. Azurite is closely

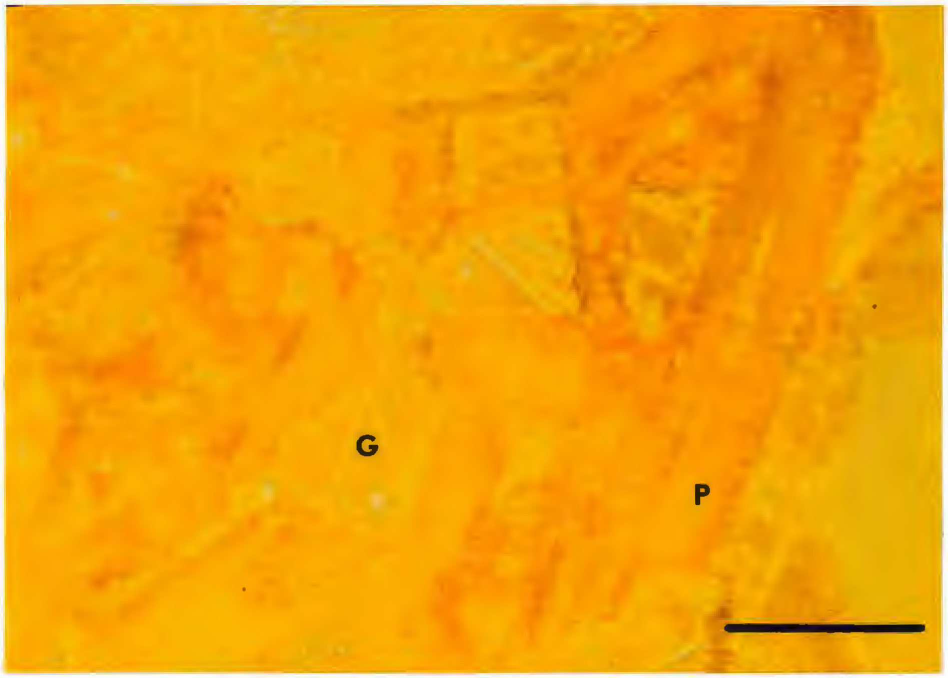


PLATE 39. Photomicrograph of tabular pyrostilpnite crystals (P) with brownish red internal reflection in galena (G). Reflected light. Partially crossed polars. Bar=0.3 mm. Sample no. 20-22-6.

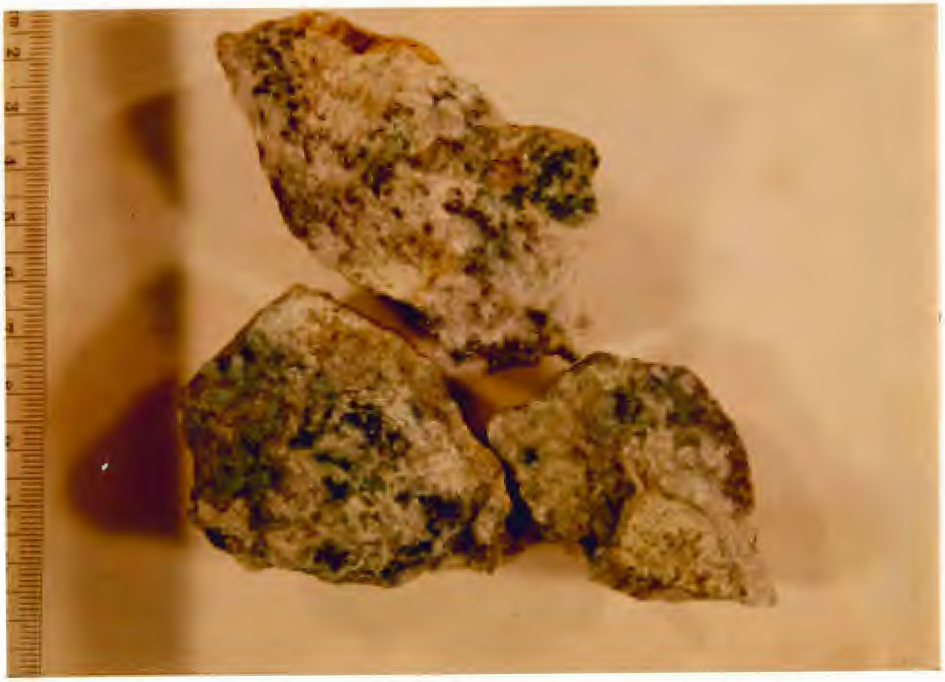


PLATE 40. Photograph of supergene malachite and azurite along fractures in mineralized quartz vein samples. Scale in cm. Sample no. ADIT-1-1.

associated with malachite (Plate 40). In one sample, malachite forms beautiful successive rims of replacement in association with chalcopyrite and covellite (Plate 41).

Azurite

Anhedral, fine-grained to microcrystalline azurite occurs in trace amounts along fractures in mineralized quartz veins at the surface. Azurite is closly associated with malachite, but is less abundant than the latter (Plate 40). Azurite replaces chalcopyrite along grain boundaries and microfractures.

Covellite

Covellite occurs as anhedral, granular grains along microfractures in mineralized quartz veins and as a microcrystalline secondary alteration product of chalcopyrite (Plate 36). Malachite and azurite are commonly associated with covellite (Plate 41).

Neodigenite

Neodigenite is very rare and is present in only one sample, 24-2B, where it replaces chalcopyrite along grain boundaries and microfractures. It occurs as anhedral microcrystalline grains and is found in association with malachite and covellite (Plate 42).

Potassium Feldspar

Potassium feldspar occurs in trace amounts along fractures in mineralized quartz veins. It is present as microcrystalline anhedral grains and is best indicated

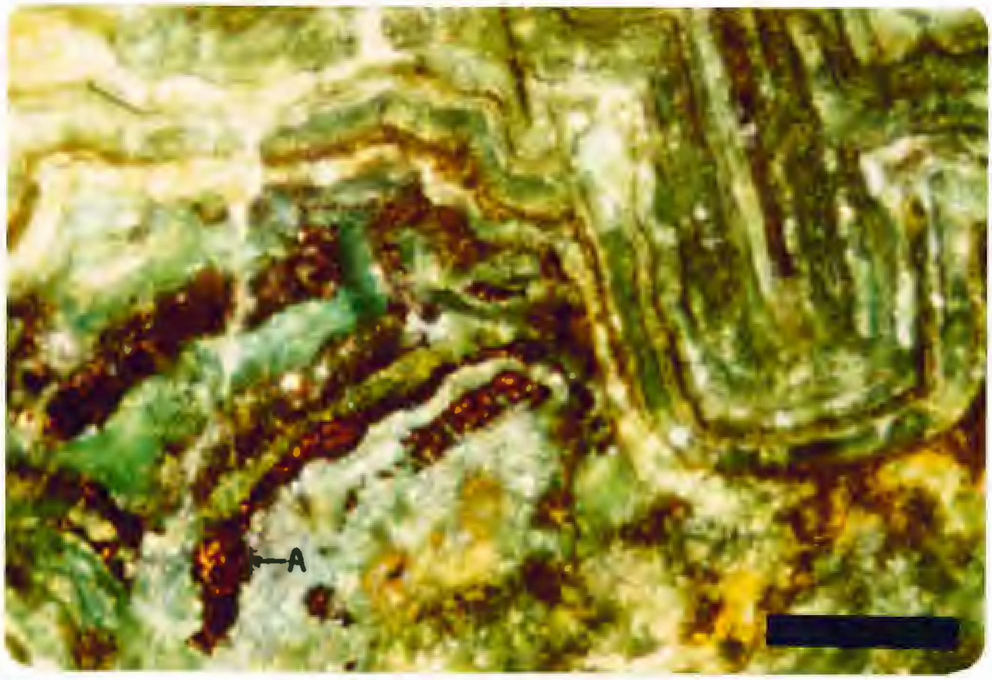


PLATE 41. Photomicrograph of successive zones of malachite and a small amount of covellite (A) after chalcopyrite. Reflected light. Crossed polars. Bar=0.48 mm. Sample no. 20-22-8.

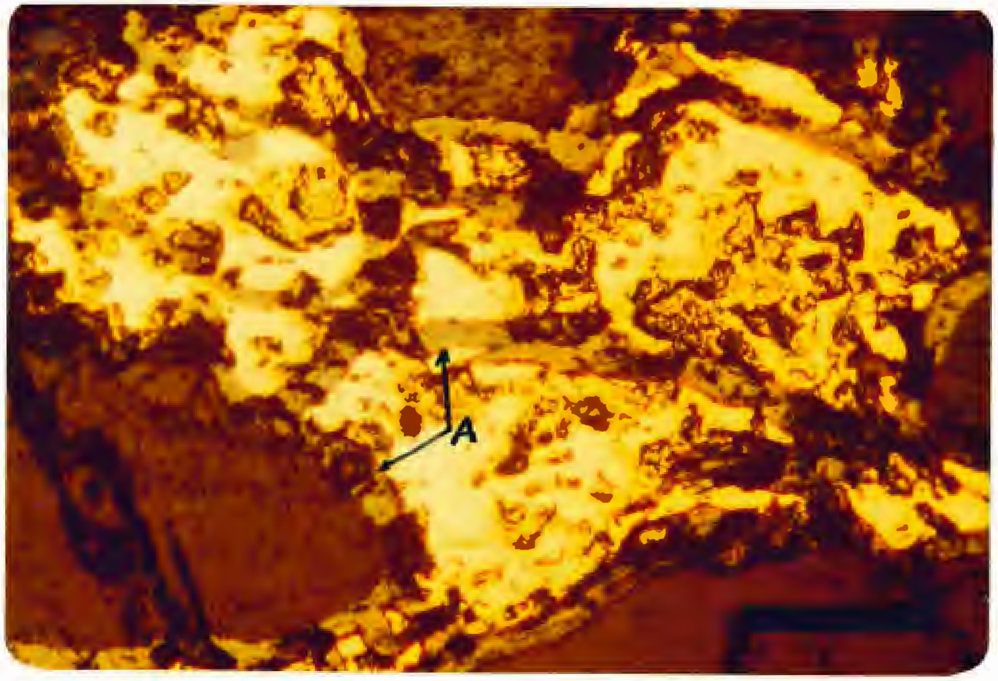


PLATE 42. Photomicrograph of neodigenite (A) replacing chalcopyrite along grain boundaries and microfractures. Reflected light. Uncrossed polars. Bar=0.48 mm. Sample no. 24-2B.

by hand sample staining. K feldspar is commonly associated with metallic minerals in this occurrence although it may also be found separately.

Carbonate

Calcite and 5 to 10 percent ankerite occur as grains ≤ 1 mm in diameter along fractures in mineralized quartz veins. Deformation textures such as deformed twin lamellae are common. Medium- to coarse-grained pods of carbonate grains ≤ 1 mm in diameter are found, but are not common.

Depositional Sequence

The sequential deposition of ore minerals is indicated by younger minerals which embay and fill fractures in older minerals. The sequence is summarized in Figure 11; from oldest to youngest the sequence is as follows: pyrite, gold, sphalerite, chalcopyrite, telluride, galena and argentiferous tetrahedrite, and pyrostilpnite. Malachite, azurite, covellite, and neodigenite occur as secondary minerals. The fracture-filling nature of the ore minerals in the quartz veins indicates most, if not all, of the quartz was deposited before ore mineral deposition.

Atomic absorption analyses indicate several ppm gold present in mineralized veins containing no visible gold. Studies of other deposits with gold mineralization indicate nonvisible gold is commonly found as inclusions within pyrite grains, or as separate grains

```
                                 TIME
               OLDEST -------------------------- YOUNGEST

QUARTZ         ----- - - - - - - - - - - - - - - - -

POTASSIUM          ----?----?----?----?----?----?----?
FELDSPAR

CARBONATE          ----?----?----?----?----?----?----?

PYRITE             ----

GOLD                   ----

SPHALERITE                 ----

CHALCOPYRITE                   ----

TELLURIDE                          ----

GALENA                                 ----

TETRAHEDRITE                           ----

PYROSTILPNITE                              ----

MALACHITE*                                     ----

AZURITE*                                       ----

COVELLITE*                                     ----

NEODIGENITE*                                   ----
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FIGURE 11 - PARAGENETIC SEQUENCE OF ORE AND GANGUE MINERALS AS FRACTURE FILLINGS IN QUARTZ VEINS.

*Secondary Minerals

in close proximity to pyrite. Experimental work indicates that up to 2,000 ppm gold can substitute into the pyrite lattice before any gold is visible microscopically (Kurauti, 1941). This suggests that a gold-bearing pyrite phase may have occurred in the Boulder Bay area and could be placed early in the paragenetic sequence of the ore minerals if the sequence is similar to that in other deposits. Although visible gold is not found in pyrite grains of the Boulder Bay area, many Precambrian gold-quartz deposits without visible gold contain an early gold-bearing pyrite phase (Boyle, 1979).

Ore and gangue minerals present in the fractured quartz veins of the Boulder Bay area indicate that mineralizing fluids carried small amounts of silica, carbonate, antimony, sulphur, potassium, and trace amounts of metals in solution. Comparisons of the ore and gangue mineral assemblage found in the Boulder Bay area with assemblages from other Precambrian gold-quartz deposits, which have been extensively studied, suggest that a moderate to low temperature fluid (400° to 100°C) was the mineralizing agent (Boyle, 1979). The lack of exsolved chalcopyrite in sphalerite grains also suggests a moderate to low temperature fluid which was undersaturated in copper (Ramdohr, 1969).

Several periods of shearing along quartz veins during both quartz and ore mineral deposition are indicated by a number of features. Ribboned quartz is elongate parallel to vein walls, and granodiorite adjacent to vein walls is also sheared (Plate 27). This indicates movement after quartz deposition and possibly at various stages during quartz deposition. Ore minerals and small amounts of potassium feldspar and carbonate occur as fracture fillings which may be traced parallel to vein walls over the length of an exposed vein. This indicates deposition of ore and associated minerals following the development of fractures in quartz veins. Finally, the local fractured habit of both pyrite and tetrahedrite indicates renewed shearing along quartz veins during deposition of the ore minerals (Plate 43). Initial and sporadically renewed movements were undoubtedly very important in providing permeable channels for migrating mineralizing solutions.

Alteration Associated with Quartz Veins

Zoned alteration is associated with a number of mineralized quartz veins and several smaller unmineralized veins in the granodiorite stock. Three zones of alteration can be recognized on the basis of thin section study. These zones are, from the quartz vein outwards, silicification, sericitization, and large biotites.

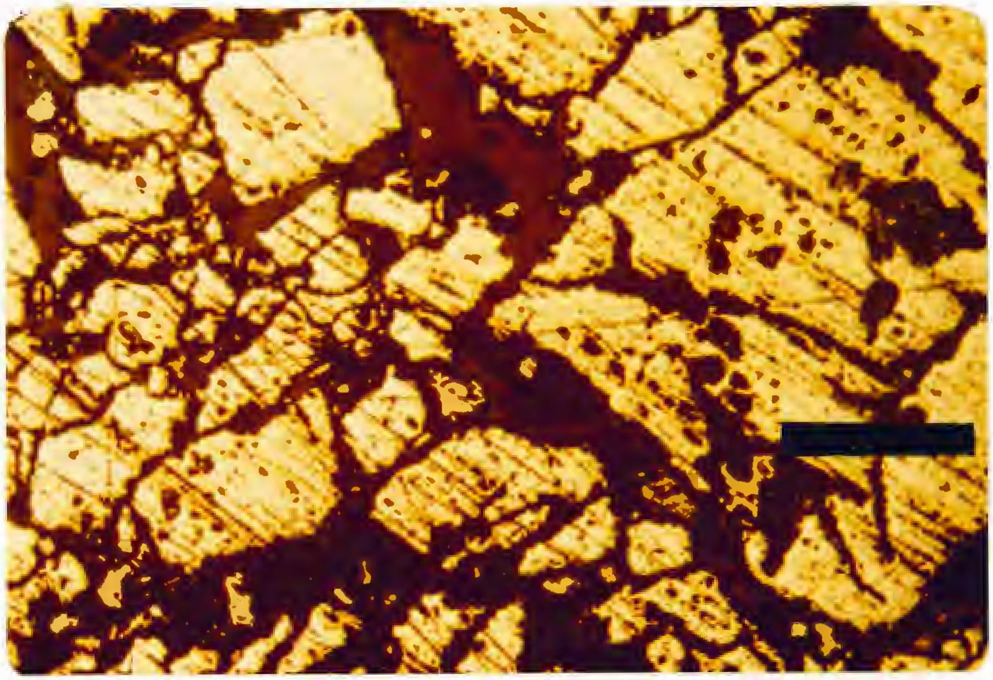

PLATE 43. Photomicrograph of pyrite crystals fractured and broken in place. Indicates shearing along quartz veins following early stages of sulphide mineralization. Reflected light. Partially crossed polars. Bar=0.48 mm. Sample no. 20-1.

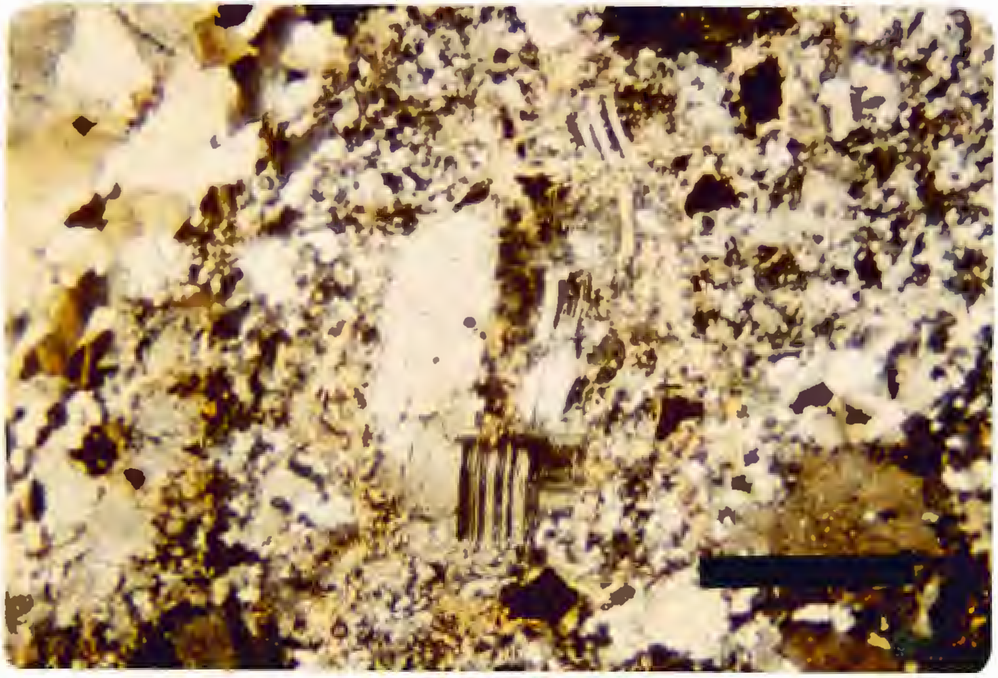

PLATE 44. Photomicrograph of altered granodiorite next to quartz vein (upper left). Zone of sericitization (center) in cataclastic granodiorite. Zones of silicification and large biotite absent. Crossed polars. Bar=0.5 mm. Sample no. RZ-4-7.

Zone of Silicification

A zone of silicification, rarely more than 5 cm. wide, is difficult to distinguish from the more prevalent and obvious zone of sericitization, because of gradational contacts. Aphanitic to microcrystalline grains of anhedral quartz replace feldspars in the granodiorite. Quartz may form up to 40 percent of the rock next to the quartz vein, decreasing in abundance to 15 or 20 percent away from the vein. Amphibole is absent and only trace amounts of carbonate and sericite occur. Euhedral to subhedral fine-grained pyrite locally makes up 5 percent of the rock.

Zone of Sericitization

Sericitization is indicated by the development of a lighter colored, or bleached, zone in the rock next to quartz veins. The zone varies in width from several centimeters to several meters and is gradational with the inner zone of silicification. Locally, silicification is absent and sericitized rock abuts directly on the quartz vein. The outer edge of the sericitized zone commonly contains sporadic large biotites in trace amounts. However, sericitization ends abruptly at the edge of the biotite zone.

The lighter color of the sericite zone in the granodiorite is the result of the strong alteration of amphibole and the removal of disseminated hematite from plagioclase phenocrysts. Amphibole, biotite, and feldspars are commonly altered to sericite with rare shreds of muscovite (20 to 30 percent of the rock), calcite (10 to 15 percent), and chlorite (5 percent). Euhedral to subhedral, fine-grained pyrite locally forms 2 to 3 percent of the rock (Plate 44).

Cataclastic textures are common in the zone of sericitization with deformed and microfractured plagioclase twin lamellae. Locally, a small amount of mortar texture is exhibited by plagioclase crystals (Plate 44).

Biotite Zone

A zone of biotite, up to 0.5 meters wide in places, appears to be developed around quartz veins as a retrograde alteration. The zone locally contains no more than 1 percent medium-grained, subhedral, brown biotite (after hornblende), and 1 to 2 percent subhedral to anhedral, fine-grained to aphanitic sericite, pyrite, and carbonate. The paucity of alteration minerals in this zone makes it difficult to distinguish from unaltered granodiorite. However, the zone can be distinguished by the retrograde alteration of hornblende to biotite, and its spatial association with the quartz veins. The biotite zone is best seen in drill core where continuous portions of the granodiorite can be viewed on either side of the quartz veins. Biotite gradually decreases in abundance away from the zone of sericitization into unaltered granodiorite which contains no biotite.

Irregular patches of altered granodiorite up to 1 meter across occur without quartz veining. Biotite and pyrite (3 to 5 percent) are present in these altered portions of the granodiorite stock and in some plugs and dacite dikes. Small amounts of carbonate and chlorite (1 to 2 percent) are also present in the rock. The patches of alteration are similar mineralogically and texturally to the zone of large biotites developed around some quartz veins and veinlets, but occur without the zones of silicification and sericitization.

SUMMARY AND CONCLUSIONS

The Boulder Bay area is located in the east-central portion of the Vermilion district in an Archean (>2.7 b.y.) greenstone-granite terrain. The area is in the southern portion of the Superior Province of the Canadian Shield. Rocks of the district comprise a nearly linear belt of steeply dipping and complexly folded and faulted greenschist facies metavolcanic and metasedimentary units. These greenstones are bounded on the north by the Vermilion batholith, on the east by the Saganaga batholith, and on the south by the Giants Range batholith. Folding, regional metamorphism, and faulting are thought to have occurred contemporaneously with the emplacement of the granitic batholiths during the Algoman orogeny (2.7 b.y.). Faulting on a regional scale occurred at the end of the orogeny.

Bedrock in the Boulder Bay area consists of the Lower Precambrian Newton Lake Formation metavolcanic-metasedimentary sequence, with associated intrusions. The Newton Lake Formation is the youngest of four formally designated units in the east-central portion of the Vermilion district. The predominantly metagreywacke-slate and felsic volcaniclastic rocks of the Knife Lake Group and Lake Vermilion Formation stratigraphically underlie the Newton Lake Formation in the central part of the district and may intertongue with it to the east.

Felsic to intermediate volcaniclastic rocks make up the Newton Lake Formation east of Newton Lake, whereas west of it, mafic flows and sills dominate. The various rock units interfinger in the Newton Lake area. Southwest of Shagawa Lake, in the Boulder Bay area, a second interfingering may occur between dominantly mafic rocks to the northeast and felsic rocks to the southwest.

Rock types present in the Boulder Bay area include basalt flows (by far the most abundant), gabbro intrusions, banded iron formations, muscovite phyllite, metagreywacke, rhyolite sills or stocks, a granodiorite stock and associated apophyses, and dacite dikes. Quartz veins are also present.

The volcanic-sedimentary rock sequence in the Boulder Bay area, like sequences in other greenstone belts in the Superior Province, is interpreted to have been deposited mainly in a subaqueous environment. The sedimentary rocks were probably derived from volcanic deposits, and transported to basins adjacent to the volcanic piles where deposition occurred. The close association of iron formation and volcanic rocks throughout the Vermilion district also indicates a volcanic source for the iron formation and possible deposition by volcanic exhalative processes.

During the Algoman orogeny the volcanic-sedimentary sequence in the Boulder Bay area was folded, intruded by a granodiorite stock and its apophyses, and faulted. All rocks were metamorphosed under greenschist facies conditions and show varying degrees of cataclasis depending on their proximity to fault zones.

Analyses of selected basalts, gabbro, and metasedimentary rocks indicate the majority of the rock units in the Boulder Bay area are tholeiitic. Some of the distinctive properties of Archean volcanic rocks, such as low alkalis, were found in the Boulder Bay samples. These rocks are similar to rocks in other portions of the Vermilion district and in the Superior Province.

The granodiorite stock in the central portion of the Boulder Bay area is roughly cylindrical in shape and plunges to the northwest at a steep angle. The contact between the stock and the surrounding metabasalts is commonly sheared and nearly vertical. Zoned contact metasomatism is developed in the metabasalts in contact with the pluton. Sulphide-bearing quartz veins, commonly surrounded by zones of alteration, cut the stock.

Whole rock analyses of granodiorite samples indicate the rock is chemically calc-alkaline, and is chemically similar to intermediate extrusive rocks in the Superior Province. Intrusive dacite porphyries in the Ely Greenstone and extrusive dacites from other portions of the Newton Lake Formation are commonly calc-alkaline, as well.

Three compositional types of dikes are found in the Boulder Bay area: dacite, which is the most abundant, quartz latite, and granite. The mineralogical similarity and close spatial association of the dacite dikes to the granodiorite stock suggest the dikes represent more rapidly cooled hypabyssal equivalents of the stock. The quartz latite and granite dikes post-date the intrusion of the stock since they crosscut both the stock and surrounding rocks. These dike rocks may represent subsequent injections of stock material and differentiation of the granodiorite magma chamber, or injections from one or more entirely separate and more felsic magmatic sources.

Quartz veins present in the granodiorite stock include large subhorizontal sulphide-bearing veins, and small irregular veinlets with a wide range in orientation. Ribboned quartz in quartz veins and sheared granodiorite in contact with the veins is common. The subhorizontal orientation of the large quartz veins may reflect deposition from solutions preferentially channeled along tension cracks or low angle faults. The irregular quartz veinlets may have resulted from quartz deposition in fractures formed in the solid outer margins of the stock, before crystallization of the entire pluton was completed.

An irregular contact metasomatic aureole is developed in metabasalt flows surrounding the granodiorite stock. The aureole consists of two mineralogic zones; an inner zone characterized by abundant quartz and carbonate, and an outer zone with abundant sericite and carbonate. The margins of the granodiorite stock adjacent to the metabasalts are also altered. Shearing is typical and the development of sericite and carbonate in the contact zone is prevalent. Analyses of granodiorite from the margins of the stock and basalts in the thermal aureole suggest a migration of K_2O, Na_2O, and volatiles out of the intrusion and into the country rock.

Two periods of deformation are indicated in Boulder Bay area rocks. Cleavage and schistosity in the area show a strong east-northeast strike (average 65°) with dips to the southeast at 75° or more, with local reversals in dip due to faulting. This orientation is similar to that in other portions of the Vermilion district. Sedimentary bedding also shows an east-northeast trend, with dips to the southeast at 75° or more. Early folds in the area are isoclinal, strike about the common east-northeast structural trend, appear to plunge vertically, and have overturned southern limbs. A second period of deformation, whose axis is roughly at right angles to the east-northeast structural grain, is suggested by west-northwest trending open folds with vertical axes in the limbs of the isoclinal folds and by locally abundant crenulations in rock cleavage.

Six major east-northeast trending faults of unknown displacement are indicated in the Boulder Bay area by linear topographic lows, increased rock fissility, and by the elongation and deformation of primary features. Fault planes, where observed, and rock schistosity trend parallel to other major structural features, and dip to the south at 75° or more.

Ore minerals occur in shattered quartz veins in the granodiorite stock as fracture fillings and are most abundant in those fractures which parallel vein walls. The sequential deposition of ore minerals in these veins, from oldest to youngest, is as follows: pyrite, gold, sphalerite, chalcopyrite, telluride, galena and argentiferous tetrahedrite, and pyrostilpnite. Malachite, azurite, covellite, and neodigenite were deposited by supergene processes. The fracture filling habit of the ore minerals in the quartz veins indicate quartz deposition preceded ore mineral deposition. Repeated periods of shearing occurred along quartz veins both during quartz and ore mineral deposition.

Zoned alteration accompanied the development of mineralized quartz veins and several smaller unmineralized veinlets in the granodiorite stock. From the veins outwards, these zones of alteration are silicification, sericitization, and a zone of large biotites.

Comparisons of ore and gangue mineral assemblages present in the Boulder Bay quartz veins with mineral assemblages from extensively studied Precambrian stockwork vein gold deposits elsewhere indicate the mineralizing agent was a moderate to low temperature (400-100°C) fluid.

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APPENDIX I

SAMPLE LOCATIONS

Note: All grid lines are oriented parallel to one another, and are 18° west of True North (Plate 1). For simplification, locations are given as though these N18°W grid lines trended True North. Locations refer to footage and direction from grid line; N - S directions are north or south of the base line, E - W directions are east or west of the given grid line.

Surface Sample No.	Grid Line	Location
52-8	52 West	1260 North
52-13N	52 West	1260 North
48-17	48 West	700 North, 140 East
48-21	48 West	960 North, 80 West
48-23	48 West	1540 North, 90 East
48-7	48 West	1180 South, 120 East
48-10	48 West	1750 South, 30 East
44-20	44 West	1830 South, 20 East
44-30	44 West	650 North
44-31	44 West	1700 North
44-10	44 West	540 South, 70 East
44-8	44 West	900 North
40-2	40 West	440 South, 60 East
40-1	40 West	820 North, 50 West
40-12	40 West	1520 North, 20 East
40-6	40 West	1080 South, 80 West
40-8	40 West	1600 South, 10 West
10-3	36 West	800 South, 100 West
36-1	36 West	700 North, 60 West
36-5	36 West	20 North
36-3	36 West	680 North, 200 East
36-10	36 West	60 North, 60 East
36-18	36 West	540 South, 60 West
32-1	32 West	910 North
32-9N	32 West	910 North
MNER-82	32 West	910 North
MNER-71	32 West	1150 South, 40 East
MNER-75	32 West	910 South, 150 East

Surface Sample No.	Grid Line	Location
Adit-1	28 West	400 South, 100 East
Adit-1-1	28 West	400 South, 100 East
Adit-1-2	28 West	400 South, 100 East
28-16S	28 West	1600 South, 30 West
28-2	28 West	40 South, 140 West
28-20	28 West	2060 South, 180 West
28-6	28 West	920 North, 100 West
MNER-21	28 West	520 North, 20 West
29-9	28 West	400 South, 100 East
24-2A	24 West	390 South, 100 East
24-2B	24 West	390 South, 100 East
24-7	24 West	800 South, 110 East
24-8	24 West	1300 South
Alt-31	24 West	120 North
24-12	24 West	1600 South, 100 East
P-7	24 West	450 South, 300 East
20-5	20 West	480 South, 200 East
20-22-2	20 West	580 South, 70 West
20-22-6	20 West	580 South, 70 West
20-1	20 West	580 South, 130 West
20-22-8	20 West	580 South, 70 West
P-11	20 West	500 South
20-10	20 West	1620 South, 50 East
20-7	20 West	240 North
20-9	20 West	960 South, 140 East
Alt-1-H	20 West	1200 South, 60 East
ALt-2E	20 West	1200 South, 60 East
16-9S	16 West	900 South, 20 West
16-4	16 West	1900 South, 180 East
MNER-210	16 West	1040 South, 180 West
MNER-154	16 West	590 North
MNER-150	16 West	50 South, 80 West
Alt-1E	16 West	930 South
12-4	12 West	1200 South, 70 East
12-7	12 West	1260 South, 70 West
MNER-215	12 WEst	440 South, 300 East
12-3	12 West	1580 South
MNER-211	12 West	420 South, 30 East
MNER-213	12 West	475 South, 200 East
MNER-222	8 West	740 South, 20 East
8-3	8 West	440 North
8-9	8 West	1300 South
8-1	8 West	400 South, 160 East
8-2	8 West	400 South, 160 East
8-2	8 West	400 North, 10 East
Alt-8E	8 West	400 South, 110 West

Surface Sample No.	Grid Line	Location
MNER-229	4 West	400 South, 150 West
4-1	4 West	240 South
4-5	4 West	640 North, 30 East
MNER-230	4 West	50 South, 30 East
4-4	4 West	0 North, 170 West
0-2	00	1440 North, 20 East
0-1	00	120 South, 50 West
0-3	00	1500 North
MNER-5	00	600 North, 40 West
4E-1	4 East	680 North
4E-2	4 East	540 North
4E-3	4 East	980 North
4E-4	4 East	1130 North
4E-5	4 East	1800 North, 10 West
8E-1	8 East	370 South, 100 East
8E-2	8 East	1180 North
8E-3	8 East	1280 North, 80 East
8E-4	8 East	1200 South, 80 West

Drill Core Sample No.	Diamond Drill Hole No.	Depth (in feet)
RZ-1-5	RZ-1	184.3
RZ-1-10	RZ-1	122.0
RZ-1-12C	RZ-1	273.0
RZ-1-13	RZ-1	308.0
RZ-1-15	RZ-1	351.0
RZ-3-4	RZ-3	29.0
RZ-3-4B	RZ-3	30.0
RZ-3-10	RZ-3	186.0
RZ-3-11	RZ-3	382.0
RZ-3-13	RZ-3	366.0
RZ-4-2	RZ-4	57.5
RZ-4-4	RZ-4	94.0
RZ-4-7	RZ-4	135.0
RZ-4-9	RZ-4	145.4
RZ-4-19	RZ-4	277.5
RZ-4-23	RZ-4	343.0
RZ-4-40	RZ-4	250.0

APPENDIX II

TABLE 1. Petrography and Average Mineral Percentages in Metabasalts

Minerals	Massive Metabasalt	Variolitic Metabasalt	Fragmental Metabasalt	Magnetite-rich Metabasalt
Chlorite		30%		
Epidote	70-90%	tr-1%		60-75%
Amphibole				
Hornblende	both present			
Actinolite		5%		
Relict Plagioclase	20%	Present in varioles		
Untwinned Plagioclase	2%			
Quartz	2%	5%		
Quartz filled Amygdules	1% (<2 mm)			
Carbonate	1%	15% (as cross-cutting veins)		
Sericite	1%			
Opaques		15%		
Pyrite	10-15% (locally)			
Magnetite	3%			15-20%

Ilmenite				5-15%
Leucoxene	frequent alteration products of ilmenite and magnetite			
Hematite				3%
Goethite				
Sphene				tr
Apatite	tr			
Olivine		tr		
Clays		30%		
COMMENTS:	Phenocrysts: 20% plagio. Groundmass: 80%.	Varioles: 10-15% of rock; slightly siliceous. Trace of microphenocrysts of pseudomorphed plagioclase.	VRF's: up to 30% of rock. Mineralogically similar to massive metabasalts.	No phenocrysts present. Mineralogically similar to non-magnetic flows.

TABLE 1. (Continued)

Minerals	Sheared Metabasalt	Fault Breccia	Metabasalt-Inner Contact Zone	Metabasalt-Outer Contact Zone
Chlorite	20-30%	60-70% of fragments		tr
Epidote		5% of frags.		tr
Plagioclase	present*	present*		10-15%, relict, sericitized
Quartz	present*	tr-10% in frags.	40%	5-10%
Carbonate	present*	2-3% of frags. matrix of calcite (60-80%)	40%	5-15%
Sericite	present	2-3% of frags.	5%	40-50%
Opaques	20-30%	20% of frags.	tr of magnetite and ilmenite	1-10% magnetite
Pyrite			15%	
*COMMENTS:	Mineralogically similar to massive flows. Foliated.	Locally up to 40% of rock are fragments, <2 cm long. Silicified.	Absence of epidote & chlorite; as contact is approached, more silicified.	Gradational with inner zone; less silicified than inner zone; also gradational with metabasalts.

TABLE 2. Petrography and Average Mineral Percentages of Some Rocks in the Boulder Bay Area

Minerals	Meta-Quartz Gabbro	Banded Iron Formations	Muscovite Phyllite	Metagreywacke
Augite	40%			
Plagioclase	40% (highly saussuritized)		tr	5-10% as phenocrysts
Quartz	tr	30-40% as jasper & chert	30-40%	10-20% as fine-grained phenocrysts; also 20-25% of matrix
Orthoclase	tr			
Hornblende	5-15% (alteration product of augite along rims & fractures)			
Saussurite	5-20% (alteration product from plagio.)			
Chlorite	tr			25-30% of matrix
Epidote	tr			
Magnetite	tr (skeletal)	30-40%		
Apatite	tr			
Hematite		20-30%		
Pyrite		10-15% locally	1%	

TABLE 2. (Continued)

Calcite		tr		1-2% carbonate in matrix
Muscovite			60-70%	20-25% of matrix
Iron Oxides			tr	tr
Rock Fragments				1-5%
COMMENTS:	One sample is crosscut by irregular veinlets of quartz, carbonate & hematite.	Alternating silica-rich and iron-rich layers. Dark grey tuffaceous layers, 1 cm thick, interbedded locally.	"Sericite schist". Possibly of volcanic origin. Foliated & crosscutting crenulations.	Matrix: 70-80% Phenocrysts: 20-30%, including rock fragments. Fine-grained to microcrystalline matrix. Rock fragments of siltstone &/or mafic volcanic rock fragments, 1 mm long, some flattened. Rock is foliated, sheared, and shows recrystallization.

TABLE 3. Petrography and Average Mineral Percentages of some Intrusive Rocks in the Boulder Bay Area

Minerals	Metarhyolite Intrusives	Granodiorite	Dacite Dikes	Quartz Latite Dikes	Granite Dikes
Plagioclase	10-20% (An$_{10}$) bimodal size	Oligoclase phenocrysts: 30-60% of rk; 5% in grndms, oscillatory zoning	20-30% as phenocrysts, med-grnd; 40-50% in grndmass	euh-subh, unzoned grains	15%, anhedral-subhedral
Potassium Feldspar	40-50% in groundmass	10-20% in grndmass as microcline; locally graphic, poikilitic, microperthite	5-15% as pheno's, microcline, microperthitic	subh, microperthitic microcline	65% microperthitic microcline
Quartz	15-25% in groundmass	10-15% fine-grained in groundmass.	10-15%	present in groundmass	20%, strained, graphic, & myrmekitic
Hornblende		5-15% in groundmass, locally altered to biotite, chlorite & opaques	5-15% as phenocrysts	tr, aphanitic, subh-euh, microphenocrysts	

TABLE 3. (Continued)

Opaques		tr	tr	tr	
Hematite		tr	tr	tr	
Pyrite	tr, euh, 1mm wide	3%, disseminated			
Iron Oxides	1% disseminated in groundmass	tr			
Sericite	10% in groundmass	tr	tr	tr	tr
Clays		tr	tr	tr	tr
Sphene		tr			
Apatite		tr			tr
Biotite		tr (med-c grained)	tr (med-c grained)	tr	
Chlorite		tr	tr	tr	
COMMENTS:	Pheno's: 10-15%. Grndmass: 85-90%.	Pheno's: 45-60%. Matrix: 40-55%. Pheno's show alteration to quartz, more calcic zones to clays, ser.	Pheno's: 30-60% Matrix: 40-70%. Matrix fn-grained to microcrystalline.	Feldspars slightly altered to sericite, clays. Hornblendes altered to biotite, chlorite & opaques.	Feldspars fresh & only locally altered to sericite & clays.