THE GEOLOGY OF THE EARLY PRECAMBRIAN ROCKS OF THE JASPER LAKE AREA, COOK COUNTY, NORTHEASTERN MINNESOTA

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA

BY
WILLIAM CHARLES FEIRN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

December, 1977

FRONTISPIECE--VIEW OF JASPER LAKE FROM KNOB IN NW$\frac{1}{4}$, Sec. 18, T.65N, R.5W.

ABSTRACT

The rocks of the Jasper Lake area, located within the eastern Vermilion district in Cook County, northeastern Minnesota, represent the basal portion of a thick (3500-6400 meters) metavolcanic-metasedimentary sequence. The area contains three dominantly igneous units: a greenstone unit, a pyroclastic unit, and an andesite intrusive unit. The rocks within the district were shown to have been complexly faulted and isoclinally folded by Gruner (1941). All units have been metamorphosed to greenschist facies.

The oldest unit consists of predominantly massive metavolcanics (including basalt, diabase, andesite, and minor dacite) and herein is referred to as the Jasper Lake greenstone. The unit is linear in outline, 1000-1500 meters thick, vertical, and trends east-west.

Based upon the presence of pillow structures and quench textures observed in the basalts at several localities, these rocks are interpreted as subaqueous lava flows. Hypabyssal diabase and andesite-dacite intrusions within the flows were contemporaneous and probably consanguineous with them.

The Jasper Lake pyroclastic unit, and the associated Jasper Lake andesite, are believed to overlie the greenstone conformably, and are approximately vertical in attitude trending west-northwest. The pyroclastic unit consists of volcanic breccias, tuffs,

and lesser amounts of conglomerate and graywacke-argillite. Clasts range from 0.1 mm to 1.2 meters in diameter and are composed dominantly of porphyritic andesite with very minor amounts of basalt, dacite, and tuff. Some of the basaltic clasts may have been derived from the older greenstone unit. The presence of unsorted, angular to sub-rounded fragments within the unit suggest deposition by volcanic mudflows or lahars.

The Jasper Lake andesite unit trends west-northwest with largely vertical contacts, and is composed predominantly of porphyritic augite andesite with lesser amounts of massive, porphyritic hornblende andesite-dacite. The rock is typically fine-grained to aphanitic, and locally vesicular to amygdaloidal, thereby representing a shallow, hypabyssal intrusion which may have reached the surface locally. It exhibits chilled margins up to 50 meters wide and is subconcordant with bedding indications in the surrounding pyroclastic unit.

These rocks are conformably overlain by a well-bedded, graded graywacke-slate unit at least 1.6 km thick.

The Saganaga tonalite batholith, dated at 2.7-2.75 billion years old (Goldich, 1968), intrudes the greenstone unit along its northern margin. Locally, along the contact with the greenstone, the intrusion raised the grade of metamorphism to amphibolite facies along a zone 30-60 meters wide. Late retrograde prehnite-pumpellyite facies metamorphism also affected the rocks in this zone.

The units of the Knife Lake Group, including the Ogishke conglomerate described by Gruner (1941), are vertical in attitude and trend northeastward, truncating the rocks of the Jasper Lake area on the west. These rocks contain Saganaga tonalite detritus, unlike the Jasper Lake units. The Ogishke conglomerate also locally overlies the Jasper Lake greenstone along the northwest margin of the greenstone.

Two periods of folding have affected the area. Initial isoclinal folding of the Jasper Lake units along west-northwest-trending fold axes occurred contemporaneously with the Saganaga tonalite intrusion. A second period of folding produced deformation in the eastern Vermilion district, but apparently not within the Jasper Lake units. This episode involved folding along steep northeast-trending fold axes due to later rise of the Saganaga tonalite, after deposition of the Knife Lake units.

Two periods of faulting, which post-date folding, have affected the area. Faulting within the Jasper Lake units along dominantly west-northwest trends occurred after the first folding episode during Saganaga intrusion. The second period of faulting, trending northeastward, affected the entire eastern Vermilion district, and truncated the faults within the Jasper Lake units.

Detailed study in the area indicates that the basalt-andesite-dacite suite of volcanic rocks at Jasper Lake represent the oldest part of the regional volcanic pile, because of the lack of Saganaga detritus as in younger units, and suggest deposition in a setting similar to modern island-arc tectonic environments.

TABLE OF CONTENTS

ILLUSTRATIONS

Plates Page

TABLES

INTRODUCTION

Location

The area of study, approximately triangular in shape, consists of about 10 square kilometers in Cook and Lake Counties in northeastern Minnesota. It is centered around Jasper Lake in the Boundary Waters Canoe Area of the Superior National Forest, and is located 62.5 kilometers northwest of Grand Marais, Minnesota (Fig. 1). Most of the area is located in T.65N., R.5W., and R.6W. within the Ogishkemuncie Lake 7.5-minute quadrangle with small portions in the Ester Lake and Gillis Lake quadrangles to the north and east respectively.

The area is most readily accessible by canoe via the Seagull Lake port of entry at the end of the Gunflint Trail. It is approximately a 10 kilometer trip from the Seagull Lake landing, west-southwest to Jasper Lake on the northeast edge of the map area.

Statement of Problem

The Jasper Lake area is a contact zone involving several complexly interrelated Early Precambrian units (Plate 2). The majority of the area consists of three dominantly igneous units: a greenstone unit, a pyroclastic unit, and an andesite intrusive unit. These units make up the basal portion of a thick (up to 6400

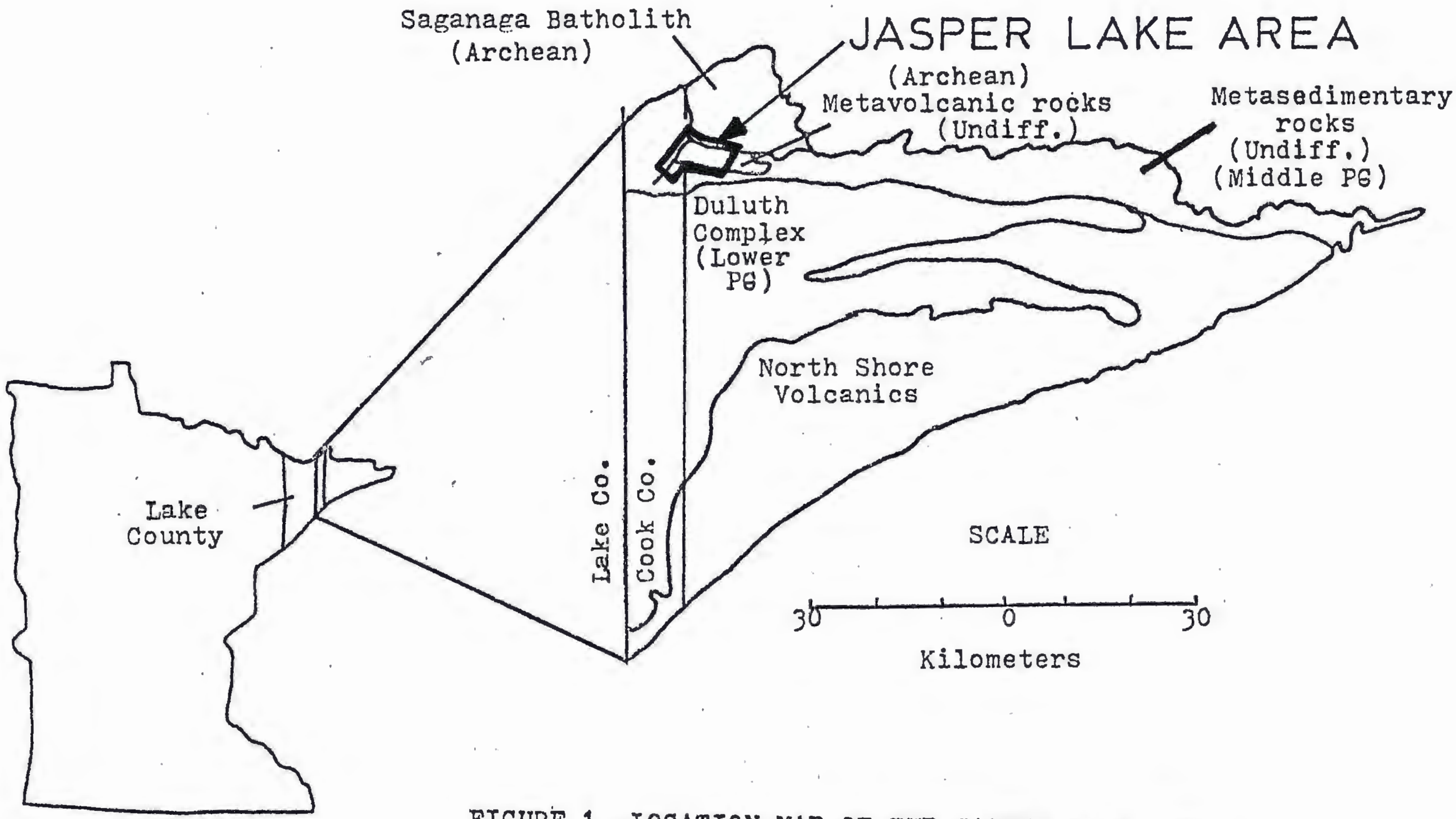


FIGURE 1--LOCATION MAP OF THE JASPER LAKE AREA, COOK COUNTY, NORTHEASTERN MINNESOTA

meters, Gruner, 1941) metavolcanic-metasedimentary pile. The Jasper Lake rocks are overlain by an upper dominantly metasedimentary portion of the pile which outcrops to the north, west, and south of the area. The Saganaga tonalite intrudes the greenstone unit to the northeast and contributed detritus to a portion of the surrounding upper portion of the pile.

This study was initiated with three main objectives; (1) To examine in detail the complex structural and petrogenetic relationships between the Early Precambrian greenstone, pyroclastic, and andesite intrusive units and the surrounding terrane. This will help to determine the origin and depositional environment of the pyroclastic unit and the mode of emplacement of the Jasper Lake andesite intrusive. (2) To examine the contact metamorphism of the greenstone by the Saganaga tonalite. (3) To decipher the geologic history of the Jasper Lake area.

Previous Work

The Jasper Lake area was first studied by Winchell (1900) who completed a general geologic map of Minnesota on a county basis. Distribution and gross relationships of major rock units were mapped, with brief petrographic descriptions included. Clements (1903) summarized the complete stratigraphic, structural, and petrographic knowledge of the Vermilion iron-bearing district of northern Minnesota. The Jasper Lake area was interpreted as consisting almost wholly of Ely Greenstone and Ogishke conglomerate with a very small area of Knife Lake slates east of Jasper Lake. This study formed the basis for a major structural study of the Knife Lake area in northeastern Minnesota undertaken over 13 years by Gruner (1941).

Gruner produced a geologic map at a scale of 3,520 feet to the inch of the eastern Vermilion district which showed the rock units as being divided into large fault-bounded structural provinces (Fig. 2). He established the location of the main northeast-southwest-trending fault bounding the west end of the Jasper Lake area and indicated the approximate vertical attitude of rocks elsewhere throughout the eastern Vermilion district as well as around Jasper Lake. He also further divided the Knife Lake Group into 19 separate units although no specific petrography or mapping was done in the Jasper Lake area.

Grout, Sharp, and Schwartz (1959) conducted a general study of the geology of Cook County and did some detailed work on the Saganaga tonalite. General petrology and structure were noted, and a few chemical analyses of various phases of the tonalite were completed.

Goldich and others (1961), Hanson (1968), Tilton and Gruenfelder (1968), Hart and Davis (1969), Hanson

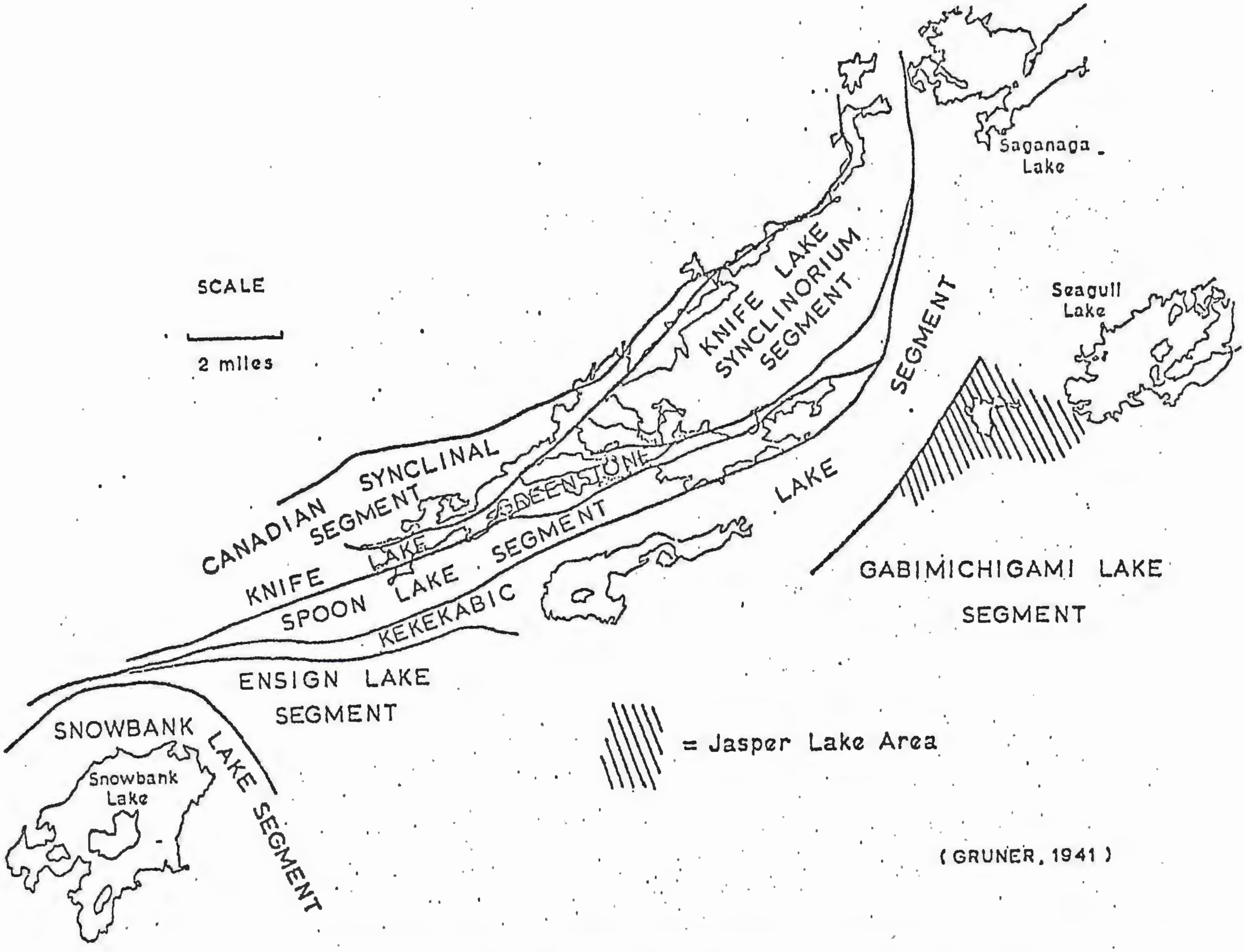


FIGURE 2--GENERALIZED MAP OF THE EASTERN VERMILION DISTRICT SHOWING GRUNER'S FAULT-BOUNDED PROVINCES (after Gruner, 1941)

and others (1971), Weiblen, et al. (1971), and Catanzaro and Hanson (1971) have dated the Saganaga tonalite by Rb-Sr whole rock analysis, U-Pb ages on sphene, and U-Pb ages on zircon. All dates obtained suggest an age of 2700 to 2750 million years.

Methods of Study

Approximately 23 days during the summer of 1976 were spent in the field. Mapping was done throughout the area by pace and compass traverse using 7.5-minute quadrangle base maps. The objective was to cover all outcrops in the area. Plate 2 is a geologic map of the area.

Nearly 300 rock samples were collected. Ninety-two samples were used for petrographic study. Modal analyses were accomplished by counting at least 600 to 1000 points per thin section. X-ray diffractometry was used to identify some minerals. Slabs were stained for potassium feldspar content. Whole-rock chemical analyses of selected samples were done using atomic absorption methods by K. Ramlal at the University of Manitoba, Winnipeg, Canada.

Clast and pebble counts of pebble types and numbers in the conglomerate samples of the pyroclastic unit using a 1 cm grid helped determine the environment of deposition and source area of the unit. The number counted depended on the size of the sample.

Acknowledgements

The author greatly appreciated the assistance given by Dr. Donald M. Davidson, Jr. of the University of Minnesota, Duluth, who suggested the study and served as thesis advisor. Special thanks are extended to Dr. John C. Green and Dr. Richard W. Ojakangas, also of the University of Minnesota, Duluth, for their very helpful discussions and suggestions during the study. The writer also wishes to acknowledge Dr. Donald Poe and Dr. Ronald Frost, both of the University of Minnesota, Duluth, for their special interest in the project.

Financial support given by the Minnesota Geological Survey aided in field and laboratory expenses and is greatly appreciated.

Discussions with fellow graduate students, especially Randee Zarth, Mark Severson, Curt Everson, and Richard Churchill, regarding geologic interpretation and writing were very helpful. Duane Wagner, Robert Wahlstrom, and Dan Severson served as willing and able field assistants.

INTRODUCTION TO REGIONAL GEOLOGY

Definition

The Vermilion district was defined by Clements (1903) as a narrow belt of metavolcanic and metasedimentary rocks 160 km by 5-10 km that stretches from the vicinity of Tower, near Lake Vermilion in northern St. Louis County, northeastward to Saganaga Lake in northern Cook County on the International Boundary (Fig. 3). It contains rocks which typify Early Precambrian greenstone-granite complexes of the Canadian Shield (McGlynn, 1970). These rocks are at least 2700 million years old (Goldich, 1968, Jahn and Murthy, 1971) and are among the best studied and exposed of these complexes in northern Minnesota (Sims and Morey, 1972).

The Jasper Lake area lies within the eastern part of the Vermilion district, defined here as the portion east of Knife Lake. The Saganaga tonalite bounds the district on the northeast, while the Vermilion granite-migmatite massif and Giants Range granite lie to the northwest and south, respectively. The rocks of the Vermilion district, Vermilion batholith, and Saganaga tonalite continue across the border into Canada.

Stratigraphy

The sequence of the eastern Vermilion district consists of complex interfingering lithologies and

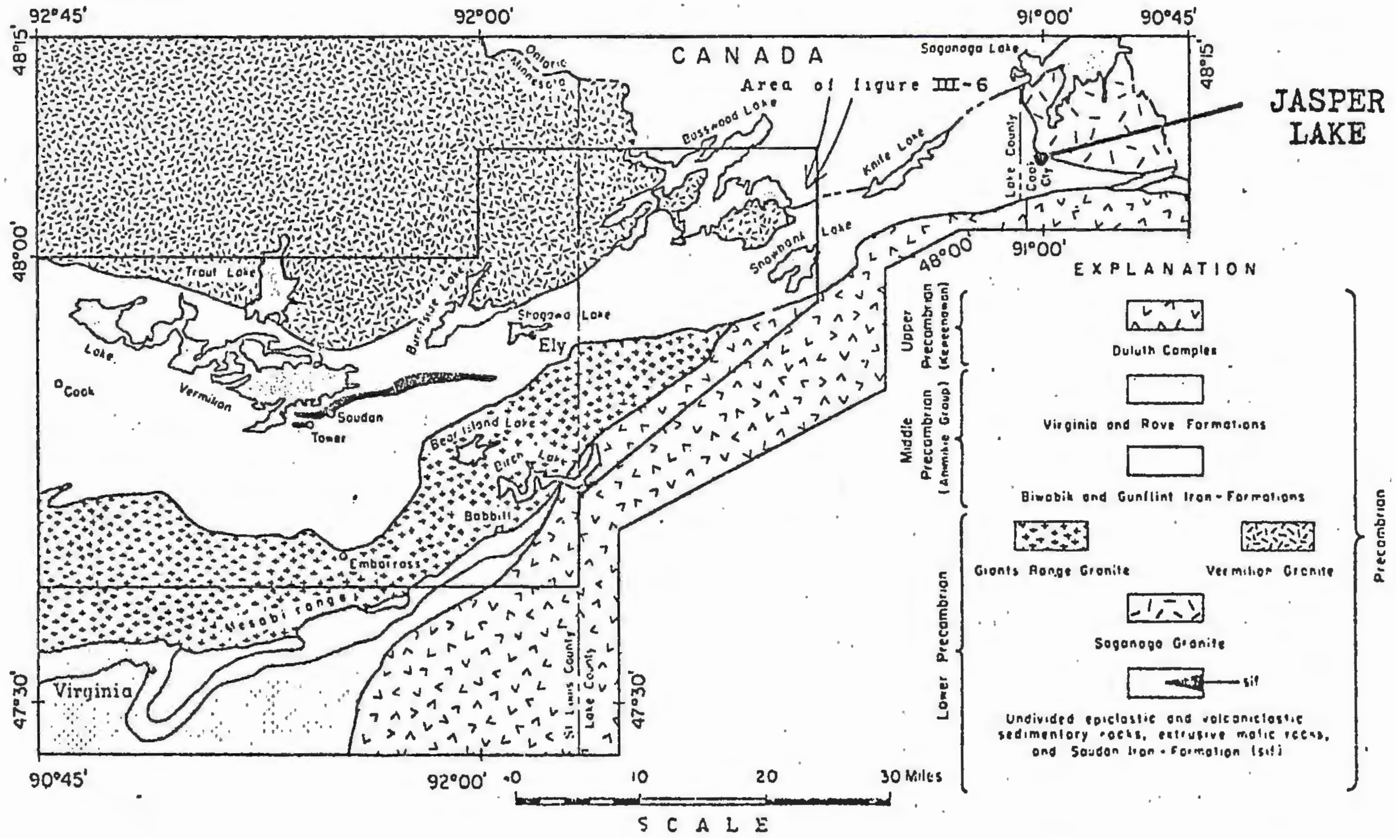


FIGURE 3--GENERAL GEOLOGIC MAP OF THE VERMILION DISTRICT (after Sims, 1972)

repetitions of rock types (Fig. 4). The rocks generally trend northeastward, and are steeply inclined, with top directions dominantly to the northwest as determined from graded beds and pillow structures. A reversal in trend occurs just east of Ogishkemuncie Lake, where the rocks strike northwestward, with primary structures indicating top direction generally to the southwest. At Jasper Lake the rocks strike east-west.

In the Jasper Lake area, the oldest known strata which form the base of the sequence are mafic, predominantly massive or pillowed metavolcanics (i.e. metabasalts, diabase, andesites) which will be referred to as the Jasper Lake greenstone unit. The eastward extension of this greenstone unit, the Chub Lake Volcanic Complex, is found in the Long Island Lake quadrangle approximately 10 km away (Morey, et al., 1968). The base of the unit has not been observed and is probably unexposed.

The Jasper Lake greenstone unit is overlain by what is referred to as the Jasper Lake pyroclastic unit and the associated Jasper Lake andesite unit. Gruner (1941) described the pyroclastic unit as consisting of predominantly agglomerate, volcanic breccia, tuff, and lesser conglomerate containing clasts of hornblende andesite. The andesite intrusive, made up of porphyritic and massive hornblende andesite, was interpreted

		1941 E. Vermilion district (Gruner)		1977 Jasper Lake area (this study)		1971 Long Island Lake Quad (Morey et al., 1968)
ALGONKIAN SYSTEM		Unconformity				
	Algoman Series	granites, syenites hornblendite feldspar porphyry (time?)		Unconformity		Unconformity
	Knife Lake Series	graywacke, slate tuff, conglomerate, etc. (19 units)	ARCHEAN	Ogishke conglomerate	ARCHEAN	
		Unconformity		Unconformity		
ARCHEAN SYSTEM	Laurentian Series	Saganaga tonalite		Saganaga tonalite		Saganaga tonalite
		Acid intrusives/extr.		Graywacke-slate		
	Keewatin Series	Soudan Iron Fm.				
		sediments & pyroclastics		Andesite intr.		
		andesite intr.		Pyroclastics		Chub Lake Volcanic Complex
		Ely Greenstone		Greenstone		

FIGURE 4--STRATIGRAPHIC COLUMN OF THE EASTERN VERMILION DISTRICT AND THE JASPER LAKE AREA

to be a volcanic flow interstratified within the pyroclastic unit and intruding parts of the greenstone. The structure and stratigraphic correlation of these two units is uncertain, as they may represent either members of the Chub Lake Volcanic Complex to the east, older units of the Knife Lake Group cropping out to the west, or a unit distinct in age from either of the above.

An unknown thickness of graywacke-slate conformably overlies the pyroclastic unit. Gruner (1941) considered these rocks as part of the Knife Lake Group, although no definite correlation with well-defined Knife Lake has been attempted.

The units described above are stratigraphically overlain by a 3500-6400 meter thick sequence of dominantly metagraywacke-slate and felsic volcaniclastic rocks (volcanic breccias, tuffs, agglomerates) which comprise the Knife Lake Group (Gruner, 1941). These complexly interlayered rocks are roughly equivalent lithologically to the Lake Vermilion Formation in the western part of the district (Morey and others, 1970), both of which contain scattered lenses of pillowed or massive mafic volcanic rocks, dacitic tuffs, agglomerates, and porphyries, and a large thickness of metagraywacke-slate.

The Saganaga batholith intruded this metavolcanic-metasedimentary sequence, and was also unroofed and eroded during Knife Lake time. This is indicated by the presence of clasts of Saganaga tonalite as well as greenstone in the conglomerate units interbedded with graywackes and tuffs of the Knife Lake Group.

Also, during the Algoman orogeny, granitic rocks of the Vermilion and Giants Range batholiths intruded rocks of the Vermilion district contemporaneously with regional deformation (Sims and Morey, 1972).

A thin, patchy veneer of glacial deposits covers some areas in the eastern Vermilion district.

Lithology

Jasper Lake Greenstone

Morey, et al. (1971) described the eastern portion of this greenstone unit, known as the Chub Lake Volcanic Complex, as consisting of 60 percent metabasalt and associated fragmental rocks, 30 percent meta-andesitic agglomerate, conglomerate, tuff, and flows, and 10 percent interfingered metagraywacke and slate. Over 90 percent of the metabasalt is extrusive, commonly exhibiting pillow structures with top directions mainly facing to the south. It is intruded by several tabular bodies of metadiabase. Epiclastic and lesser pyroclastic rocks are locally intercalated with the metabasalts. The pyroclastics are commonly crudely bedded and graded, whereas the epiclastics possess pebble- to silt-size clasts of metadiabase in a finer grained matrix.

Jasper Lake Pyroclastic Unit

Gruner (1941) referred to this unit as a greenstone conglomerate or agglomerate, containing predominantly angular to subangular, 1 mm to 60 cm in diameter fragments. The fragments are slightly different in color from the matrix and consist of two types: porphyritic hornblende andesite and dense aphanitic andesite. The rocks show almost no visible bedding or banding.

Jasper Lake Andesite Unit

No detailed description of this unit has been made. Gruner (1941) referred to it as a hornblende andesite porphyry flow but gave no further details as to its mineralogy.

Graywacke-Slate

The graywacke-slate in this area was described by Gruner in 1941 as a brownish-gray weathering, highly bedded and banded rock. The rock is gray on a fresh surface showing considerable graded bedding indicating top directions predominantly to the south. The average thickness of the layers was estimated to be one-half inch.

Saganaga Batholith

The Saganaga batholith, at the far end of the eastern end of the district, is a composite intrusion and consists of several rock types (Hanson and Goldich, 1972). The dominant phase is a gray, medium to coarse-grained tonalite, although the composition ranges from granodiorite to hornblende diorite at its margin. It is characterized by large (about 1 cm across) quartz aggregates that resemble phenocrysts, known as quartz 'eyes'. The tonalite intrudes the mafic volcanics and the lower Knife Lake Group and is overlain by the upper volcanic-sedimentary sequence. More detailed discussion of the structure and petrography of the Saganaga batholith is presented by Goldich, et al. (1972) and Hanson and Goldich (1972).

Knife Lake Group

Gruner (1941) divided the Knife Lake Group into 19 lithologic units, most of which are either epiclastic or volcaniclastic. These rocks all show evidence of volcanogenic origin. In approximate order of decreasing abundance, they are: graywackes, slate, agglomerate, conglomerate, and tuffaceous sandstone. Gruner gave brief field descriptions of all 19 units. The igneous rocks, which comprise the remainder of the group, include basalt flows and intrusions and porphyritic andesites , which are either flows or intrusive rocks (Sims, 1972).

The volcanic rocks and their derivative graywacke-type sedimentary rocks comprise a thick, complex volcanic pile that is grossly similar to the other greenstone belts in the Superior Province (Goodwin, 1968). In those areas that have been studied, the sedimentary rocks were derived largely from reworked dacitic pyroclastic deposits, rather than epiclastic deposits, and laid down in adjacent basins by turbidity currents (Ojakangas, 1972). But the presence of Saganaga tonalite and greenstone clasts in conglomerates of the Knife Lake Group indicate at least local weathering and erosion of once consolidated material (Gruner, 1941).

Quaternary Deposits

Glacial drift covers relatively few parts of the eastern Vermilion district, but does reach several feet of thickness in some areas. Many outcrops, especially along lake shores show good glacially polished and grooved surfaces. Seventeen measured striation directions, all within the Jasper Lake area, occur within a span of N 5° E to N 30° E.

Structure

Folds

In the eastern Vermilion district, at least two generations of folding can be inferred from Gruner's geologic map (1941). The metavolcanic-metasedimentary rocks in this area trend in two major directions, northwest and east-northeast. These trends reflect the presence of an older northwest-trending generation and a younger northeast-trending generation. The rocks on the south side of the Saganaga batholith are interpreted as being affected by the older fold generation, either prior to or contemporaneous with intrusion of the batholith (Sims, 1972). They strike N 60-70° W, and are deformed into tight westward-trending fold axes, referred to as part of the Agamok Synclinorium (Gruner, 1941). This northwest-trending segment is truncated on the northwest by rocks folded on northeast-trending axes. These folds are tight to close, plunging southeastward, and are interpreted as having been folded during or after the late stages of emplacement of the Saganaga batholith (Gruner, 1941). These collectively have been referred to as the Knife Lake Synclinorium by Gruner. The later northeast-trending fold generation is by far the dominant type, and overprints any older fold generations in the district.

Faults

The Vermilion district is cut by several dominantly east- and northeast-trending, high-angle longitudinal faults which divide the area into structural belts or segments (Gruner, 1941, Sims and others, 1968)(Fig. 2). In places, these faults cut out huge thicknesses of both the upper and lower parts of the metavolcanic-metasedimentary sequence. These large displacements and the rapid lateral facies changes make it nearly impossible to correlate rocks from one fault block with another (Gruner, 1941). The faults roughly parallel the regional strike of the strata, making estimation of displacement extremely difficult. Gruner (1941) has estimated fault displacements in miles horizontally (up to 3-4 miles or 5-6.5 kilometers), and thousands of feet vertically (up to 10,000 feet or 3,050 meters). Several smaller transverse faults with much smaller displacements vary in trend and cross-cut the main faults.

All Early Precambrian rocks of the district were affected by the faulting, which largely occurred subsequent to intrusion of the batholiths approximately 2.7-2.75 billion years ago (Goldich, 1968, Jahn and Murthy, 1971).

Metamorphism

The rocks in the Vermilion district contain mineral assemblages of dominantly greenschist facies metamorphism as defined by Turner (1968). Adjacent to batholithic intrusions, e.g. the Saganaga batholith in the eastern Vermilion district, and near some faults, amphibolite facies is reached (Sims, 1972).

DESCRIPTION OF THE JASPER LAKE UNITS

General Characteristics and Relationships

The three units of the Jasper Lake area are approximately vertical in attitude and trend west-northwest.

The Jasper Lake greenstone is linear in outline and extends from SE Sec. 7 to NW Sec. 21 in T.65N., R.5W. It is approximately 5 km long and 1 km wide and comprises the northern one-third of the map area. The greenstone represents approximately 1000-1500 meters of continuous stratigraphic thickness.

The Jasper Lake pyroclastic unit comprises approximately 5 km^2 of area directly south of the Jasper Lake greenstone unit. It stretches from the northern portion of Sec. 18, T.65N., R.5W. to just north of Mueller Lake in the SE$\frac{1}{4}$ of Sec. 26, T.65N., R.5W.

The Jasper Lake andesite is a flattened horseshoe-shaped intrusion centered around Jasper Lake which intrudes the pyroclastic unit and also clearly cross-cuts the greenstone in the NW$\frac{1}{4}$ of Sec. 21, T.65N., R.5W. It is roughly 1.6 km wide across the middle of the horseshoe, and 4 km long and located predominantly within the southern portion of Sections 17 and 18, and the northern portion of Sections 19, 20, and 21 in T.65N., R.5W.

These units crop out either as high, massive and blocky, resistant knobs and roche moutonnées or as low, flat, glacially hewn surfaces mostly around lake shores. Away from the lakes, these roche moutonnées reach up to 35-55 meters high. Outcrops are scant and are generally covered by water or heavy vegetation, thus hampering observation.

Contact Relationships

The northeastern side of the greenstone has been intruded by the Saganaga batholith. The contact is characterized by a 300-350 meter wide zone of a network of branching tonalite and quartz-rich veins within the greenstone unit (Plate 3). Farthest out from the contact, the veins are composed mainly of quartz. The veins range in width from hairline to 2 meters and are composed of coarse-grained, light-greenish tonalite nearest to the main tonalite body with increasing amounts of fine-grained, pinkish to whitish-green, hairline quartz-epidote veins about 350 meters away. The greenstone is fine-grained to medium-grained in this contact zone, and apprears recrystallized up to 50 meters from the tonalite batholith at some localities. Poorly developed vertical foliation, subparallel to the contact zone, is evident locally within 5 meters of the intrusive body.

To the north, the greenstone unit is intruded by two small, remnant apophyses of the Saganaga tonalite.

PLATE 3--NETWORK OF BRANCHING TONALITIC VEINS INTRUDING METABASALT WITHIN THE GREENSTONE-SAGANAGA TONALITE CONTACT ZONE IN SE$\frac{1}{4}$, Sec. 7, T.65N., R.5W.

They intrude the greenstone in the same gradational network-like pattern as the main body, but the contact zone is only 1-3 meters wide.

The greenstone and adjacent pyroclastic unit to the south are locally separated by a west-northwest-trending, high-angle fault trending from west central Sec. 18 to SE$\frac{1}{4}$ of Sec. 17, T.65N., R.5W. Here, this contact is characterized by intense shearing of the adjacent units, iron-staining, and development of pyrite (Plate 4). General discordance in the bedding trends of both units also suggest a faulted contact in this area.

The nature of the original contact between the greenstone and pyroclastic rocks is unknown. However, a conformable relationship is noted in at least one locality on the north shore of Jasper Lake in east central Sec. 18, T.65N., R.5W. Here, a small sliver of greenstone occurs south of the east-west-trending fault; it apprears conformable with vague bedding in the pyroclastic unit.

The previously described fault, along with the greenstone and pyroclastic units, are truncated to the west by northeast-trending strata. Here the Jasper Lake units are brought into contact with younger Ogishke conglomerate strata of the Knife Lake Group by a northeast-trending, high-angle, longitudinal fault with large (3-4 km) displacement indicated (Gruner, 1941).

PLATE 4--HIGHLY SHEARED VOLCANIC BRECCIA WITHIN THE FAULT CONTACT BETWEEN THE JASPER LAKE PYROCLASTIC AND GREENSTONE UNITS WITHIN NW$\frac{1}{4}$, Sec. 18, T.65N., R.5W.

The contact is highly sheared and characterized by minor amounts of fault gouge and pyrite. At the northern extent of the area, just east of the northern tip of Redpoll Lake, in the central part of Sec. 7, T.65N., R.5W., the fault becomes a weak, poorly defined shear zone which seems to terminate to the northeast. To the east of this area, in the SE$\frac{1}{4}$ of Sec. 7, the Ogishke conglomerate unconformably overlies the greenstone. The actual contact is not exposed, but is believed to be unconformable because of the discordant northeast trend of the conglomerate strata across the fault.

The Jasper Lake andesite exhibits chilled margins up to 50 meters wide in some areas, notable south of Ray Lake in the northern portion of Section 20, T.65N., R.5W. The actual intrusive contact with adjacent units is observed in only two outcrop areas: the west-central and central parts of Section 20, T.65N., R.5W., south of Ray Lake. In these areas, the andesite grades from a dark green, porphyritic augite andesite with a fine-grained groundmass, to a massive, nearly black, fine-grained andesite with a nearly aphanitic groundmass within 2-50 meters of the contact.

The contact, where observed, is sharp, and approximately vertical in attitude, roughly parallel to bedding in the surrounding pyroclastic unit. The andesite which penetrates the greenstone unit in the eastern end of the area is almost completely a massive, dark green to black, fine-grained variety.

The southern contact of the pyroclastic unit with the graywacke-slate unit is irregular, as mapped by Gruner (1941). In this study, it was examined in only one locality south of Skindance Lake within the NW$\frac{1}{4}$, Sec. 25, T.65N., R.5W. Although the actual contact is not exposed in this area, a discordance in bedding trend was observed. However, since the topping directions of the graywacke-slate unit are dominantly to the south away from the contact, and the unit is folded along west-northwest axes (Ojakangas, personal communication, 1977), the contact is believed to be conformable.

Macroscopic Description

Jasper Lake Greenstone

The greenstone is composed of dominantly massive extrusive metabasalt and lesser intrusive metadiabase together with minor occurrences of laminated tuff and intrusive andesite to dacite. These rocks, as a whole, are characteristically light to dark green on the weathered surface with frequent light tan to reddish iron-staining, and dark green to black on fresh surfaces. The metabasalts, andesites, and dacites are typically fine-grained to aphanitic, whereas the metadiabase ranges from fine-grained to coarse-grained. Except for vague pillowed or quench texture horizons, no attempt was made to trace out single metabasalt or metadiabase units because of limited outcrop, effects of local faulting, and apparent lenticularity of the units.

The andesites and dacites are commonly porphyritic and most notably located within two small 10-50 m^2 areas within the metabasalt in the NW$\frac{1}{4}$ and north-central portion of Section 18, T.65N., R.5W. (Plate 2). They contain 1-40% plagioclase phenocrysts 2-3 mm long which protrude slightly on the weathered surface. Dacites contain 10-15% quartz grains up to 2 mm across. The andesites and dacites have an irregular extent and grade within 3-5 meters from 40% phenocrysts near their central area to 1% phenocrysts at the margin next to metabasalts.

A small, coarse-grained, tonalite-diorite stock or plug, approximately 10-20 m^2 in exposed area, intrudes the greenstone in the NW$\frac{1}{4}$, Sec. 18, T.65N., R.5W. just north of the Jasper Lake-Kingfisher Lake portage. It is observed in only a few small rubbly outcrops which are highly sheared. Its contact with the surrounding greenstone is unfortunately not exposed.

Pillow structures and quench textures, together with rare bedding in tuffs, indicate that the greenstone is vertically inclined, trending west-northwest, with top directions to the southwest, and was deposited in water.

At four localities, three along the northeast shore of Jasper Lake in west-central Section 17, T.65N., R.5W., and one along the southwest shore of Tern Lake in the central part of Section 17, T.65N., R.5W., pillow structures are observed similar to those described by Green (1970), Naldrett and Mason (1968), and Viljoen and Viljoen (1969). On Jasper Lake, the pillows are smoothly rounded and measure approximately 0.2 m by 0.3 m up to 0.6 m by 1.0 m, but are generally quite variable in size (Plate 5). The chilled rinds of these pillows range from 1 to 2 cm in thickness and are typically reddish-brown in color. In one outcrop, pillows were observed resting on a 0.5-2.0 meter thick tuffaceous unit (Plate 6). At Tern Lake, pillow rinds of the same dimensions occur. They give top directions to the east-northeast but may be deformed because of the irregular shape of the rinds.

The tuffaceous rock is dark green and finely bedded with beds up to 2 cm thick which could be traced no more than 2-3 meters within the outcrop.

The only quench texture observed in outcrop is located approximately 200 meters north of Kingfisher Lake in the NW$\frac{1}{4}$, Sec. 18, T.65N., R.5W., on the north side of a steep glacial roche moutonnée (Plate 7). The lower 3-4 meters is represented by lineated, dark green chlorite, which has replaced pyroxene needles up to 10 cm long, which trend N 10-20° E. The lineations of the needles bend and change direction and are

PLATE 5--PILLOW STRUCTURES ON THE NORTHEAST SHORE OF JASPER LAKE IN NORTH CENTRAL Sec. 17, T.65N., R.5W.

PLATE 6--PILLOW RINDS UP TO 2 CM THICK OF PILLOWS RESTING ON A TUFFACEOUS LAYER IN THE CENTRAL PORTION OF Sec. 17, T.65N., R.5W.

PLATE 7--QUENCHED UPPER PORTIONS OF BASALTIC LAVA FLOWS OVERLAIN BY THE BASE OF A MASSIVE LAVA FLOW. PEN SHOWS THE BASE OF THE MASSIVE FLOW. LOCATED NORTH OF KINGFISHER LAKE IN NW$\frac{1}{4}$, Sec. 18, T.65N., R.5W.

interrupted at distinctive intervals up to 10 cm wide, where the needles appear broken (cf. Plate 7).

The rocks composing the greenstone unit are commonly sheared, especially near contacts, and contain ubiquitous, irregular, quartz-epidote or quartz-calcite veining up to 1 cm wide.

Jasper Lake Pyroclastic Unit

The pyroclastic unit is predominantly composed of volcanic breccia and tuff with lesser volcanic conglomerate and metagraywacke or argillite. These rocks, as a whole, display a massive, blocky character with generally variable fissility observed in tuffs and especially in metagraywacke-argillite units. These rocks range from light tan to dark green to gray on weathered surfaces and are typically light green or gray on fresh fractures. Reddish-brown iron-staining of the rock is often observed, especially in shear zones.

Bedding indications within the various units indicate the beds are vertical and folded along a west-northwest trend (Plate 2). Graded beds within the tuffaceous lenses in the unit indicate top directions dominantly to the south with intermittent alternations which indicate minor folding. A minimum of 800-1000 meters in thickness is estimated for the sequence from the exposed extent of vertical strata.

Volcanic breccias within the unit are generally massive, locally with poorly developed stratification, and are composed of fragments which are unsorted and range from angular to subrounded in shape. Although the volcanic breccias are recognized quite easily in outcrop by negative weathering impressions of the volcanic fragments (Plates 8 and 9), in many cases fragments are difficult to recognize, as they blend into the matrix material causing the rock to apprear to be a massive tuff or andesite.

The fragments of the volcanic breccias vary both in size and composition. They range from fine ash particles to blocks (up to 85 cm across) according to the classification by Fisher (1961)(see Table 1). In order of decreasing abundance, the fragments are composed of: porphyritic andesite, dacite, basalt, tuff, and rare graywacke-argillite.

The tuffaceous rocks are found as small, scattered lensoid to lenticular sheets and tabular bodies interbedded within the volcanic breccia units (Plate 10). They range from light to dark green and from fine-grained to aphanitic, and commonly grade into volcanic breccia. Generally the tuffs are finely laminated with typically parallel lamina up to 2 cm thick. They occasionally display wispy, discontinuous laminations in some areas, and graded and convoluted beds in others.

Volcanic conglomerates are relatively scarce and were found only as isolated lenses in the west-central

PLATE 8--NEGATIVE WEATHERING IMPRESSIONS OF FRAGMENTS OF VOLCANIC BRECCIA FROM THE SW$\frac{1}{4}$, Sec. 18, T.65N., R.5W.

PLATE 9--LARGE, UP TO 1 METER BLOCKS OF PORPHYRITIC ANDESITE IN A VOLCANIC BRECCIA FROM TICKLE LAKE IN SE$\frac{1}{4}$, Sec. 13, T.65N., R.6W.

TABLE 1--ESTIMATES OF THE PERCENTAGE OF FRAGMENT SIZES WITHIN THE VOLCANIC BRECCIAS OF THE JASPER LAKE PYROCLASTIC UNIT. PERCENTAGES OF FRAGMENTS ARE OF THE ENTIRE UNIT. SIZE OF FRAGMENTS ARE CLASSIFIED ACCORDING TO THE CLASSIFICATION OF FISHER (1961).

Size (mm)	Fisher (1961) terminology		Percent of fragments
	Coarse	Blocks	35%
256	Fine		
64	Lapilli		50%
4	Coarse ash		10%
0.0625	Fine ash		5%

PLATE 10--FINELY LAMINATED TUFFACEOUS LAYERS WITHIN THE JASPER LAKE PYROCLASTIC UNIT FROM TICKLE LAKE IN SE¼, Sec. 13, T.65N., R.6W.

part of Section 18, T.65N., R.5W., on the far northwest side of Jasper Lake, and the southeast shore of Kingfisher Lake. These lenses are generally up to 50 meters in thickness and pinch out at both ends within 100-150 meters. All of the volcanic conglomerates are moderately to highly sheared with foliated matrix material wrapping around the clasts. The clasts range from grit to boulder size (20 cm long) and are sub- to well-rounded (Plate 11). Eight pebble counts of serial-sectioned slabs of two samples were completed. In order of decreasing abundance, the clasts are composed of: porphyritic andesite, massive (non-porphyritic) andesite, metabasalt or greenstone, graywacke-argillite, tonalite, and minor dacite, quartz grains, and unidentified mafic clots. Bedding is absent or poorly developed in the volcanic conglomerates.

Graywacke-argillite strata are observed in two localities in the area: along the faulted contact zone with the greenstone in the SE$\frac{1}{4}$, Sec. 18, T.65N., R.5W., and in a small 5-10 m^2 outcrop south of Skindance Lake (NW$\frac{1}{4}$, Sec. 25, T.65N., R.5W.). The argillites are typically finely laminated (up to 3 mm), and exhibit extreme fissility along bedding planes. The laminae are generally flat and parallel, but are also convoluted south of Skindance Lake, and offset (up to 2 cm) in some specimens by minor fault movement. Minor cross-laminations are also occasionally observed in the graywacke-argillite near the greenstone contact.

PLATE 11--FLOAT BOULDER OF SHEARED VOLCANIC CONGLOMERATE WITH ANGULAR TO SUB-ROUNDED VOLCANIC CLASTS UP TO 20 CM LONG FROM KINGFISHER LAKE IN WEST CENTRAL Sec. 18, T.65N., R.5W.

Jasper Lake Andesite

The andesite unit consists mainly of porphyritic, fine-grained to aphanitic pyroxene andesite, and lesser amounts of porphyritic plagioclase and hornblende andesite to dacite. Compositions are gradational within the unit and massive, non-porphyritic varieties are occasionally observed. These rocks, in general, are light to dark green on both weathered and fresh surfaces, and are very massive and blocky in outcrop.

The dominant lithology recognized in outcrop consists of up to 40% equant augite phenocrysts which are 0.5 to 1.0 mm long, within a fine-grained andesite matrix. In another facies of the andesite, plagioclase and hornblende phenocrysts are observed as tabular crystals 2-3 mm long which comprise up to 45% of the rock and typically occur to the exclusion of augite. The andesite contains wide chilled margins in a few localities. The rock also becomes slightly sheared near its contacts in some areas, but this is not characteristic.

In a few areas, notably the NE$\frac{1}{4}$, Sec. 19, and the SE$\frac{1}{4}$, Sec. 18 in T.65N., R.5W., the andesite is amygdaloidal. The amygdules are up to 3 cm across and irregular in shape, and are typically filled with calcite, chlorite, or quartz.

Minor, irregular hairline quartz-calcite veins cross-cut the rock in scattered locations.

Microscopic Description

Jasper Lake Greenstone

Extrusive Metabasalt

Within the Jasper Lake greenstone, the metabasalts make up 75% of the unit. In thin section, 5 of the 20 specimens of metabasalt examined displayed quench texture. The rocks are typically massive, fine-grained to aphanitic, and rarely contain amygdules. Irregular quartz-epidote to quartz-calcite-epidote veins, up to 0.3 mm wide, are observed in almost all specimens.

Even the freshest metabasalt contains very few primary minerals. The greenstones are composed largely of a metamorphic assemblage and contain: plagioclase, actinolite or hornblende, epidote, rare relict augite, magnetite, chlorite, calcite-ankerite, apatite, pyrite, sphene, leucoxene, prehnite, pumpellyite, rare quartz, and possible zircon and rutile.

Plagioclase ranges from trace amounts to 45% of the rock and occurs as tabular crystals 0.3-3.0 mm long. It is rarely twinned and generally extremely altered to sericite, epidote, actinolite, chlorite, and calcite. Plagioclase composition was determined by the Michel-Levy method on a few albite twins and was found to be albitic, in accordance with the adjacent assemblage. The grains are generally discrete with some poikilitic growth around actinolite pseudomorphs.

Actinolite and hornblende vary from 30-84% of the rock. The highly pleochroic green to brown crystals were identified as hornblende and the pale green crystals as actinolite. Actinolite is typically the predominant mafic mineral except within 30-60 meters of the Saganaga tonalite body where metamorphic hornblende is the major mafic constituent. Actinolite generally occurs as prismatic to fibrous crystals as pseudomorphs of pyroxene and plagioclase 0.3-3.0 mm long (Plate 12). In some specimens, notably KL-6 and JL-27 (Plates 13 and 14), the actinolite and plagioclase needles are greater than 3 cm long and form beautiful feathery, radiating, bow-tie and fan-shaped, quench textures. Rarely, relict augite cores, which are anhedral and up to 0.3 mm long, are recognizable within some actinolite needles. Hornblende also occurs as euhedral, prismatic grains.

Epidote and chlorite are generally closely associated with actinolite and hornblende and range from trace amounts to 15% of the rock. They occur both as alteration products within plagioclase, actinolite, and hornblende grains, and randomly replacing large portions of aphanitic groundmass material. Epidote varies from anhedral to subhedral grains 0.1 mm long to subhedral prisms up to 2 cm long within actinolite needles in quench-textured rocks. Chlorite is observed as fibrous aggregates (up to 0.1 mm) and amorphous masses interstitial between most other grains. Both epidote and chlorite contain a brownish amorphous material

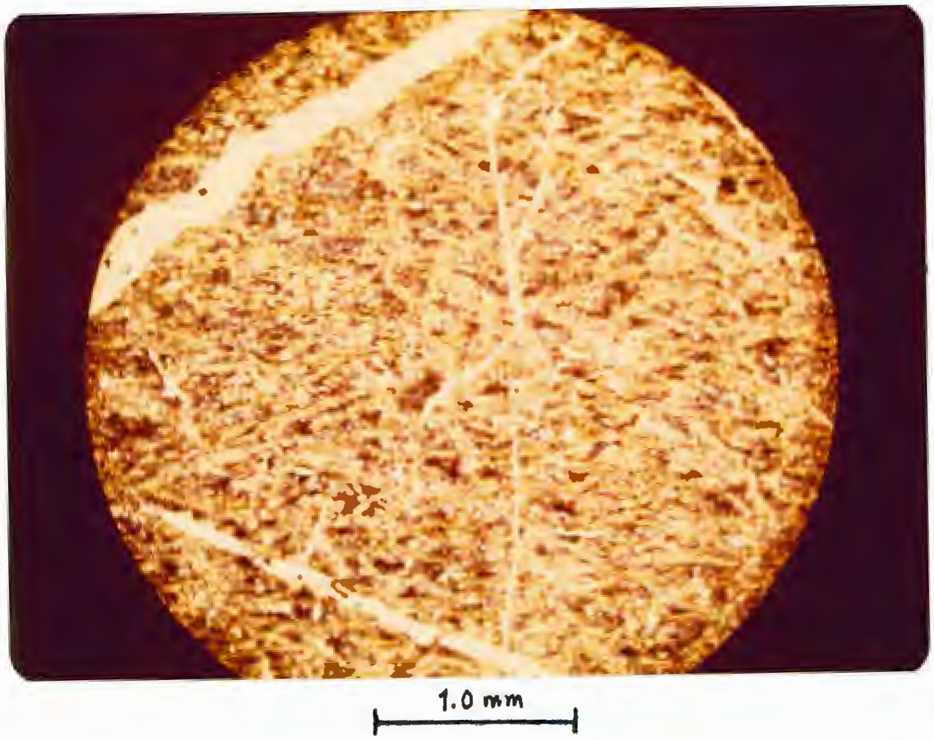


PLATE 12--PHOTOMICROGRAPH OF METABASALT WITH ACTINOLITE PSEUDOMORPHS AFTER PYROXENE (AUGITE) - Sample JL-101, N. CENTRAL Sec. 17, T.65N., R.5W.

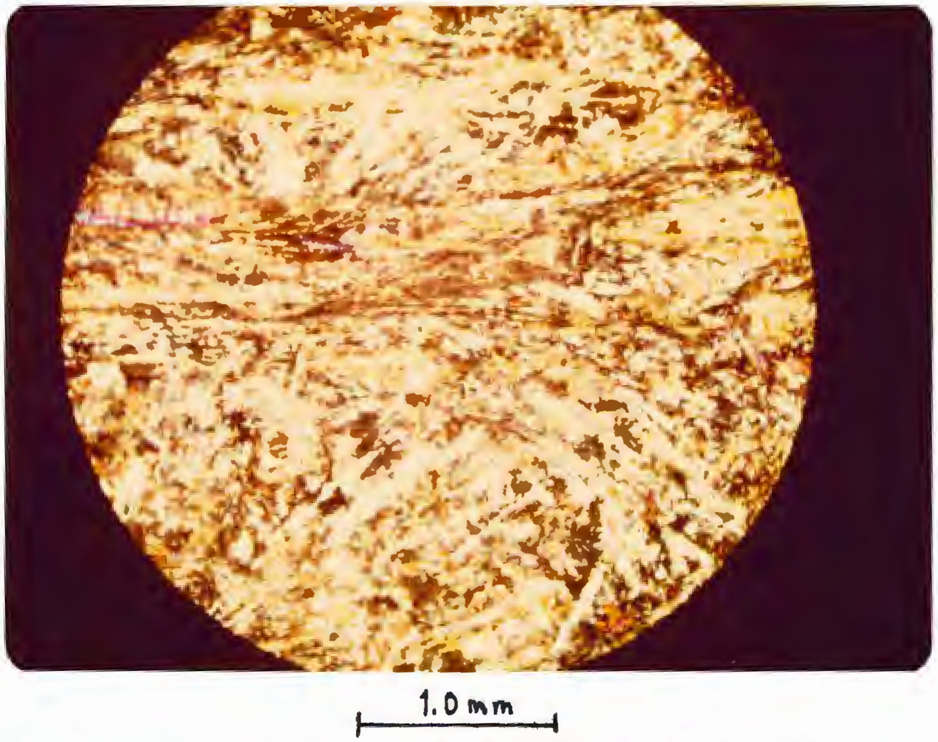


PLATE 13--PHOTOMICROGRAPH SHOWING ACTINOLITE NEEDLES PSEUDOMORPHIC AFTER QUENCHED AUGITE WITH RELICT AUGITE CORES IN A METABASALT - Sample KL-6 FROM NW¼, Sec. 8, T.65N., R.5W.

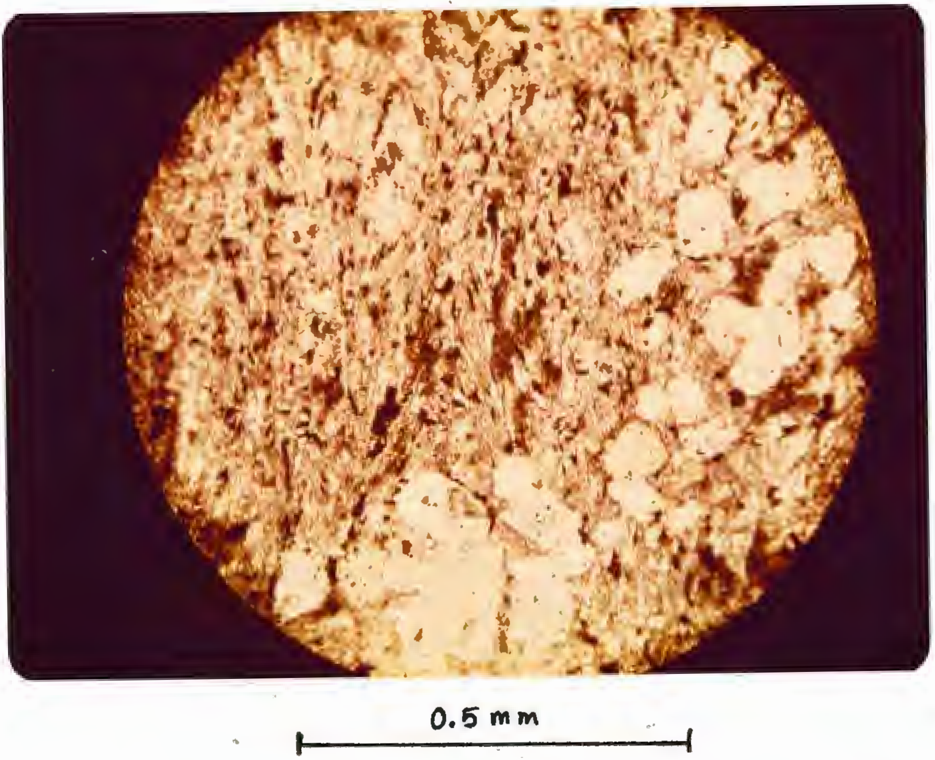


PLATE 14--PHOTOMICROGRAPH SHOWING QUENCHED PLAGIOCLASE NEEDLES RADIATING FROM EQUANT ACTINOLITE CRYSTALS - Sample JL-27 FROM N. CENTRAL Sec. 17, T.65N., R.5W.

(probably iron oxides or leucoxene) which makes up a portion of the groundmass (5-10%).

Accessory minerals such as opaques, leucoxene, apatite, sphene, zircon, and rutile generally make up from trace amounts to 1% of the total rock composition. Opaque oxides are most abundant, making up to 1% of the rock, commonly as 0.1-0.5 mm euhedral magnetite crystals. It is randomly distributed throughout the groundmass and sometimes occurs within actinolite pseudomorphs after augite. Magnetite is typically altered to fine-grained leucoxene and iron oxides. Apatite, sphene, zircon, and rutile occur as euhedral to subhedral prisms, less than 0.1 mm long, in trace amounts interstitially or within feldspar laths.

Other secondary minerals, including pyrite, calcite-ankerite, and quartz range from trace amounts to 10% of the rock. Pyrite is observed as small cubes up to 0.1 mm across, and subhedral equant grains within the groundmass. Calcite and minor ankerite occur as anhedral masses replacing portions of the rock in a patchy distribution. They rarely comprise over 1% of the rock except within 10-20 meters of faulted contacts where they locally comprise up to 80% of the rock. Generally, calcite-ankerite preferentially replaces groundmass material and plagioclase grains. Quartz is found as anhedral equant grains up to 0.5 mm long within the groundmass. It sometimes comprises nearly 10% of the rock as cavity fillings and replacement of original groundmass material. This occurrence of quartz is often closely associated with the occurrence of quartz-rich veins which cross-cut the rock.

Prehnite is rare in the greenstone unit. Small radial masses of needly crystals and anhedral massive grains approximately 0.1-0.2 mm long are preserved in a few specimens. The occurrence of prehnite is closely associated spatially with prehnite-bearing quartz-rich veins near the Saganaga tonalite.

Veining in the metabasalts ranges from hairline quartz-epidote, quartz-calcite, quartz-calcite-epidote, or calcite veins up to 2 meters wide as well as tonalite veins and dikes adjacent to the Saganaga tonalite. The veins are irregular and increase in size and number as the Saganaga batholith is approached. Within 100 meters of the intrusion, the veins are chiefly composed of quartz, plagioclase, epidote, and minor orthoclase, prehnite, and calcite grains. The veins exhibit a well-developed "comb" structure indicating crystal growth from the margins inward. The grain size ranges from 0.1 to 0.6 mm in length. With increasing distance from the intrusion, feldspars and prehnite are lost and quartz and calcite predominate. In some areas, especially farther from the intrusion, the veins are almost wholly calcite-quartz or quartz-chlorite-calcite. Near fault contacts the percentages of calcite (with minor quartz, magnetite, and chlorite) in the veins drastically increases, and calcite forms 80-90% of the veins.

Within 100-200 meters of fault contacts metabasalt mineralogy changes drastically, causing almost complete obliteration of pre-existing minerals and textures. The rocks are fine-grained to aphanitic and are almost completely replaced by calcite and chlorite aggregates in a very irregular, patchy distribution. Calcite and/or ankerite comprise up to 80% of the rock in anhedral masses and aggregates up to 1 mm long. Approximately 30-45% of the rock is composed of fibrous to massive, fine-grained chlorite aggregates less than 0.1 mm across. The remainder of the rock is comprised of up to 30% relict plagioclase (to 2 mm needles), actinolite (to 0.5 mm), magnetite (less than 0.1 mm euhedral prisms). A large number of irregular quartz-calcite veinlets up to 3 mm thick also cross-cut the rock.

Intrusive Metadiabase

The remaining 25% of the Jasper Lake greenstone is composed of light to dark green, fine- to coarse-grained metadiabase. Good ophitic texture is still preserved in most "fresh" specimens. From examination of five thin sections the major constituents are the same as in the metabasalts.

Plagioclase constitutes from 15-50% of the metadiabases and occurs as large, anhedral to euhedral laths, 1-10 mm long, which are commonly altered to chlorite and sericite, and partly replaced by calcite and ankerite. The composition of the plagioclase, using the Michel-Levy method, is albitic (An_7).

Quartz generally comprises 4-5% of the rock although one sample contained 25 percent. It occurs as anhedral to subhedral, monocrystalline, slightly strained, equant grains 0.1-2.0 mm long. Discrete quartz grains are interstitial between plagioclase and actinolite. Most metadiabase specimens also contain up to 1% micrographic intergrowths of quartz and plagioclase interstitial to large plagioclase laths (Plate 15). The feldspathic portions of the intergrowths are commonly partly altered to chlorite and sericite, and locally replaced by calcite and minor ankerite.

Actinolite needles or laths compose up to 25% of the rock. They are 0.1-1.0 mm long and are pseudomorphous after pyroxene. Actinolite less commonly occurs as fine needles with chlorite in the groundmass between large plagioclase laths. It is often highly replaced by calcite and epidote.

Chlorite makes up 10-35% of the rock and occurs mainly as massive, lamellar or amorphous replacement material of plagioclase laths and mafic constituents. It is also found as cavity fillings between quartz and plagioclase grains.

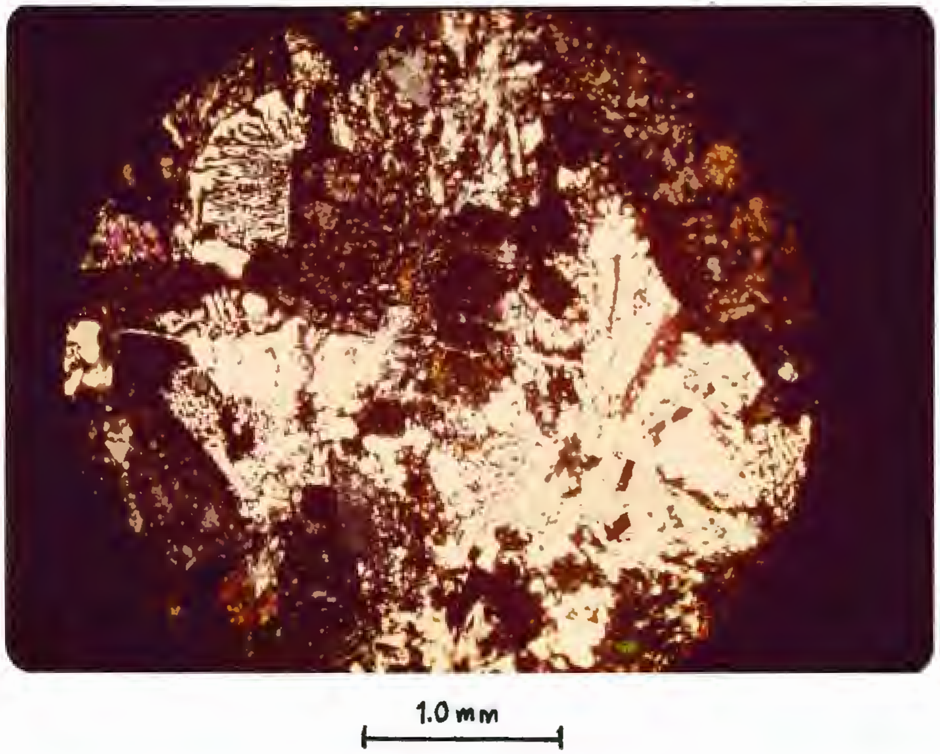


PLATE 15--PHOTOMICROGRAPH OF TYPICAL MICROGRAPHIC INTERGROWTH OF PLAGIOCLASE AND QUARTZ BETWEEN LARGER PLAGIOCLASE AND ACTINOLITE GRAINS WITHIN THE METADIABASE OF THE JASPER LAKE GREENSTONE UNIT - Sample JL-92 FROM CENTRAL Sec. 17, T.65N., R.5W.

Calcite-ankerite, and possibly siderite, range from 15-24 percent of the rock. As with the metabasalts, they are abundant within 200 meters (especially within 10-20 meters) of fault contacts and were described in the previous section.

Other minor constituents such as epidote, magnetite, leucoxene, pyrite, apatite, sphene, and zircon comprise from trace amounts to 10% of the rock. Epidote occurs as anhedral to subhedral prisms from 0.1-0.3 mm long, generally replacing plagioclase and actinolite. It usually comprises up to 5% of the rock. Epidote also occurs in interstitial spaces and in rare veins and cracks. Magnetite (1-9% of the rock) occurs as subhedral octahedra and plates up to 5 mm long. It is commonly highly altered to leucoxene and is observed between plagioclase laths as small clumps or clusters. Pyrite, apatite, zircon, and sphene constitute up to 1% of the rock as euhedral interstitial grains less than 0.1 mm long.

Intrusive Porphyritic Andesite-Dacite

Less than 1% of the Jasper Lake greenstone unit is comprised of a porphyritic hornblende andesite and lesser intrusive dacite (Plate 16). The porphyritic texture of the intrusion, as well as grain size, decreases toward the edges of the body producing a chilled margin. Its contact with the surrounding metabasalt is imperceptible. These rocks are typically light green, massive, and fine-grained and characteristically contain 15-20% tabular plagioclase phenocrysts 2-3 mm long. Two Michel-Levy determinations on well-developed albite and pericline twinned plagioclase indicate an albite composition (An_4). These phenocrysts are heavily altered to sericite and calcite, and are commonly broken in rocks near the intrusive margins.

Prismatic hornblende phenocrysts up to 2 mm long once comprised up to 15% of the rock. The hornblende is now completely replaced by pseudomorphs of chlorite and lesser actinolite with epidote, preserving only relict euhedral crystal shapes.

Rare, subhedral, equant quartz phenocrysts, up to 1 mm across occur in some areas of the intrusion comprising up to 10% of the rock and producing a more dacitic composition.

The groundmass (70-80%) is composed of plagioclase, hornblende, quartz, magnetite, and minor epidote, sphene, and rutile grains less than 0.3 mm long.

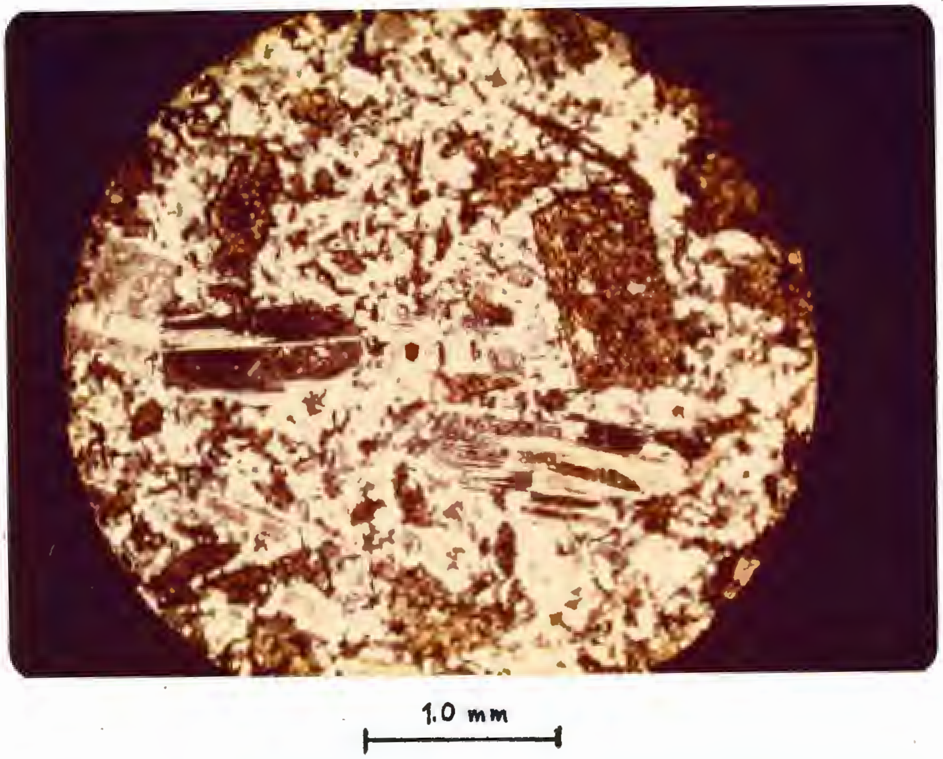


PLATE 16--PHOTOMICROGRAPH OF TYPICAL INTRUSIVE PORPHYRITIC ANDESITE-DACITE WITHIN THE JASPER LAKE GREENSTONE UNIT - Sample JL-26 FROM N. CENTRAL Sec. 18, T.65N., R.5W.

Plagioclase, hornblende pseudomorphs, and quartz occur as anhedral equant grains which produce a hypidiomorphic-granular, mosaic-like texture in the groundmass. Rare, poorly developed myrmekitic intergrowths of plagioclase and quartz are evident between small grains suggesting the presence of at least a small amount of primary potash feldspar. Magnetite comprises up to 5% of the rock as subhedral, equant crystals up to 0.1 mm long. It occurs within hornblende pseudomorphs and sprinkled interstitially throughout the groundmass. Epidote replaces mafic crystals in the groundmass normally in trace amounts, but in a few specimens comprises 7% of the rock. Small, subhedral, highly altered epidote grains, showing simple twins on (001) are found in trace amounts. Traces of sphene and rutile occur within plagioclase crystals as anhedral to subhedral, wedge-shaped and prismatic crystals, respectively.

Jasper Lake Pyroclastic Unit

Volcanic Breccia

Volcanic breccias comprise approximately 82% of the Jasper Lake pyroclastic unit in estimated areal extent. Figure 5 illustrates the distribution of the volcanic breccias within the pyroclastic unit. The matrix of the volcanic breccias is dark green, fine-grained to aphanitic, and occasionally possesses a weak foliation. The breccias contain from 30-90% of mainly

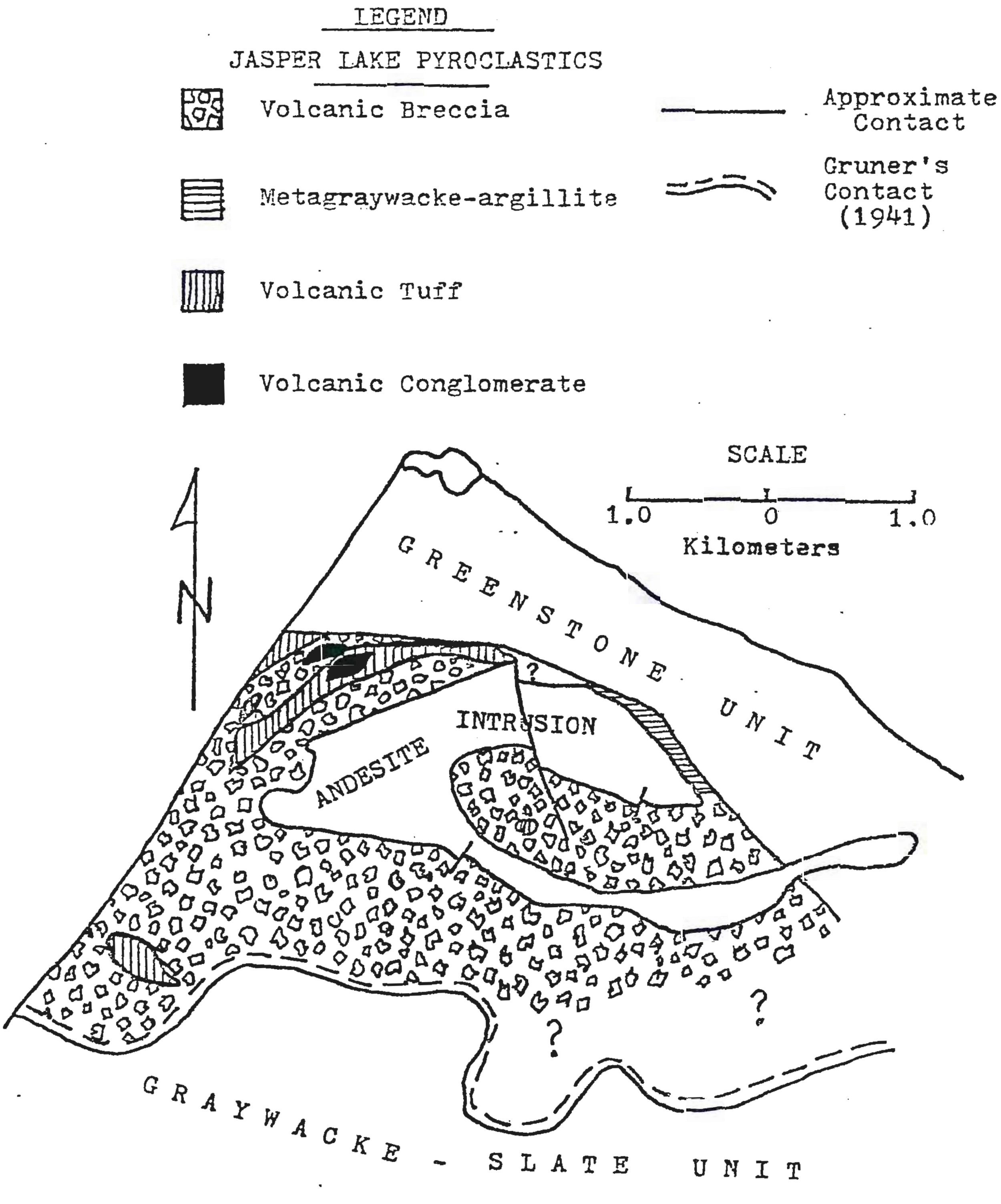


FIGURE 5--MAP SHOWING THE SPATIAL DISTRIBUTION OF ROCK TYPES WITHIN THE PYROCLASTIC UNIT IN THE JASPER LAKE AREA

angular to lesser subrounded fragments of rocks of almost completely volcanic origin.

Fragment types and the maximum percentages of these fragments of the total rock composition were observed within the volcanic breccia and are summarized in Table 2.

Thin Section Analysis of Fragments Within the Volcanic Breccia

The andesite and dacite fragments nearly everywhere comprise over 75% of the fragment types present. The majority of these fragments are very similar to, and probably derived from the same source as the Jasper Lake andesite unit (Plate 17). In general, the percentage of andesite and dacite fragments similar to the andesite unit decreases away from the intrusion as shown in Figure 6.

The andesite fragments are porphyritic and rarely non-porphyritic and typically consist of 30-70% phenocrysts of augite pseudomorphs, plagioclase, and other unidentified feldspar, up to 2 mm long. The augite pseudomorphs are equant to prismatic and are composed of actinolite and lesser chlorite. The feldspars form long, tabular crystals which are heavily replaced by sericite, chlorite, epidote, and calcite. Andesite fragments in one sample contain smooth-walled amygdules which are irregular in shape and filled with chlorite,

TABLE 2--FRAGMENT TYPES WITHIN THE VOLCANIC BRECCIA OF THE JASPER LAKE PYROCLASTIC UNIT AND ESTIMATED MAXIMUM PERCENTAGE OF THESE FRAGMENTS OF THE TOTAL COMPOSITION.

Fragment Type	Maximum Percentage
Porphyritic pyroxene andesite	95%
Porphyritic and massive hornblende andesite	75%
Porphyritic feldspar and hornblende dacite	70%
Tuff	45%
Mafic volcanics	5%
Metagraywacke-argillite	5%
Chert (?)	15%

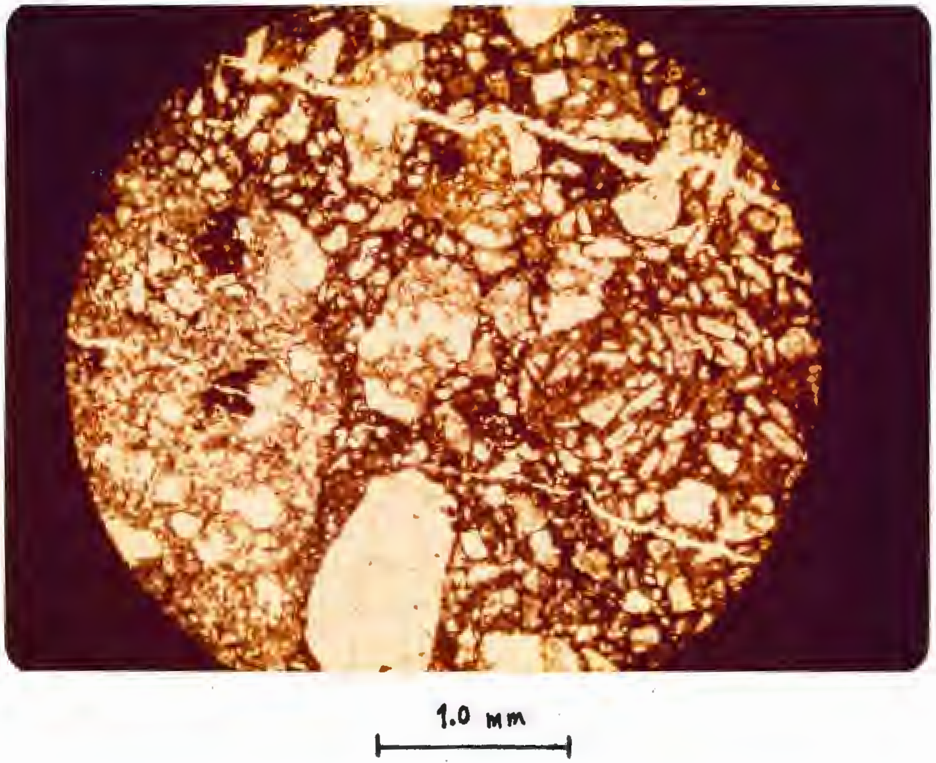


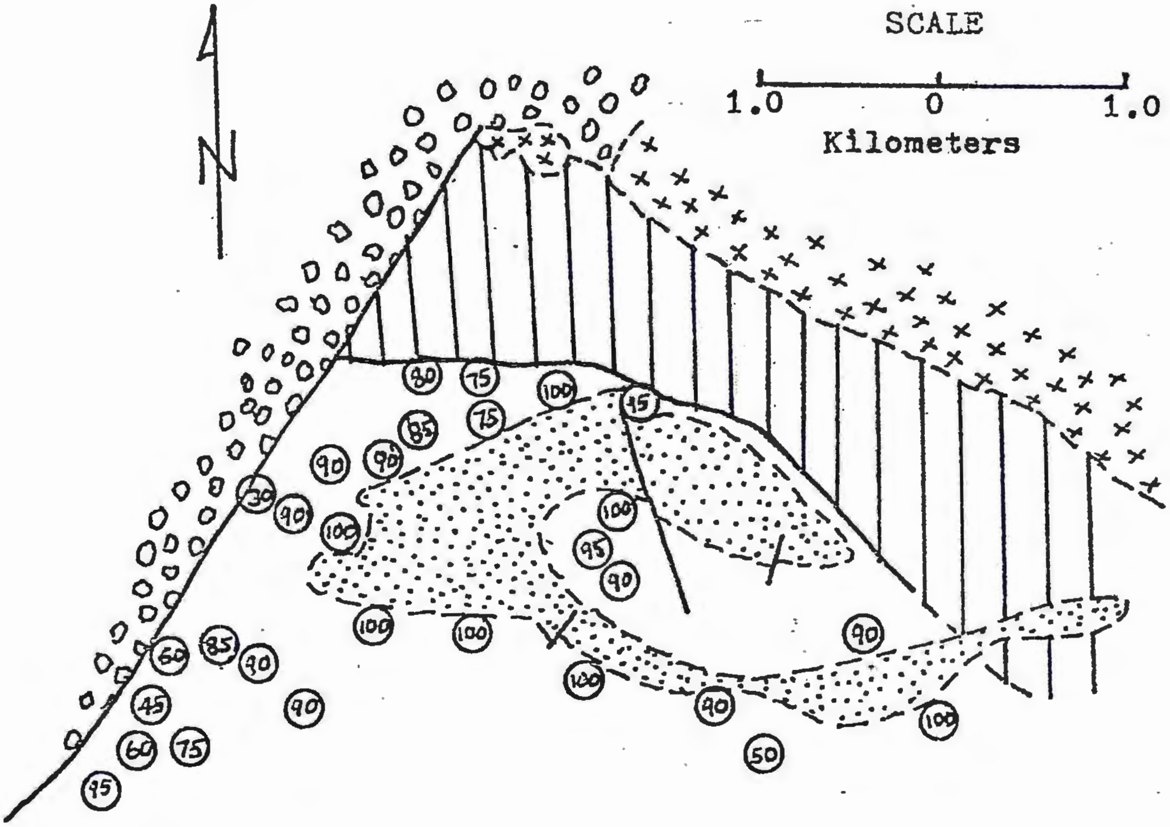
PLATE 17--PHOTOMICROGRAPH OF TYPICAL VOLCANIC BRECCIA WITH 100% PORPHYRITIC PYROXENE ANDESITE FRAGMENTS - Sample JL-61 FROM NE$\frac{1}{4}$, Sec. 19, T.65N., R.5W.

LEGEND

– – – – Approximate Contact

—— Fault

⑨⓪ Percent of fragments similar to the Jasper Lake Andesite



▨ Undiff. Knife Lake Group

☒ Saganaga Tonalite

⛆ Jasper Lake Andesite

☐ Jasper Lake Pyroclastic Unit

▥ Jasper Lake Greenstone

FIGURE 6--MAP SHOWING THE SPATIAL DISTRIBUTION OF THE PERCENTAGE OF ROCK FRAGMENTS WITHIN THE PYROCLASTIC UNIT WHICH ARE SIMILAR IN COMPOSITION TO THE JASPER LAKE ANDESITE UNIT

calcite, and quartz and comprise 75% of the fragment. The groundmass is predominantly made up of secondary chlorite and calcite, with traces of magnetite, and apatite also observed. Chlorite occurs as very fine-grained aggregates or masses and calcite replaces mainly feldspar and groundmass in an irregular, patchy fashion.

The porphyritic and non-porphyritic hornblende andesite fragments are typically found 0.5-2.0 km away from the Jasper Lake andesite and are similar to only a minor phase of that intrusion. These fragments generally contain 20-70% phenocrysts of hornblende and plagioclase up to 3 mm long. The hornblende is prismatic and replaced by chlorite, calcite, and minor epidote with some magnetite on the rims. Plagioclase is heavily altered to sericite, chlorite, epidote, and calcite, and is typically tabular. Eighty to ninety percent of the groundmass is composed of fine-grained hornblende and feldspar grains, with lesser chlorite, epidote, magnetite, and apatite comprising the remaining portion.

The dacite fragments are all porphyritic, containing 25-70% phenocrysts of plagioclase and minor hornblende, orthoclase, and quartz up to 1 mm long. The rock resembles porphyritic hornblende andesites described above with an increase in feldspars and quartz. Plagioclase phenocrysts are tabular and highly altered to sericite, magnetite, and lesser epidote. Michel-

Levy determinations on some plagioclase grains indicate an albitic (An_{4-7}) composition. Hornblende phenocrysts are prismatic, highly altered to chlorite and magnetite, and are up to 0.8 mm long. The groundmass contains quartz, plagioclase (major), orthoclase, and lesser chlorite as grains less than 0.2 mm across. Quartz comprises up to 30% of the rock, sometimes as scarce, equant phenocrysts up to 0.5 mm across. Calcite generally preferentially replaces the fine-grained groundmass and portions of plagioclase phenocrysts.

Tuff fragments are observed in relatively few specimens, mainly within breccias near Skindance Lake, but strongly resemble the tuffaceous portions of the pyroclastic unit. The fragments are typically fine-grained to aphanitic with up to 40% plagioclase laths less than 0.1 mm in length. Mafic crystals (up to 0.1 mm long) are converted to chlorite and calcite, and chlorite, epidote, and actinolite needles generally form the matrix. Some are laminated (by grain size rather than composition), with individual lamina up to 1 mm thick.

Fine-grained mafic clasts, many very similar to the metabasalts from the Jasper Lake greenstone, are observed with recognizable actinolite, plagioclase, and magnetite grains up to 0.5 mm long. The matrix is fine-grained chlorite. One breccia sample, within the NE$\frac{1}{4}$, Sec. 19, T.65N., R.5W., contains up to 45% scoriaceous basalt fragments of unknown origin, with amygdules filled with chlorite.

Metagraywacke-argillite fragments are rare and argillites are easily mistaken for chert. They are usually similar to the graywacke-argillite portion of the pyroclastic unit. These fragments commonly contain sericite in a vague subparallel arrangement within a fine-grained to aphanitic matrix too small to identify. Some fragments also may be aphanitic volcanic clasts.

Thin Section Analysis of Matrix Within the Volcanic Breccia

The matrix material of the volcanic breccias typically comprises 10-45% of the rock and is commonly hard to distinguish from the volcanic fragments. It mainly contains very fine, angular volcanic fragments, chlorite, calcite, some epidote, and minor amounts of broken hornblende, actinolite, plagioclase, and pyroxene crystals. Traces of magnetite, apatite, zircon, rutile, sphene, prehnite, and sericite are also observed in less than 0.1 mm grains. Volcanic fragments are less than 1 mm in size and appear to be derived from porphyritic andesite with minor dacite.

Chlorite mainly occurs as irregular masses and comprises most of the matrix where it replaces hornblende, pyroxene, and plagioclase crystals, fills cavities, and causes a blending of fragment boundaries with the matrix. Calcite, with minor ankerite (?), up to 0.5 mm in size, occurs as subhedral grains replacing plagioclase and large patches of the matrix.

Hornblende, pyroxene, actinolite needles, and plagioclase occur as broken crystals up to 1 mm long and making up nearly 15% of the rock. The crystals are highly altered to chlorite and sericite, and replaced by calcite. Magnetite and pyrite occur as euhedral to subhedral octahedra and cubes, respectively, up to 1 mm across sprinkled randomly throughout the rock.

Minor irregular quartz and quartz-calcite veins, up to 1 mm wide cross-cut these rocks in many areas. Very minor epidote, chlorite, and prehnite are also observed within some veins.

Tuffs

The tuffs within the Jasper Lake pyroclastics comprise about 15% of the unit (Fig. 5). A gradation exists between volcanic breccias (described above) and the tuffs. These rocks are light green and often finely bedded or laminated, with layers ranging from 0.5 mm to 4 cm thick. The rocks are typically fine-grained to aphanitic, and some possess graded bedding or convoluted beds. Minor irregular, wispy layering and cross-laminations are also observed in a few localities.

The major constituents of the tuffs include: plagioclase crystals, mafic crystals (augite and hornblende), chlorite, volcanic fragments, actinolite, and epidote. Plagioclase grains, up to 3 mm long, are commonly the dominant crystal type recognizable and comprise up to 45% of the rock. The crystals are generally tabular, some are broken, and they are commonly completely replaced by sericite and calcite. A relatively fresh, plagioclase-rich andesite tuff is illustrated in Plate 18. Mafic crystals, chiefly of augite and hornblende up to 3 mm long, comprise up to 25% of the rock. They are extremely altered to chlorite, actinolite, minor epidote, and calcite. Augite occurs as equant, stubby grains whereas hornblende is long and prismatic.

Sparse volcanic fragments and chips are observed within more massive and poorly bedded tuffaceous layers. They typically comprise less than 25% of the rock and range from 0.1 to 15 mm in diameter. The fragments are angular to rounded and are generally composed of porphyritic andesite to dacite, similar to those found in the volcanic breccias. Many are thoroughly altered to chlorite, sericite, and calcite, and occur in separate coarser-grained layers. Rare fine-grained to aphanitic argillite fragments similar to those within the volcanic breccia are also observed.

Chlorite is the dominant matrix constituent composing from 10-45% of the tuff. It is commonly platy to massive with a few discrete grains which are less than 0.1 mm in size. Chlorite mostly replaces mafic

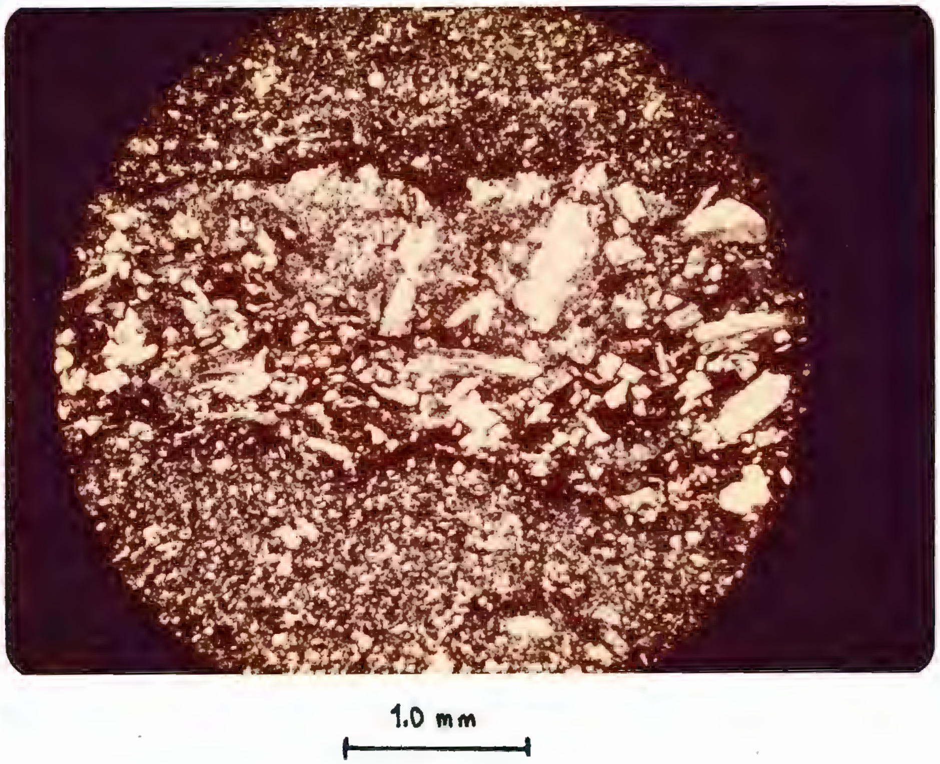


PLATE 18--CRYSTAL-LITHIC TUFF WITHIN THE JASPER LAKE PYROCLASTIC UNIT - Sample JL-63 FROM NE¼, NE¼, Sec. 19, T.65N., R.5W.

crystals and occurs as the interstitial matrix between crystals and rock fragments. It also fills cavities and some veins, rarely accompanied by prehnite.

Both actinolite and epidote, each comprising up to 15% of the rock, occur with chlorite in the matrix. Epidote is observed as irregular masses up to 0.3 mm across within the chlorite and is often surrounded by dark brown, opaque material. Actinolite is fibrous to needle-like (up to 0.4 mm) largely within the matrix but also replaces augite and some plagioclase in coarser layers.

Anhedral calcite and minor ankerite often replace large amounts of the matrix, especially near faults.

The minor constituents of the tuffs occur rather sporadically in varying amounts and include: quartz, sericite, magnetite, biotite, limonite, pyrite, and prehnite. Quartz comprises less than 5% of the rock as anhedral grains up to 0.5 mm long usually replacing several crystals and occurring in vugs and veins. Sericite and biotite comprise up to 5% of the rock as scaly patches (less than 0.1 mm long) within the matrix. Magnetite and pyrite occur as euhedral to subhedral octahedra, cubes, and equant masses up to 0.5 mm across, randomly sprinkled throughout the matrix and composing up to 5% of the rock. Rare prehnite (less than 1%) occurs as needles and radial aggregates in cavities and veins up to 0.5 mm wide.

Quartz veins up to 0.1 mm wide are observed crosscutting the rock in many specimens, and comprise less than 1% of the rock. Minor calcite and sericite also occur within these veins.

Metagraywacke-Argillite

The Jasper Lake pyroclastic unit contains roughly 2% metasediments identified as probably graywacke or argillite since they are really too fine-grained to be identified with certainty (Fig. 5). The rocks are light gray to green to black, fine-grained to more commonly aphanitic, and are therefore easily confused with cherts or very fine-grained (or aphanitic) volcanics. Some possess laminations up to 1.5 cm wide, and rare black and white color bands up to 0.5 cm wide. One specimen, south of Tern Lake, in the SE¼, Sec. 17, T.65N., R.5W., contains 0.5 cm thick cross-laminations together with up to 0.7 cm thick flat parallel laminae.

The metagraywacke-argillites are largely composed of very fine-grained to aphanitic quartz and feldspar (?) paste, chlorite, and sericite. Other identifiable constituents include: calcite, magnetite, quartz, sphene, limonite, broken plagioclase crystals, and volcanic rock fragments.

Quartz and feldspar, which comprise 40-90% of the rock, are generally too fine-grained to be distinguished and tend to give a "cherty" appearance. This material occurs as fine, granular, allotriomorphic masses of low birefringent material commonly with up to 25% fibrous sericite producing an intervening foliated texture. The sericite occurs in grains up to 0.1 mm long throughout the matrix, usually in a subparallel arrangement.

Chlorite comprises up to 40% of the rock, and occurs as massive to platy grains up to 1 mm long which are found between grains and also replace the quartz and feldspar. The predominance of chlorite in certain laminae in the color banded rocks produces the darker bands.

The minor constituents observed collectively comprise less than 10% of the rock. Calcite is the most variable component in abundance. Generally it comprises only up to 5% of the rock, but in some specimens, next to faults, it makes up to 50% of the rock. Individual, angular, monocrystalline quartz grains up to 0.1 mm long, comprise up to 2% of the rock. They are typically scattered randomly throughout the rock, regardless of any bedding which may be present.

Magnetite, limonite, leucoxene, and sphene collectively comprise less than 3% of the rock. Magnetite occurs as anhedral, equant grains, up to 0.5 mm across randomly distributed throughout the rock. Limonite and leucoxene are common amorphous alteration products of magnetite and limonite. Traces of diamond-shaped sphene less than 0.1 mm long occur randomly throughout the rock. Angular clasts of fine-grained graywacke or tuff, up to 4 mm long, also occur in trace amounts. Plagioclase grains, up to 0.2 mm long, comprise up to 3% of the rock at times as angular and broken crystals heavily altered to sericite and extremely hard to recognize.

In many graywacke-argillites, irregular, fine-grained quartz veins up to 0.1 mm wide are observed. Calcite, and minor zeolites, limonite, and magnetite occur as minor additional constituents in the veins.

Volcanic Conglomerates

Volcanic conglomerates comprise about 1% of the Jasper Lake pyroclastic unit (Fig. 5). Five thin sections were examined from one conglomerate lens (Plate 19).

Point counts were made of an average of 450 points of serial sectioned conglomerate slabs from two samples within the main conglomerate lensoid unit in the northwest portion of the pyroclastic unit. Slabs ranged from 100-400 cm^2 in area. Estimated clast types and their approximate maximum percentage of total rock composition are given in Table 3. These percentages indicate agreement of estimates both in the field and in thin section.

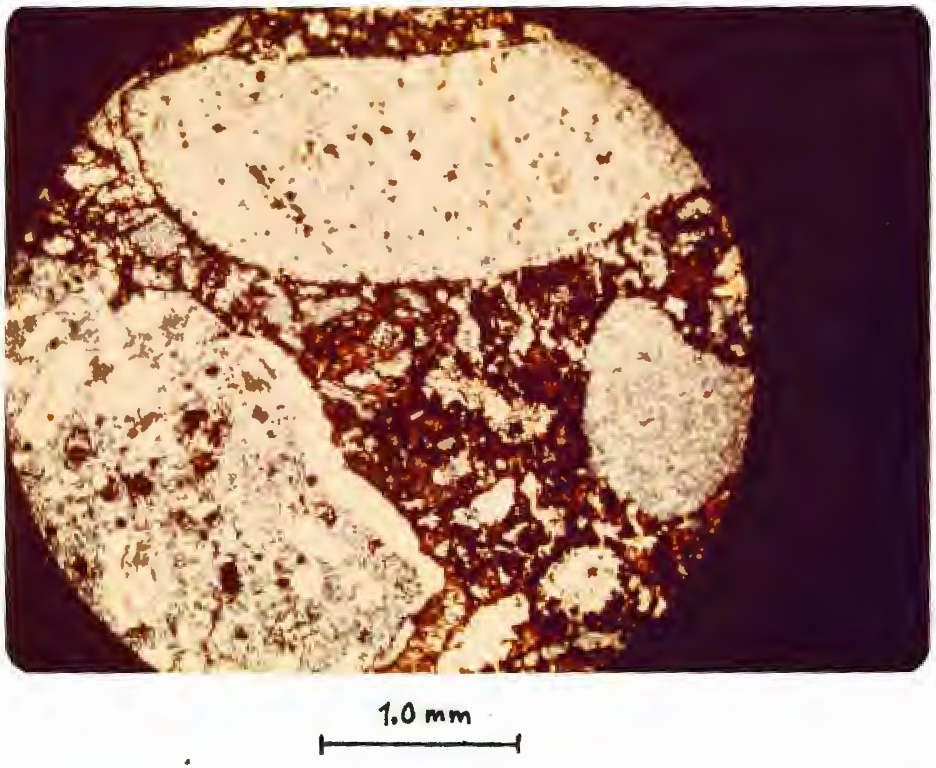


PLATE 19--PHOTOMICROGRAPH OF VOLCANIC CONGLOMERATE WITH PORPHYRITIC PYROXENE ANDESITE CLASTS (LEFT) AND METAGRAYWACKE-ARGILLITE CLASTS (RIGHT) - Sample JL-50 FROM W. CENTRAL Sec. 18, T.65N., R.5W.

TABLE 3--CLAST TYPES (AND PYRITE) WITHIN THE VOLCANIC CONGLOMERATE AND ESTIMATED MAXIMUM PERCENTAGE OF THESE FRAGMENTS OF THE TOTAL ROCK COMPOSITION. PERCENTAGES ARE ESTIMATED FROM SERIAL SECTIONED SLABS OF TWO SAMPLES UNDER A BINOCULAR MICROSCOPE.

Clast Type	Maximum Percentage
Porphyritic andesite	65%
Fine-grained andesite	47%
Metasediments	27%
Mafic clasts (greenstone)	9%
Granitic rocks	6%
Dacite	5%
Quartz or chert	2%
Unidentified mafic clasts	4%
Pyrite	1%

Description of Clasts from the Volcanic Conglomerate

Porphyritic pyroxene and less hornblende andesite are the principal andesitic compositional types present, and comprise over 50% of the clast types in the conglomerates. They are basically similar to the Jasper Lake andesite intrusion in composition and texture as described in the following section.

Dacite, greenstone, and unidentified mafic clasts were all observed only in hand specimen under a binocular microscope. Dacite clasts are light green to tan, fine-grained, and contain both tabular plagioclase phenocrysts up to 3 mm long (up to 25%), and equant quartz grains up to 2 mm across (up to 15%). The groundmass material is light greenish and fibrous, and wraps around quartz and plagioclase. It probably consists of a mixture of chlorite, actinolite, and epidote.

Mafic or greenstone clasts are observed as dark green, very fine-grained fragments which are commonly iron-stained. All grains in the rock are green, probably indicating a mixture of actinolite, chlorite, epidote, and plagioclase of a metabasalt or andesite. These fragments bear a striking similarity to the metabasalts of the Jasper Lake greenstone unit.

Polycrystalline quartz grains and/or chert clasts are rarely observed in some conglomerates as anhedral equant grains up to 0.2 mm long. They resemble the polycrystalline vein quartz in many veins throughout the Jasper Lake rocks. Whether they represent vein quartz or chert is uncertain.

Pyrite is ubiquitous throughout the volcanic conglomerates as euhedral cubes up to 1.5 mm across.

A small amount of fine-grained black clasts are unidentified. Because of their dark color and probable mafic affinity, they are most likely fine-grained metabasalts.

The metasedimentary clasts bear a strong resemblance to the metagraywacke-argillite described above.

The final clast type observed within the volcanic conglomerates are the intrusive (granitic) clast types, more specifically, of tonalite to granodiorite. They are typically light green to gray and fine-grained to medium-grained rocks with an allotriomorphic to hypidiomorphic-granular texture. These clasts are mainly composed of plagioclase, quartz, and orthoclase with lesser amounts of chlorite and calcite. Sericite, epidote, magnetite, and limonite occur in trace amounts. Plagioclase comprises 40-50% of the granitic clasts as tabular grains up to 2 mm long which are sometimes bent and deformed. These grains are commonly partly altered to sericite and calcite. Michel-Levy determinations indicate an albitic composition (An_2).

A variety of other constituents also occur in minor amounts in the granitic clasts. Equant quartz grains, up to 3 mm long, are somewhat undulatory and strained composing 20-30% of the granitic fragments. Orthoclase comprises 5-10% of these fragments as up to 3 mm grains, which are commonly poikilitic around plagioclase and quartz and often highly replaced by calcite. Altered biotite comprises 5% of the granitic fragment composition as scaly masses up to 1 mm long which have been converted to pseudomorphs composed of chlorite, limonite, and magnetite. Three percent chlorite occurs as aggregates around larger grains, especially biotite. Calcite represents 5-7% of the rock replacing mainly feldspar and some quartz. Sericite occurs as less than 0.1 mm scaly grains within feldspar. Epidote is rare, but is observed as (less than 0.1 mm long) anhedral grains within biotite pseudomorphs.

Description of the Matrix Within the Volcanic Conglomerate

The matrix material (particles less than 1 mm across) of the volcanic conglomerates comprises from 20 to 40 percent of the rock. The original material is commonly replaced by calcite making original minerals difficult to infer.

The major portion of the matrix is comprised of angular to subrounded chips of volcanic material less than 1 mm across. They range from porphyritic andesite to dacite and are commonly largely replaced by calcite.

Quartz grains compose up to 15% of the matrix mainly as secondary cavity fillings and lesser discrete, slightly strained detrital grains up to 0.3 mm long.

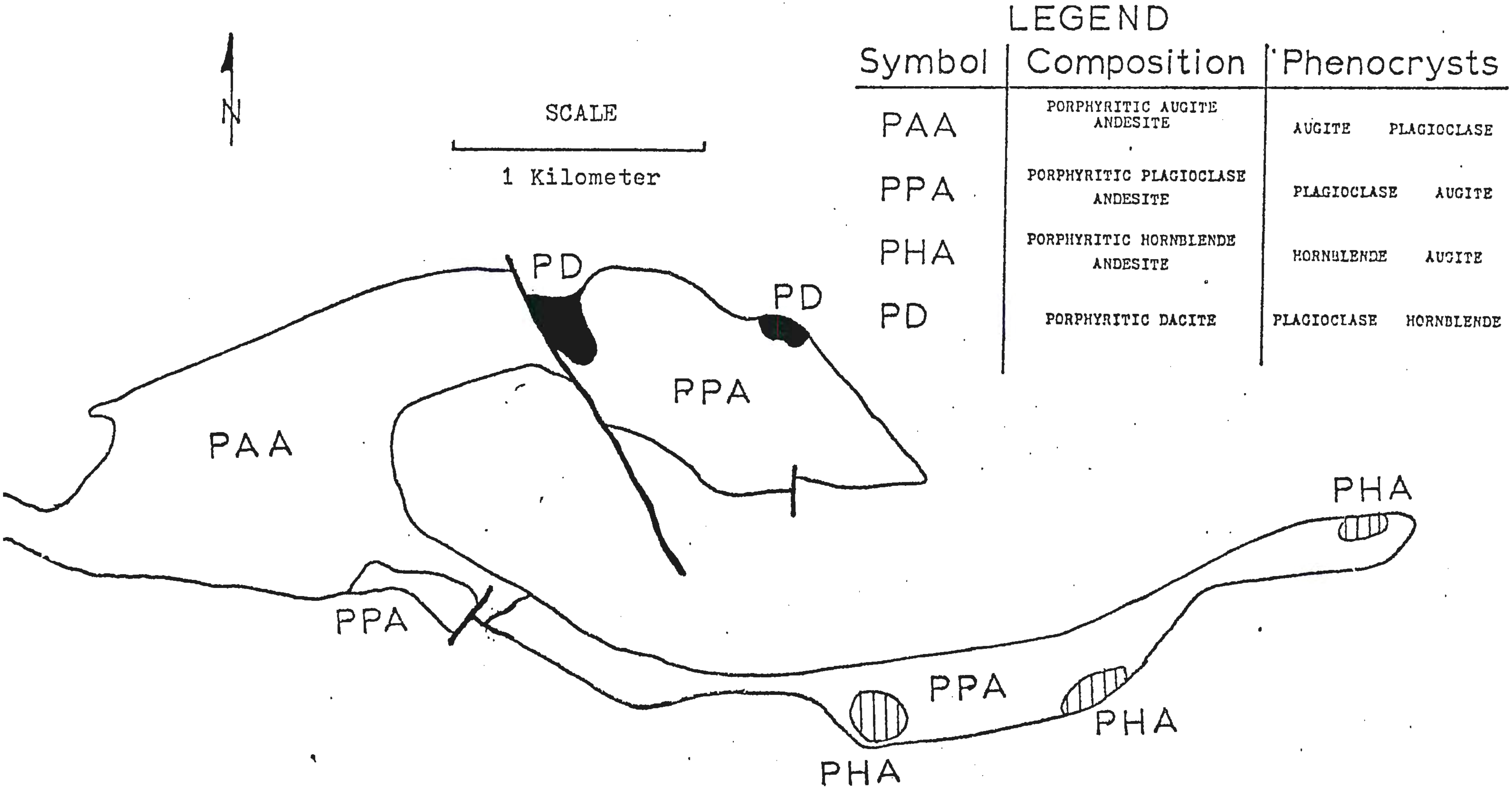
Chlorite represents up to 8% of the rock as scaly grains, up to 0.2 mm long, which surround and replace volcanic clasts. It generally forms most of the material between volcanic clasts and chips.

Pseudomorphs of broken plagioclase laths comprise up to 10% of the rock. They are up to 0.5 mm long and are completely replaced by a mass of calcite, chlorite, and sericite. In a few specimens, limonite comprises up to 20% of the matrix material.

Jasper Lake Andesite

The Jasper Lake andesite unit is composed of approximately 90% porphyritic augite andesite, 5% porphyritic hornblende-plagioclase dacite, and 5% porphyritic hornblende andesite. Minor non-porphyritic augite andesite of the same mineral composition as the main phase, is observed in a few localities. The body essentially grades in composition between the three rock types which show an irregular spatial distribution as shown in Figure 7.

Examination of 17 thin sections from random areas within the andesite body indicates the rocks to be porphyritic with a fine-grained to aphanitic groundmass. It is typically light green to black and exhibits tan to reddish-brown iron-staining in a few localities.



LEGEND

Symbol	Composition	Phenocrysts
PAA	PORPHYRITIC AUGITE ANDESITE	AUGITE PLAGIOCLASE
PPA	PORPHYRITIC PLAGIOCLASE ANDESITE	PLAGIOCLASE AUGITE
PHA	PORPHYRITIC HORNBLENDE ANDESITE	HORNBLENDE AUGITE
PD	PORPHYRITIC DACITE	PLAGIOCLASE HORNBLENDE

FIGURE 7--SPATIAL DISTRIBUTION OF ANDESITE AND DACITE PHASES WITHIN THE JASPER LAKE ANDESITE UNIT

The following phenocryst types occur in decreasing abundance in the andesite unit: plagioclase, actinolite pseudomorphs after augite, augite, hornblende, and quartz.

Plagioclase phenocrysts, comprising up to 40% of the rock, are usually lath-like or tabular and up to 4 mm long. They are mostly replaced by calcite and epidote, together with lesser amounts of chlorite, actinolite, and minor magnetite. Michel-Levy determinations indicate an albitic (An_{6-8}) composition.

Augite phenocrysts comprise up to 40% of the rock, and are now pseudomorphs composed of fibrous and needle-like actinolite patches and lesser chlorite (Plate 20). These phenocrysts are usually equant to short and stubby to tabular and range up to 2 mm long. They typically show relict polysynthetic (on (001)) or simple twinning along (100). Relict augite within these phenocrysts occurs in 1-2% of the phenocrysts. In a few specimens, notably JL-75 in the SW¼, Sec. 17, T.65N., R.5W., (Plate 21), primary augite phenocrysts are still preserved with little actinolite alteration. Some specimens contain up to 1% chlorite pseudomorphs after short, stubby pyroxene (up to 1.5 mm long).

Quartz phenocrysts are normally quite rare, but comprise up to 2% of some specimens. These phenocrysts are up to 1 mm across, subhedral to euhedral with few 6-sided crystals, and altered slightly to sericite.

PLATE 20--PHOTOMICROGRAPH OF PORPHYRITIC AUGITE ANDESITE WITH ACTINOLITE PSEUDOMORPHS AFTER AUGITE - Sample JL-60 FROM NE¼, Sec. 19, T.65N., R.5W.

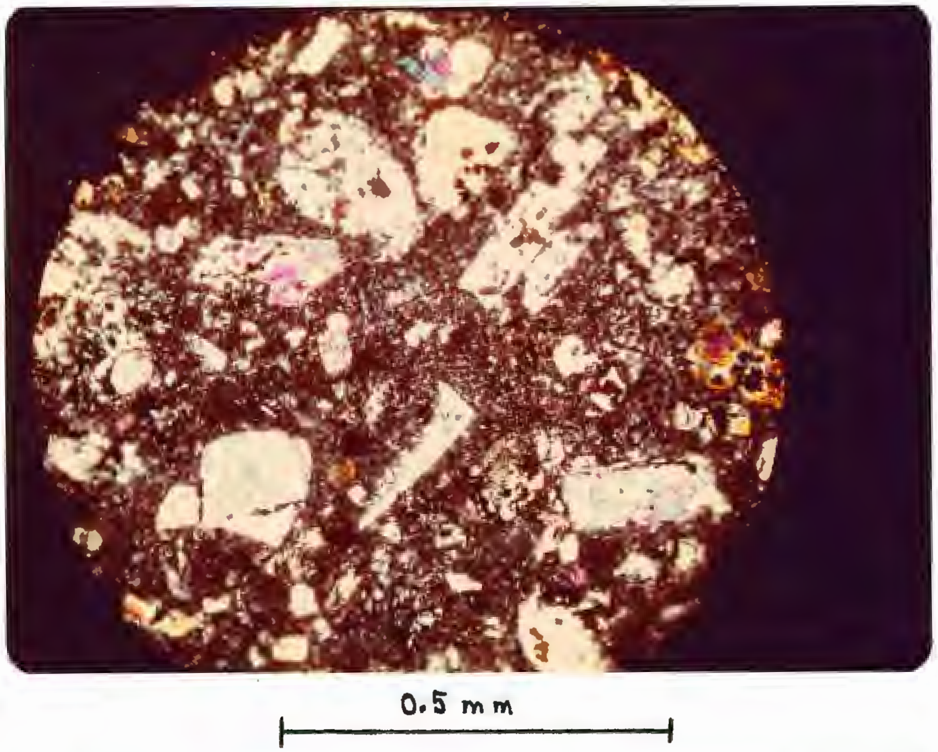


PLATE 21--PHOTOMICROGRAPH OF PORPHYRITIC AUGITE ANDESITE WITH ORIGINAL AUGITE PHENOCRYSTS PRESERVED - Sample JL-75 FROM SW¼, Sec. 17, T.65N., R.5W.

Some phenocrysts are also replaced by calcite and minor epidote. It is the increased amount of quartz (greater than 10%) both as phenocrysts and in the groundmass which causes andesite to grade into dacite in some portions of the intrusive body.

The rock contains up to 25% amygdules in a few specimens, which are irregular and smoothly rounded, up to 1 cm across (Plate 22). They are commonly filled with chlorite and calcite, and lesser amounts of quartz, epidote, and magnetite.

Irregular quartz and quartz-epidote veins, up to 5 cm wide commonly cross-cut the andesite. Minor calcite and chlorite are found locally in the veins.

The groundmass of the andesites and dacites is composed predominantly of plagioclase, chlorite, epidote, quartz, calcite, and minor amounts of orthoclase, magnetite, sericite, sphene, apatite, pyrite, and rutile.

Plagioclase, including both phenocrysts and groundmass, comprises up to 90% of the rocks. In the dacites, and some andesites, it accounts for the bulk of the groundmass material occurring as tabular and lathy crystals less than 0.2 mm long, commonly heavily replaced by epidote and calcite.

Chlorite comprises up to 45% of the rock, particularly in the andesites, as massive patches. It is commonly pseudomorphous after plagioclase and pyroxene phenocrysts, replaces and fills in space between grains

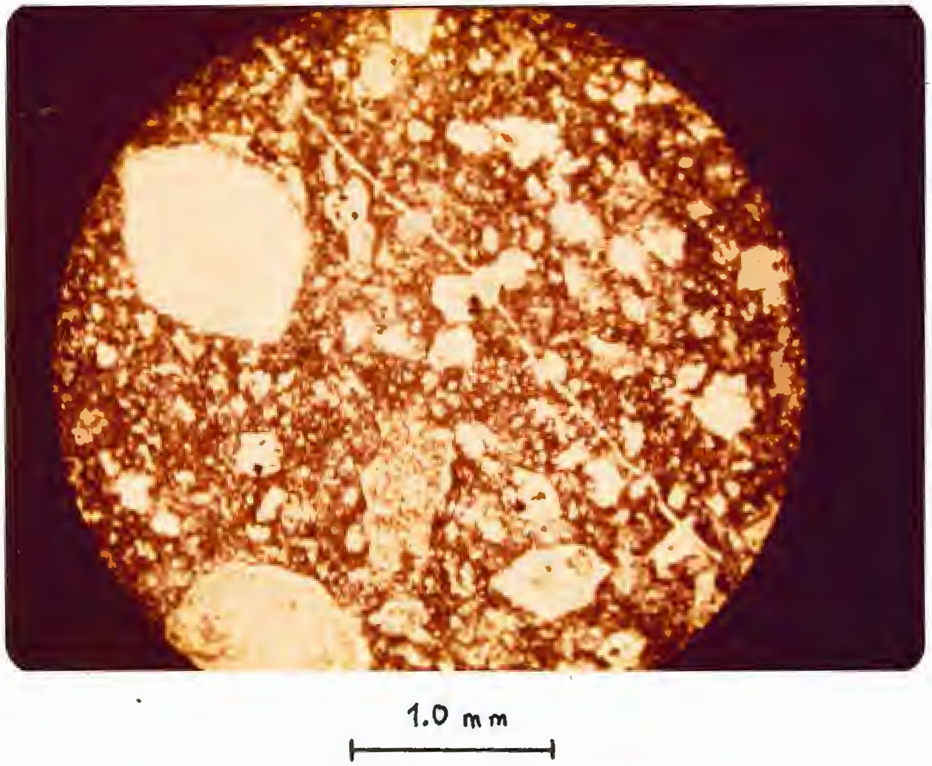


PLATE 22--PHOTOMICROGRAPH OF AN AMYGDALOIDAL PORPHYRITIC PYROXENE ANDESITE WITH CHLORITE LINED, CALCITE AND QUARTZ FILLED AMYGDULES - Sample TL-26 FROM SE$\frac{1}{4}$, Sec. 13, T.65N., R.6W.

within the groundmass, and fills voids in amygdules and holes within phenocrysts.

Epidote makes up to 10% of the rock predominantly within the groundmass. It occurs as subhedral to anhedral masses, grains, and clots, up to 1 mm long, replacing both plagioclase and mafic crystals in the groundmass and within amygdules.

Quartz constitutes up to 10% of the groundmass in some dacite portions of the intrusion as anhedral, equant grains up to 0.2 mm long interstitial between plagioclase and as secondary replacement of plagioclase and void fillings in amygdules and cavities. Minor, equant phenocrysts are observed that are up to 2 mm across.

Calcite replaces up to 30% of the rock at some localities regardless of composition, especially near faults. It typically occurs as irregular patches up to 1 mm across replacing much of the groundmass, particularly plagioclase, and lesser portions of the mafic constituents.

Orthoclase, recognized by staining techniques, occurs in trace amounts within dacites as anhedral grains, usually around plagioclase, up to 0.1 mm long.

Magnetite comprises up to 5% of the rock as anhedral masses to subhedral to euhedral octahedra up to 0.8 mm across. It is typically randomly distributed throughout the matrix, and generally partly altered to limonite and leucoxene.

Sericite, in trace amounts, occurs as scaly aggregates less than 0.1 mm long, within and around plagioclase. Sphene, apatite, and rutile occur as prismatic crystals less than 0.1 mm long, randomly distributed throughout the matrix and within plagioclase crystals. Pyrite comprises up to 1% of the groundmass as euhedral to subhedral cubic crystals, up to 0.1 mm across, randomly distributed throughout the rock.

Saganaga Tonalite Border Phase

Two thin sections were examined of the Saganaga tonalite adjacent to the Jasper Lake greenstone unit from the NW¼, Sec. 17, T.65N., R.5W., along the shore of Alpine Lake and within the SE¼, Sec. 7, T.65N., R.5W. The Saganaga batholith in these areas consists of a light green to gray, medium- to coarse-grained tonalite which is locally sheared. The texture is typically allotriomorphic to hypidiomorphic-granular and the rock is usually cross-cut by up to 2% irregular quartz-calcite veinlets.

The tonalite is composed of 45-75% plagioclase, 17-25% quartz, 5-15% chlorite, 3-10% calcite, traces to 1% potash feldspar, and minor, up to 1% magnetite, apatite, epidote, zircon, and prehnite (Plate 23). Plagioclase occurs as tabular crystals, 1-5 mm long, which are thoroughly saussuritized and sericitized, and somewhat

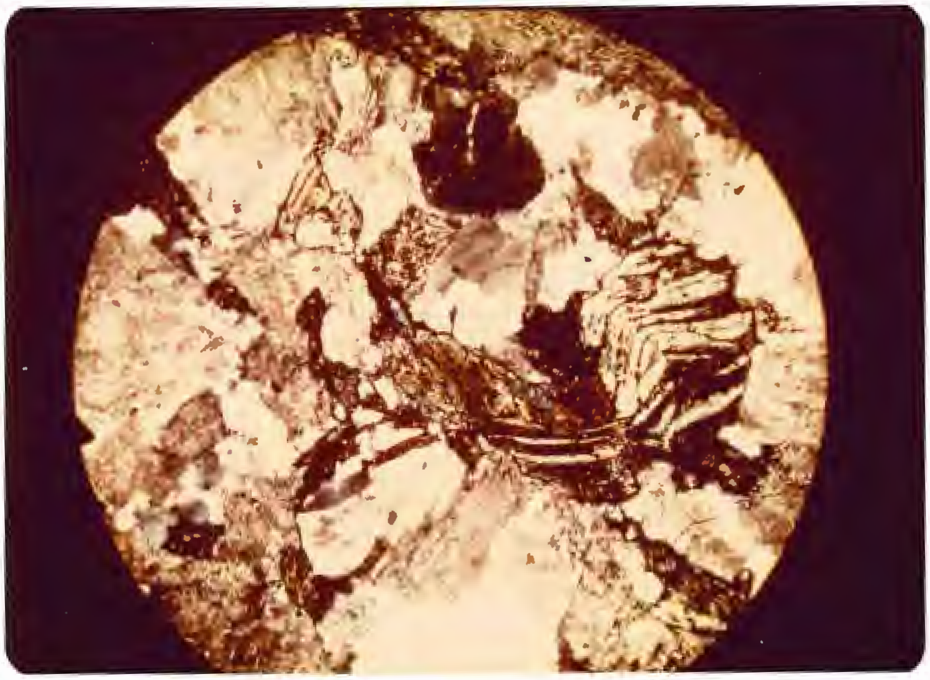


PLATE 23--PHOTOMICROGRAPH OF SLIGHTLY SHEARED BORDER PHASE OF THE SAGANAGA TONALITE. DOMINANTLY SAUSSURITIZED FELDSPAR WITH DARK, STRAINED CHLORITE PSEUDOMORPHS (RIGHT CENTER) AND CLEAR QUARTZ (BOTTOM) - Sample JL-103, FROM NW$\frac{1}{4}$, Sec. 17, T.65N., R.5W.

altered to chlorite. A few Michel-Levy determinations indicate an albitic composition (An_3). Quartz and orthoclase (minor microcline) have grown between the plagioclase as equant and tabular grains, respectively, which are 0.1 to 3.5 mm long. Chlorite and epidote form pseudomorphs after hornblende and biotite grains up to 1 mm long, preserving only relict crystal outlines. Traces of epidote, magnetite, apatite, and zircon occur as small euhedral crystals within plagioclase and quartz grains. Prehnite forms very fine, irregular veinlets, less than 0.1 mm wide within the rock. Calcite also occurs as a minor secondary replacement of chlorite and plagioclase in a patchy distribution.

A small amount of fracturing and deformation is evident in both thin sections examined. Quartz and feldspar grains show moderate fracturing together with slight undulatory extinction. Chlorite pseudomorphs of hornblende and biotite are largely bent, commonly wrapping around more competent grains. Some quartz-calcite veinlets show minor offsets in some areas and quartz appears to be somewhat recrystallized in many areas.

Intrusive Tonalite-Diorite

The tonalite-diorite intrusion was examined under a binocular microscope only, and bears a close resemblance to the border phase of the Saganaga tonalite where it comes in contact with the greenstone to the north.

The tonalite-diorite is composed of roughly 40-50% plagioclase, 10-30% quartz, and 20-25% hornblende or biotite (now mostly chlorite), with minor amounts of magnetite, potash feldspar, and sericite. Plagioclase occurs as short, stubby, tabular to equant crystals, 0.5-5.0 mm long. Slight sericitization is visible from potassium cobaltinitrite stain as small, irregular masses less than 0.5 mm across within plagioclase grains. Quartz occurs as equant grains 0.5-15.0 mm across, often quite conspicuous on broken surfaces. Interstitial areas are filled with irregular and massive chlorite aggregates with few relict hornblende and minor biotite grains (up to 3 mm long) within the chlorite. Minor pyrite and magnetite, less than 2 mm long, are visible as subhedral to euhedral blocky crystals between chlorite in the groundmass. They are often quite altered to iron oxides producing the red stain on the rock. Potash feldspar grains, less than 1 mm long, comprise traces to 5% of the rock between plagioclase and quartz grains.

Geochemistry of Two Samples within the Jasper Lake Greenstone Unit

Two chemical analyses, one, of a quench textured basaltic komatiite (KL-6), and one of a metadiabase (JL-92), from the Jasper Lake greenstone unit, were performed by K. Ramlal of the University of Manitoba, using atomic absorption methods. Sample KL-6 is located on the north side of a glacial roche moutonnée, north of Kingfisher Lake, in the NW$\frac{1}{4}$, Sec. 18, T.65N., R.5W., and sample JL-92 is located on the far southwest shore of the eastern extension of Jasper Lake, in the central part of Sec. 17, T.65N., R.5W.

These samples were chosen to establish how the rocks at Jasper Lake compare in chemical composition with basaltic rocks observed in other areas throughout the world and within the Vermilion district. Both samples displayed relatively slight effects of metamorphic recrystallization as indicated by the presence of relict pyroxene. Primary skeletal quench textures occur in KL-6, and relict ophitic and micrographic textures are present in JL-92. They were selected from petrographic evidence of their homogeneous and unsheared structure, and lack of observed metasomatic alteration.

Sample KL-6

The fact that this sample contains the typical greenschist mineralogy of a metabasalt with a quenched (pyroxene) texture suggests it may be classified as a basaltic komatiite.

In comparison with basaltic and ultramafic komatiite compositions described from several worldwide locations, including Canada, U.S.A., Australia, and South Africa, the Jasper Lake sample KL-6 most closely resembles the type Barberton composition from Swaziland (Viljoen and Viljoen, 1969) and basaltic komatiites in the Vermilion district, Minnesota (Green and Schulz, 1977), (Table 4, Figures 8 and 9). These samples contain comparable equal weight percentages of Al_2O_3, MgO, and CaO and are also quite close in their values of TiO_2 and MnO.. Ultramafic komatiite compositions do not compare with chemical compositions of basaltic komatiites or KL-6, and is correlated with the presence of olivine within ultramafic, and not in basaltic komatiites (See Table 4).

Brooks and Hart (1974) pose the following chemical criteria for the recognition of basaltic komatiites: SiO_2 = 46-53%, CaO/Al_2O_3 greater than 1, MgO greater than 9%, TiO_2 less than 0.9%, and K_2O less than 0.9%. Jasper Lake sample KL-6 satisfies all of these criteria except that CaO/Al_2O_3 is less than 1 (0.66). However, Green and Schulz (1977) suggest that CaO/Al_2O_3 should be restricted to values roughly equal to one, as some of the type Barberton komatiites (Viljoen and Viljoen, 1969), contain values less than one and do not satisfy this criterion of Brooks and Hart. Some of the most important compositional parameters of the Brooks and Hart criteria are illustrated in Figures 8 and 9.

A second set of chemical criteria for distinguishing basaltic komatiites from tholeiitic rocks was proposed by Naldrett and Arndt (1975). They suggest a plot

TABLE 4--COMPARISON OF CHEMICAL ANALYSES OF BASALTIC AND PERIDOTITIC KOMATIITES (Recalc. H_2O-CO_2-free)

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	49.34	47.93	46.95	53.75	53.29	48.85	48.60	52.83	44.39	45.88	43.87
TiO_2	0.69	0.98	0.96	0.87	0.57	1.14	0.99	0.16	0.24	0.23	0.22
Al_2O_3	11.36	8.33	8.44	10.02	5.50	7.55	14.10	9.49	5.72	4.36	5.93
Fe_2O_3	1.89	2.10	2.40	1.25	1.00	2.02	3.40	10.71	4.80	10.57	3.70
FeO	12.87	15.01	13.91	9.90	9.06	11.09	6.80	10.71	5.41		6.59
MnO	0.25	0.27	0.23	0.22	0.22	0.02	0.17	0.17	0.17	0.22	0.14
MgO	13.13	11.86	13.37	10.30	15.56	16.73	12.10	14.21	34.69	36.12	34.24
CaO	7.54	11.48	11.79	10.18	13.09	11.43	12.00	10.22	4.28	2.61	4.51
Na_2O	2.67	1.77	1.62	2.70	1.23	0.81	1.56	2.00	0.26		0.30
K_2O	0.29	0.06	0.14	0.47	0.09	0.07	0.10	0.12	0.04		0.07
P_2O_5	0.06	0.22	0.18	0.06	0.05	0.30	0.10	0.07			0.01
Cr_2O_3							0.13				0.41
NiO							0.04				
Total	100.00	100.01	99.99	99.72	99.66	100.01	99.90	99.98	100.00	99.99	99.99

(After Green and Schulz, 1977)

TABLE 4--Continued

1 - KL-6, Jasper Lake area, this paper, K. Ramlal, Analyst.

2 - E-205, Vermilion district, Green and Schulz, 1977, No. 2, Table 3.

3 - E-151a, Vermilion district, Green and Schulz, 1977, No. 1, Table 3.

4 - Average Barberton-type basaltic komatiite, Viljoen and Viljoen, 1969, Nos. 1,2,3,4,5, p. 74.

5 - Average Badplass-type basaltic komatiite, Viljoen and Viljoen, 1969.

6 - Michipocoten basaltic komatiite, V-53, Brooks and Hart, 1972.

7 - Average of 21 Olivine-poor Tertiary basalts, Baffin Is., Clarke, 1970.

8 - Average of 9 Lower Paleozoic basaltic komatiites, Rambler, Newfoundland, Gale, 1973.

9 - Plate spinifex peridotite, Mt. Ida, Yilgarn Block, Western Australia, Nesbitt, R.W., 1970.

10 - S.A. 85, Olivine peridotite, overlying lens at Dundonald, Naldrett and Mason, 1968.

11 - Spinifex peridotite flow unit, Munro Township, Ontario, Pyke, et al., 1973.

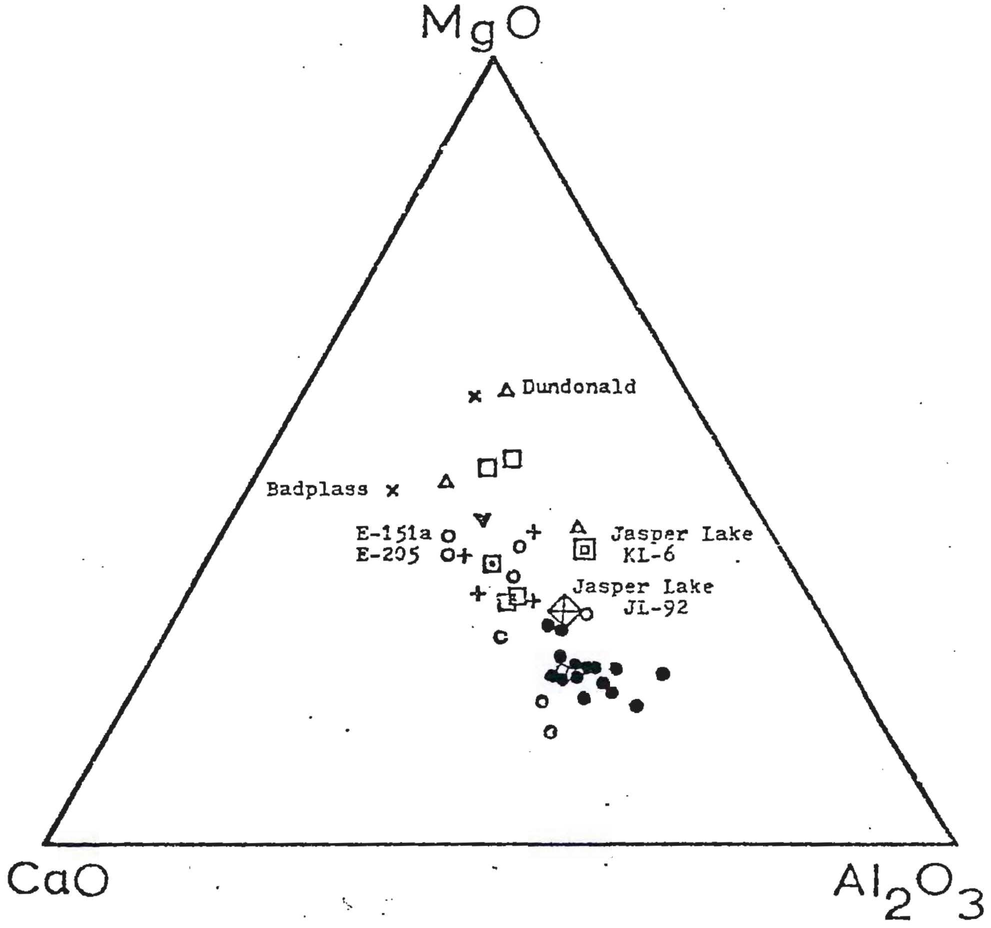


FIGURE 8--MgO-CaO-Al_2O_3 DIAGRAM (WT.%) OF BASALTIC KOMATIITES AND ASSOCIATED ROCKS COMPARED WITH THE JASPER LAKE SAMPLES (after Green and Schulz, 1977)

FIGURE 8--Continued

SYMBOLS USED

open circles - Vermilion district basaltic komatiites and Ave. Swaziland olivine tholeiites

dots - other Vermilion district basalts

open triangles - Canadian Archean komatiites and mafic basalts

solid inverted triangle - Newfoundland Paleozoic komatiite

\+ - Barberton basaltic komatiites

× - other South African komatiites

□ - Baffin Bay Tertiary basalts

▣ - Alaska

⧈ - Jasper Lake basaltic komatiites, Sample KL-6

◈ - Jasper Lake diabase (Fe-tholeiite) Sample JL-92

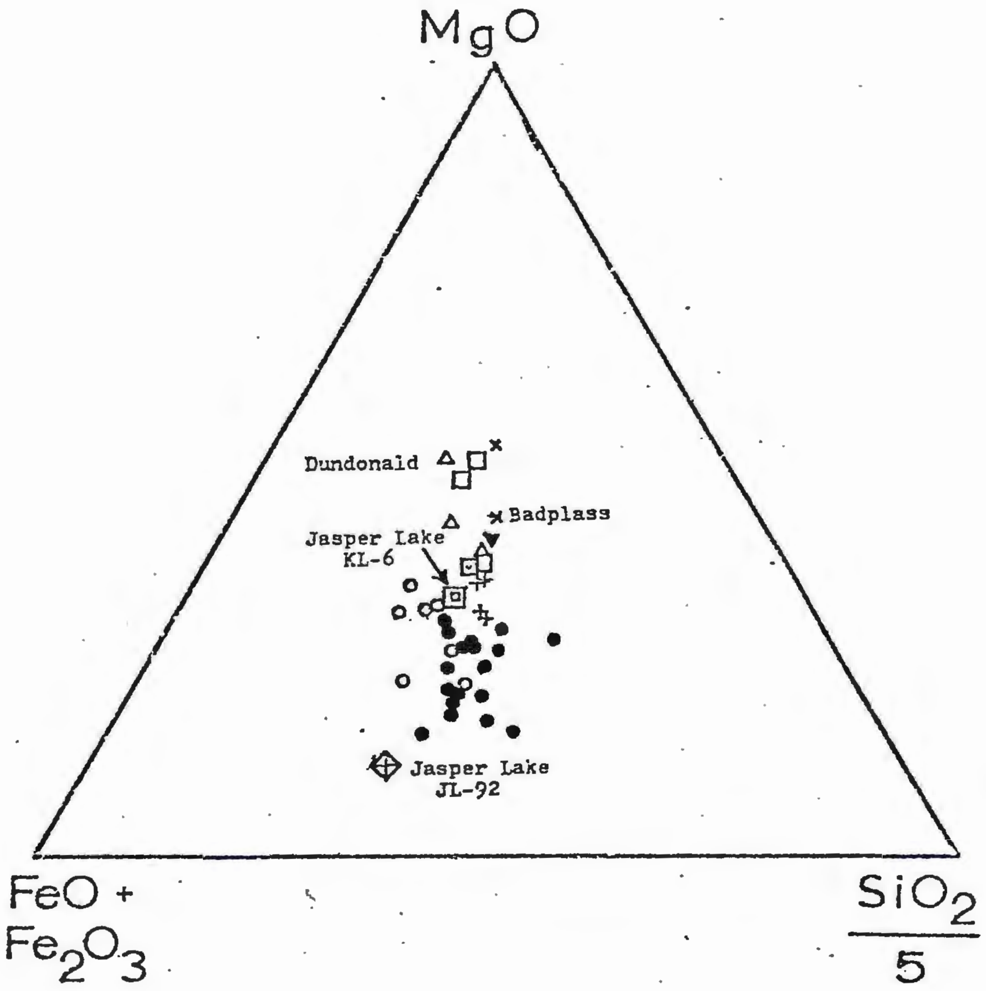


FIGURE 9--MgO-Total Iron-(SiO_2)/5 DIAGRAM OF BASALTIC KOMATIITES AND ASSOCIATED ROCKS COMPARED WITH THE JASPER LAKE SAMPLES (after Green and Schulz, 1977)

of wt. % Al_2O_3 vs. total FeO/(Total FeO + MgO) and a TiO_2 content of 1%. The Jasper Lake basaltic komatiite (KL-6) plots well within the komatiitic field as shown in Figure 10.

Sample JL-92

In comparison with Keweenawan diabases, tholeiites, basaltic komatiites, and Fe-tholeiites, the Jasper Lake diabase (JL-92) resembles tholeiites, and iron tholeiites most closely (Naldrett and Arndt, 1975) (Table 5, Figures 8, 9, and 10). They are comparable particularly in their abundances of Fe_2O_3 and MgO.

Interpretation

The basalts of the greenstone unit, together with the andesites and dacites of the pyroclastic unit in the Jasper Lake area, may be representative of the gradation in composition from basaltic komatiites (KL-6) into tholeiites (JL-92), andesites, and dacites, which has been established within the central Vermilion district by Green and Schulz (1977) (Figures 8 and 9). The basaltic komatiite (sample KL-6) near Jasper Lake is probably closely associated in origin (consanguineous) with tholeiites (sample JL-92).

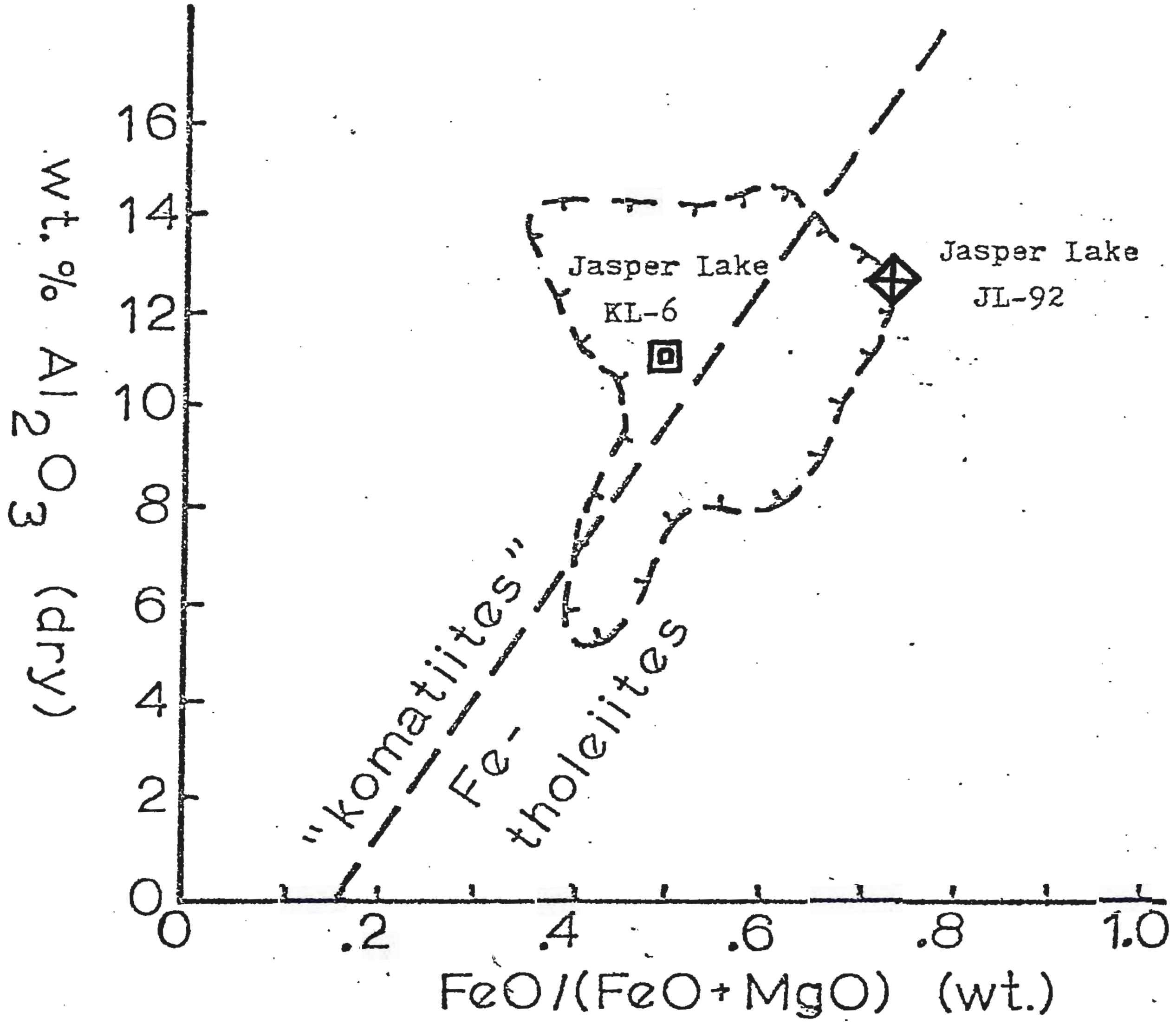


FIGURE 10--Al_2O_3 VS. TOTAL FeO/(TOTAL FeO + MgO) DIAGRAM (WT.%) SHOWING BASALTIC KOMATIITE COMPOSITIONS TOGETHER WITH THE JASPER LAKE SAMPLES (after Naldrett and Arndt, 1975, and Green and Schulz, 1977)

TABLE 5--COMPARISON OF CHEMICAL ANALYSES OF JASPER LAKE (ARCHEAN) METADIABASE, KEEWENAWAN DIABASE AND AVERAGE THOLEIITES

	1	2	3	4	5
SiO_2	46.90	47.01	51.57	50.90	48.10
TiO_2	1.44	3.20	0.80	1.33	1.49
Al_2O_3	11.98	15.57	15.91	16.05	15.88
Fe_2O_3	3.29	2.32	2.74	2.33	2.23
FeO	16.30	11.57	7.04	8.66	10.16
MnO	0.29	0.20	0.17	0.18	0.18
MgO	5.55	5.25	6.73	6.15	7.54
CaO	6.94	9.77	11.74	9.30	8.82
Na_2O	2.68	3.00	2.41	2.06	3.26
K_2O	0.24	0.31	0.44	0.76	0.49
P_2O_5	0.18	0.32	0.11	0.20	0.16
H_2O^+	3.07	1.64	0.45	1.74	1.44
H_2O^-	0.07				
CO_2	1.13				0.14
S	0.20				
Total Less O=S	100.16	100.16	100.11	99.66	99.89

TABLE 5--Continued

1 - Jasper Lake diabase within greenstone unit, this paper, Sample JL-92, K. Ramlal, analyst

2 - Olivine tholeiite, Albemarle Island, Galapagos (McBirney and Williams, 1969, p. 121, No. 63)

3 - Tholeiite, Talasea, New Britain (Lowder and Carmichael, 1970, p. 27, No. 311)

4 - Sub-diabasic basalt, Ely Greenstone (Green, 1970, p. 16, No. 9, Sample EG-17)

5 - Diabasic dike, (Olivine basaltic andesite), Keweenawan dike, (Green, 1970, p. 16, No. 12, Sample M-7129)

Summary of the Jasper Lake Units

Age and Correlation

In his construction of the stratigraphic column of the eastern Vermilion district, Gruner (1941) designated all greenstone units as Ely Greenstone, as had been done earlier by Winchell (1899) and Clements (1903). Thus, all greenstone was assumed equivalent to the type exposure at Ely and, therefore, also referred to as the lowest unit of the Archean as it is at Ely. In recent years it has been recognized that all greenstone occurrences in northern Minnesota are not necessarily the same formation as that at the type locality at Ely. Morey and others (1970) have now described and redefined the Ely Greenstone. The Jasper Lake greenstone, separated from the town of Ely by some 65 km of highly complexly folded and faulted Precambrian terrain, cannot be confidently correlated with the Ely Greenstone.

Gruner (1941) designated the Jasper Lake pyroclastic unit as a portion of the Knife Lake Group and assumed it to have been deposited after the intrusion of the Saganaga batholith. Because Saganaga detritus is absent from the pyroclastic unit, it is probably older than the Ogishke conglomerate and other units of the Knife Lake Group which contain Saganaga clasts.

At present, both the Jasper Lake greenstone and pyroclastic units can only be reliably correlated with other rocks within the Gabimichigami Lake segment of

Gruner (1941)(the Chub Lake Volcanics to the southeast). They are considered older than 2.7-2.75 billion years, the date of the Saganaga batholith (Goldich and others, 1961) which intrudes the greenstone.

The greenstone "belt", as mapped by Gruner (1941) continues to the east off the Jasper Lake map area. Morey and others (1968) mapped the far eastern extent of the "belt" some 20-21 km to the east-southeast of Jasper Lake, near Chub Lake in the Long Island Lake quadrangle. They designated this volcanic unit as the Chub Lake Volcanic complex, which is truncated by Middle Precambrian units to the east. From their map, the complex consists of at least an 800-1000 meter thick sequence of metabasalt and associated fragmental rocks to the north, and meta-andesitic agglomerate, conglomerate, tuff, flows, and minor metagrawacke and slate to the south. All units are vertical and the metabasalts commonly exhibit pillow structures which indicate top directions to the south.

The continuity in outcrop between the units of the Jasper Lake area and those in the Long Island Lake quadrangle, and the strong similarities in attitude and lithology of the two stratigraphic sequences suggests that the Jasper Lake greenstone is probably correlative with the lower portion (northern) of the Chub Lake Volcanic complex. Likewise, the Jasper Lake pyroclastic unit probably continues eastward into the Long Island Lake quadrangle and is probably correlative with the upper (southern), dominantly andesitic, portion of the Chub Lake Volcanic complex. Further work within the intervening area between Jasper and Chub Lakes could substantiate this correlation.

The Jasper Lake andesite was referred to as Ely Greenstone flows by Clements (1903), and later andesitic flows deposited sometime after the greenstone by Gruner (1941).

In this study it has been established that the andesite unit is an intrusive body, rather than a flow, displaying 50 meter wide chilled margins. The andesite to dacite composition of the unit also suggests that it is not part of the greenstone unit, and particularly not the Ely Greenstone. From the subconcordant nature of the Jasper Lake andesite intrusion, the chilled margins displayed, and the similarity in composition of the intrusive and the fragments within the adjacent pyroclastic unit, it is reasonable to suggest the unit was intruded approximately contemporaneously with the pyroclastic unit. The units were therefore derived from the same andesitic volcanic center.

The Jasper Lake andesite is younger than the underlying greenstone unit, and is certainly older than the Ogishke conglomerate of the Knife Lake Group to the west. The age relationships between the Jasper Lake andesite and the Saganaga tonalite intrusion remain uncertain.

Interpretation

The presence of massive, quenched and pillowed basalts, usually of tholeiitic composition in association with occasional komatiitic basalts (Brooks and Hart, 1974), as observed in many areas including Jasper Lake, has been interpreted to represent many types of tectonic environments: sea floor (Gale, 1973), island arcs (Brooks and Hart, 1972), and primitive crust (Viljoen and Viljoen, 1969).

The most striking characteristic of such rocks from the greenstone unit at Jasper Lake is their interlayering with intermediate to felsic members, namely a basalt-andesite-dacite suite. The evidence is compelling that these Archean volcanic associations are analogous to modern island arc environments and tectonic settings (Wilson et al., 1965, Baragar and Goodwin, 1969, Folinsbee et al., 1968, Anhaeusser et al., 1969, and Hart et al., 1970).

The occurrence of both pillow structures and quench textures in the mafic lavas within the Jasper Lake greenstone characterize submarine volcanic flow eruption and deposition. The poorly developed vesicularity of the basalts and lack of observed flow-surface features, also suggest subaqueous deposition. Therefore, massive, fine-grained basaltic flows within this mafic sequence also are interpreted as mostly or wholly submarine.

Metadiabase within the Jasper Lake greenstone is thought to have been intruded contemporaneously with the basalts forming large, irregular, discordant bodies mainly within the eastern portion of the unit. They are believed to be consanguineous with the basalts because of their mafic character, and probably were intruded at shallow depths within the dominantly basaltic volcanic pile.

Small, irregular and discordant intrusive plugs and/or stocks of porphyritic andesite-dacite probably represent contemporaneous intrusions either with the basalt flows, the Jasper Lake andesite, or even some later time. The andesite-dacite intrusions probably are representative of late-stage differentiates from an original mafic magma. These bodies never reached the surface, but attained shallow levels within the volcanic pile producing their fine-grained groundmass.

The occurrence of a few small lenses of finely laminated tuff within the greenstone unit suggests probable brief interruptions of lava flow extrusion during volcanic activity. Possible erosion or non-deposition of basaltic flows allowed for a brief period of deposition of tuffaceous material. This material was probably deposited as volcanic ash emanations from a nearby volcanic center. Pillows also rest directly on tuffaceous layers indicating subsequent submarine eruption.

After an initial episode of basaltic eruption and build-up of a large, thick, platform of mafic lavas (forming the greenstone unit), andesitic, and later dacitic volcanism commenced. Pyroclastic debris was deposited along the flanks of the growing volcano(es) and sloughed into adjacent basins or depressions. Mudflows swept down valleys and depressions, incorporating all types of debris over which they passed.

The Jasper Lake pyroclastic unit probably originated in one of two principal ways - either the debris was eroded from an adjacent source area(s) underlain by unconsolidated andesite and dacite volcanic rocks and deposited largely by volcanic mudflows or lahars (second-cycle lahars), or it is a primary pyroclastic deposit. Differentiation between the two possibilities is difficult on the basis of the information known.

The major portion of the pyroclastic unit, consisting of massive, unsorted, volcanic breccia, appears to have been deposited by large, turbulent mudflows of volcanic origin. Similar breccia lithologies have been observed and described in various parts of the world (Jagger, 1908, Anderson, 1933, Morimoto and Ossaka, 1955, Mullineaux and Crandell, 1962, Fiske, 1963, Fiske and Matsuda, 1964, Schmincke, 1967, Lydon, 1968).

Terminology for such mudflow-type deposits is confused. The terms lahar, pyroclastic flow, and volcanic mudflow are commonly used interchangeably. Lahar is an Indonesian word which refers to all types of hot or cold mudflows, of volcanic origin or otherwise, and are essentially epiclastic (Fisher, 1961). Therefore, volcanic mudflows, either hot or cold, can be generally termed lahars.

Mudflows, as defined by MacDonald (1972), are essentially slurries of fine material mixed with water to form a mud that flows down a mountainside under the driving force of gravity.

Pyroclastic flows are defined by Fiske (1963) as flows of freshly erupted pyroclastic debris which usually contains pumice, vesicular fragments or glass shards. They have been confused with lahars, as characteristics of both depositional mechanisms are extremely difficult to distinguish.

Application of Fisher's (1960) criteria for distinguishing lahar deposits from pyroclastic flow deposits to these rocks indicates the Jasper Lake volcanic breccias were probably deposited as lahars. Lack of sorting, mixing from lower contacts (e.g. fragments of underlying greenstone, tuff, or graywacke-argillite), and large rounded fragments indicate deposition by either lahars or pyroclastic flows, but tends to preclude deposition from the air. The Jasper Lake breccias, like those near Mt. Rainier, Washington (Fisher, 1960), are heterogeneous in composition consisting of fragments from clearly different sources, lack vesicular or glassy fragments, and contain rounded and broken mineral fragments (especially plagioclase) in various stages of alteration, which all indicate deposition by lahars. In addition, there is no evidence of fumarolic action, a characteristic of pyroclastic flow deposits (Williams, 1949, 1956).

Many volcanic breccias of the Jasper Lake area do not display a variety of distinguishing characteristics, and could be attributed to either lahar or pyroclastic flow deposition. Therefore, deposition of the volcanic breccias, in general, was probably a result of a combination of the two mechanisms, with the laharic mechanism recognizably dominant.

Most of the Jasper Lake volcanogenic rocks were probably deposited in water. Thin interbeds of massive and finely laminated tuffs, lapilli-tuffs, and graywacke-argillites within the volcanic breccias, similar to those within the Tertiary Ohanapecosh Formation in Washington (Fiske and others, 1963) suggest subaqueous deposition. The poor sorting, occasional vertical grading, continuous and even bedding, and rare graded and convoluted beds, suggest deposition in quiet water, possibly partially by turbidity currents, as suggested by Fiske (1963). This could have taken place by rapid settling from ash falls in fairly quiet water or slower settling from masses of suspended ash or epiclastic detritus that washed into the basin.

Sedimentary structures such as irregular bedding, wispy cross-laminations, rip-up clasts within tuffs, slump structures, and fine laminae observed within tuffs and graywacke-argillites suggest deposition by weak, intermittent currents, similar to those found in lakes or embayments of the sea (Fiske and others, 1963).

The occurrence of relatively minor lenses of volcanic conglomerate, and minor graywacke-argillite within the pyroclastic unit indicates at least a short period of reworking of unconsolidated debris, other than by lahars. Volcanic conglomerates, occurring in a few, thick, lensoid bodies, may indicate shallow water, possibly fluvial reworking of pyroclastic debris in some areas, or merely a sudden increase in current action in a deep water environment.

Because of their highly sheared nature, these conglomerates may actually represent fault slivers from the younger conglomerates to the west of the Jasper Lake area. Tonalitic clasts within the volcanic conglomerate may have been derived from unknown older granitic rocks, as suggested for similar cobbles in conglomerate east of Ely, Minnesota by Green (1972), but they do not resemble Saganaga tonalite.

The eruptions supplying the debris of the pyroclastic unit may have occurred either above or below water. Most lahars probably occurred from eruptions of solid material on land (Anderson, 1933) before entering a submerged oceanic basin, since no evidence of quenched debris, commonly resulting from subaqueous eruptions is observed.

No volcanic vents which could have supplied the andesitic and dacitic debris of the pyroclastic unit have been documented. The increase both in size (up to 1 meter) and percentage of Jasper Lake andesite fragments near the andesite intrusive unit, indicate that the volcanic vent was probably quite close or within a few kilometers. Since the strata are presently approximately vertical in attitude, this volcanic neck may lie beneath the surface, or may have long since been eroded away. Another possible vent area could have been to the north, where the Saganaga tonalite batholith presently lies. Subsequent folding and erosion after intrusion of the batholith may have destroyed all evidence of a volcanic neck or previous volcanic vent area. Other, more distant volcanic vents which served as source areas for the accidental andesite, dacite, and scoriaceous basalt fragments which were observed particularly within the southern portion of the pyroclastic unit, cannot, as yet, be correlated to known rock types.

The Jasper Lake andesite represents a large, flattened, horseshoe-shaped intrusive body which was emplaced within both the pyroclastic unit and the greenstone unit. The andesite possesses chilled margins within areas where its contact with adjacent units is observable supporting a truly intrusive origin. The roughly parallel relationship between the outline of the andesite unit and the vague bedding recognized within the pyroclastic unit indicates the intrusion is subconcordant.

The extreme similarity between the andesite intrusive rock type and the lithologies of the fragments of the pyroclastic unit suggest emplacement of the intrusion was contemporaneous with andesitic pyroclastic accumulation. The andesite intrusion represents a probable subconcordant apophysis or sill from the main andesitic volcanic vent which was the source for the major portion of the pyroclastic unit. Intrusion probably occurred when the pyroclastic debris was relatively cool, accounting for the formation of wide chilled margins on the intrusive body.

The variation in mineralogic composition of the Jasper Lake andesite unit from dominantly andesite to dacite, and from largely augite and plagioclase phenocrysts to very minor amphibole phenocrysts, has been observed in other areas throughout the world, principally within island arc tectonic environments. The lavas of Mt. Victory and extinct Mt. Trafalgar in southeastern Papua, near New Guinea, range from olivine basalts to dacites, the most voluminous type being andesite (Taylor, 1958), which is similar to the sequence at Jasper Lake. Jakes and Smith (1970) concluded that these variations in phenocryst types within both andesites and dacites could be accounted for by fractional crystallization of an original mafic parent magma in concordance with Bowen's reaction series (Bowen, 1928). This is in agreement with Carmichael, Turner, and Verhoogen (1974), who also note that these mineralogic variations in phenocryst type within andesites and dacites of island arc environments is common.

The tonalite-diorite intrusive, similar in mineralogy and its coarse-grained character to the Saganaga tonalite border phase, is thought to represent a cupola from the main Saganaga batholith that intruded the greenstone. Its true source and relationship with surrounding rock units can only be assumed given present exposures.

CONTACT METAMORPHISM OF THE JASPER LAKE UNITS

Description of Mineral Assemblages

Two distinct zones have been mapped within the metamorphic aureole of the Saganaga tonalite batholith on the basis of mineral assemblages observed in thin section (Fig. 11). Zone A is observed thoughout all of the Jasper Lake units up to within 30-60 meters of the Saganaga tonalite contact and is characterized by the assemblage epidote-actinolite-chlorite-albite. Less commonly observed additional phases include calcite, quartz, ankerite, sericite, and rare pumpellyite. Zone B occurs only within the greenstone unit, within 30-60 meters of the Saganaga tonalite contact, and is characterized by a hornblende-calcic plagioclase assemblage. Chlorite and epidote are virtually absent in this zone.

Within Zone A, the mineral assemblage is dominantly metamorphic, although minor relict, primary igneous minerals are observed and original igneous textures are still preserved. The main minerals developed in this zone are 13-60 percent epidote and actinolite, and very minor rare pumpellyite. Epidote occurs as aggregates of pale yellow granules, prisms, or needles within chlorite, within interstices, or as granules replacing plagioclase. Needles of pale green actinolite are

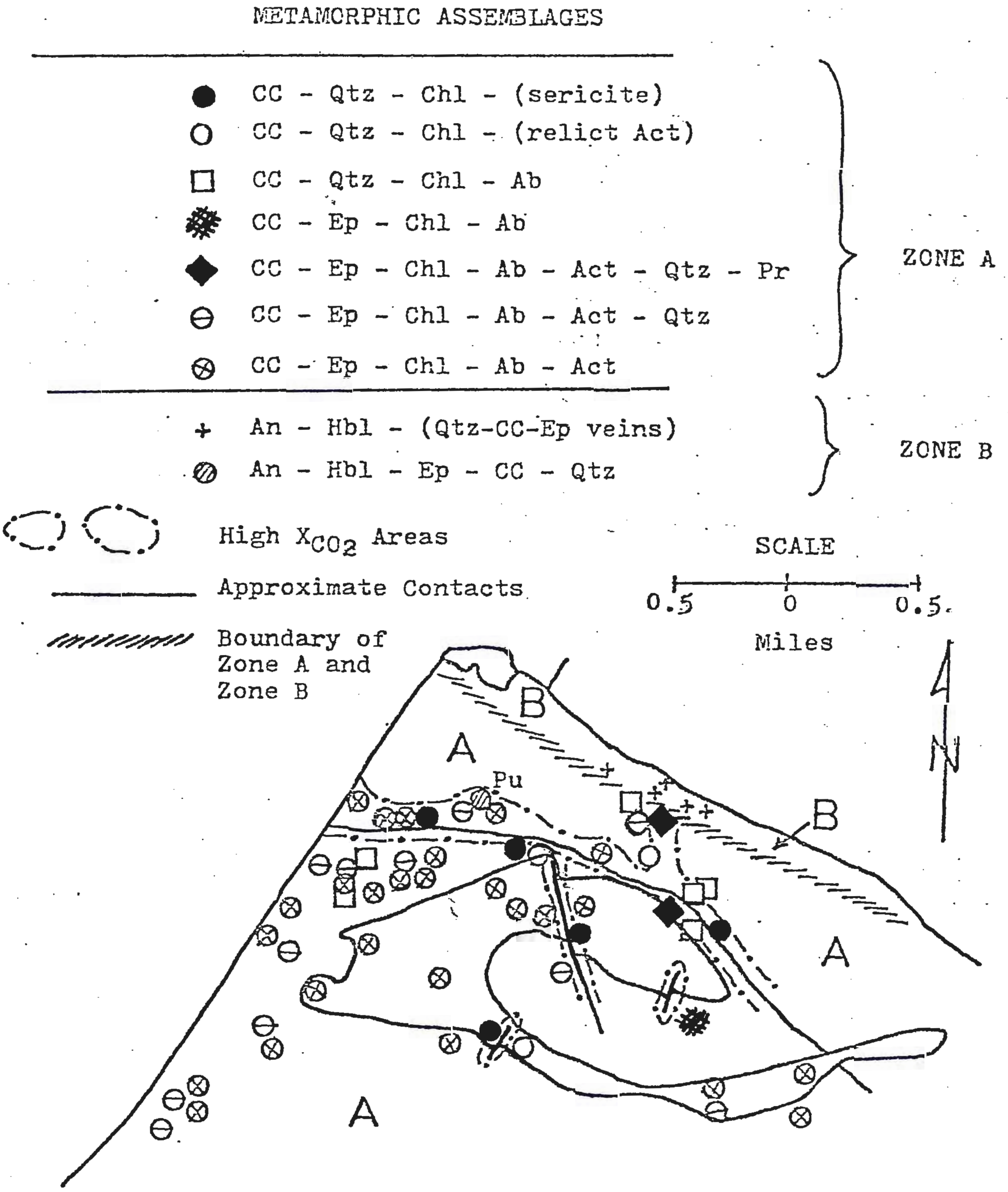


FIGURE 11--AREAL DISTRIBUTION OF METAMORPHIC ZONES AND ASSEMBLAGES WITHIN THE JASPER LAKE UNITS, COOK COUNTY, MINNESOTA

FIGURE 11--*Continued*

MINERAL SYMBOLS USED

CC = Calcite
Chl = Chlorite
Ab = Albite
An = Anorthite
Hbl = Hornblende
Ep = Epidote
Qtz = Quartz
Act = Actinolite
Pr = Prehnite
Pu = Pumpellyite

pseudomorphs after primary pyroxene (augite). Relict augite cores within actinolite pseudomorphs are occasionally observed. Greenish chlorite is apparently in Zone A possessing anomalous purplish interference colors in contrast to the dark green, nearly isotropic character of lower grade chlorite. Pumpellyite is observed as small, radiating clusters of needles in one locality within the greenstone unit, probably as remnants from older, lower grade metamorphic conditions. Quartz, calcite, sphene, magnetite, and sericite occur as accessory phases throughout the zone.

In Zone B, the mineral assemblage is essentially metamorphic although the fine grain size of the basalts is still preserved. At some localities, within 5-10 meters of the intrusive contact, the basalt has become more granular. Actinolite and chlorite have been completely replaced by hornblende which is euhedral to subhedral, dark green to slightly brownish, prismatic, and up to 5 mm long. Plagioclase within this zone is anhedral to subhedral, granoblastic, and occasionally appears to have grown around amphibole. Epidote occurs in minor amounts with quartz in late vein fillings. Magnetite together with ilmenite, increase in abundance, and comprise up to 3% of the rock.

Prehnite is observed within the Jasper Lake greenstone unit almost exclusively within Zone B. It occurs as small, anhedral grains and fine, acicular to massive aggregates predominantly within quartz-epidote or quartz-calcite veins associated with the Saganaga tonalite batholith. In a few specimens, prehnite occurs within the basalt flows near the tonalite intrusive contact or in close association with prehnite in quartz-epidote-calcite veins. Within the basaltic units, prehnite occurs as discrete grains which tend to "overprint" basalt mineralogy.

Adjacent to observed faults which cut the Jasper Lake area there is a significant change in the metamorphic mineral assemblages. Within approximately 10-20 meters of the faults, the mineral assemblage predominantly consists of calcite-chlorite-quartz-magnetite, with lesser amounts of ankerite and sphene. Approximately 20 meters from the fault, relict actinolite, albite, and epidote can be recognized, and greater than 20 meters away, the usual greenschist assemblage with subordinate calcite is observed. Within 10-20 meters of the fault, original igneous textures are completely replaced by these metamorphic mineralogic changes.

Definition of Metamorphic Facies

The metamorphic assemblage of Zone A is characteristic of the greenschist facies as defined by Turner (1968), particularly as the albite-epidote hornfels facies (Turner, 1968), which is mineralogically inseparable from the greenschist facies in mafic rocks, and is now considered a lower pressure portion of the greenschist facies by Miyashiro (1973).

The metamorphic assemblage of Zone B is typical of both the amphibolite and hornblende-hornfels facies as defined by Turner (1968). Miyashiro (1973) suggests the amphibolite facies could apply to both contact and regional metamorphic terrains.

The metamorphic assemblage of prehnite-quartz-epidote-calcite within veins near the Saganaga intrusive is indicative of the prehnite-pumpellyite facies as defined by Turner (1968).

Interpretation of Conditions of Metamorphism

The Jasper Lake units have undergone two stages of contact metamorphism, an initial contact metamorphism recognized in two mappable metamorphic zones, and a later distinct retrograde prehnite-pumpellyite facies metasomatism in and around veins and veinlets of the Saganaga tonalite intrusive within the greenstone.

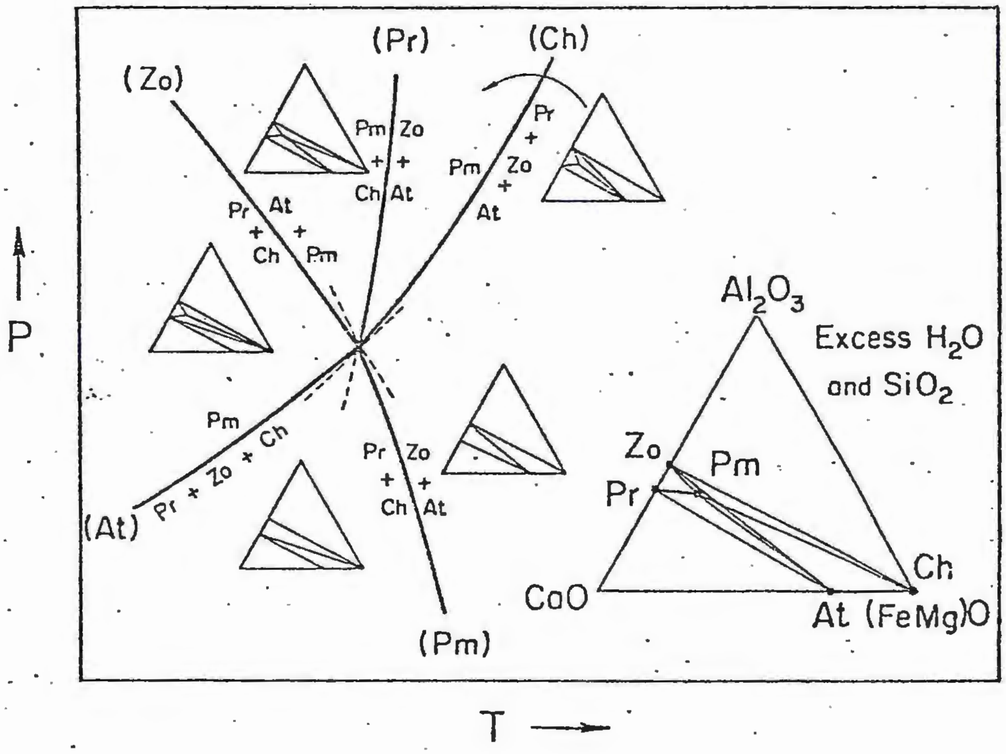
From experimentally determined P-T relations within the facies recognized at Jasper Lake, various physical parameters can be suggested for metamorphism of the Jasper Lake units.

The Karmutsen basalts of Kuniyoshi and Liou (1976) exhibit similar mineralogic changes observed in Zone A of the Jasper Lake area, indicating probably similar metamorphic processes affected the rocks from both areas.

Kuniyoshi and Liou (1976) concluded that thermal metamorphism probably occurred at relatively high X_{CO2} and X_{O_2}, and suggests a set of four reactions as possible explanation for the chemical changes such as have been observed in the rocks at Jasper Lake. These reactions explain the increased production of actinolite (converted from pyroxene), calcite, and quartz as well as the increased abundance of calcite and epidote toward the contact.

The occurrence of pumpellyite within the Jasper Lake greenstone unit, in Zone A, has also been observed in isolated areas within the Karmutsen basalts and is interpreted as a relict occurrence from earlier lower grade, prehnite-pumpellyite facies metamorphism which affected both areas. Kuniyoshi and Liou (1976) suggest that differing host rock composition or affect of the fluid phase on the host rock in this locality, preserved the pumpellyite. At Jasper Lake, the absence of a pumpellyite-actinolite assemblage, which is transitional between prehnite-pumpellyite and greenschist facies, indicates metamorphism occurred under relatively low pressure conditions (Seki, 1969)(Fig. 12).

Physical conditions can be suggested for the prehnite-pumpellyite to greenschist facies metamorphic transition within Zone A of the Jasper Lake units. Prehnite-pumpellyite burial metamorphism of the Karmutsen volcanics is thought to have occurred from



Zoisite (Zo) = $Ca_2Al_3Si_3O_{12}(OH)$
Prehnite (Pr) = $Ca_2Al_2Si_2O_{10}(OH)_2$
Pumpellyite (Pu) = $Ca_4(Mg, Fe)Al_5Si_6O_{21}(OH)_7$
Actinolite (At) = $Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$
Chlorite (Ch) = $(Fe, Mg)_3Si_2O_5(OH)_4$

FIGURE 12--SCHEMATIC PHASE RELATIONS OF ZOISITE-PREHNITE-PUMPELLYITE-ACTINOLITE-CHLORITE IN THE PRESENCE OF EXCESS QUARTZ AND FLUID IN THE SYSTEM $CaO-Al_2O_3-(Fe,Mg)O-SiO_2-H_2O$ (after Kuniyoshi and Liou, 1976)

250-350°C and pressures less than 3 kb = P_{fluid} (Kuniyoshi, 1972). Nitsch (1970) demonstrated that the prehnite-pumpellyite-chlorite-quartz association is stable up to 345°C, and that the actinolite-chlorite-epidote-quartz assemblage of the greenschist facies is stable above 350°C (if $P_{fluid} = P_{total} = 2$ kb). Therefore, at Jasper Lake, 350°C could be considered the minimum temperature for greenschist metamorphism in Zone A, and similarly, the maximum temperature for prehnite-pumpellyite facies metasomatism in Zone B.

Physical conditions can also be suggested for greenschist to amphibolite facies metamorphism in the Jasper Lake greenstone unit. Liou et al. (1974) has indicated an upper temperature boundary of 475°C for the type greenschist facies assemblage observed in Zone A. He also delineated a lower temperature limit of 550°C ($P_{fluid} = P_{total} = 2$ kb) for the amphibolite facies observed in Zone B. Therefore, metamorphism within the Jasper Lake greenstone unit occurred at temperatures of at least 550°C and $P_{fluid} = P_{total} = 2$ kb.

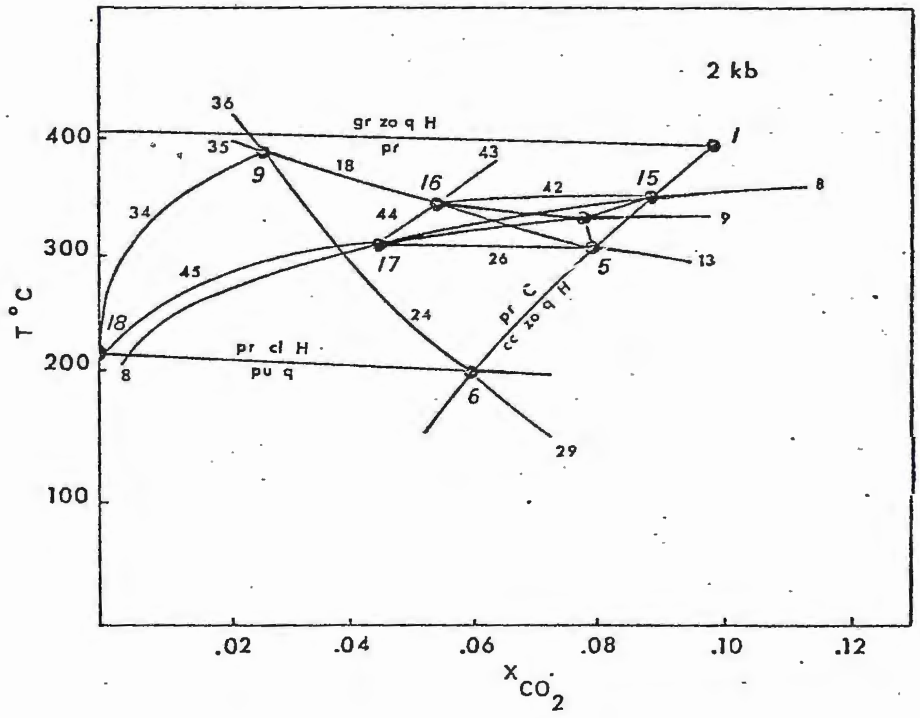
The mineralogic transition from Zone A to Zone B has been studied by Kuniyoshi and Liou (1976) who suggest a number of reactions to explain this transition in basaltic rocks. They conclude that substitution of Al and Na for Si ions in amphibole and chlorite causes an increase in Al_2O_3 and a decrease in SiO_2 component in these rocks, producing the observed mineralogic change. Also, Ernst (1968) explains that Al occupies an increased number of octahedral and tetrahedral sites in the silicate structure, and as temperature rises, Fe and Mg ions are more and more rejected by amphiboles, and are fixed in ilmenite and magnetite in amphibolites (e.g. in Zone B).

The occurrences of prehnite, mainly within Zone B of the Jasper Lake unit, indicates a late hydrothermal event of retrograde prehnite-pumpellyite facies metasomatism for which physical conditions can be suggested. Glassley (1974) constructed a phase diagram for the system $CaO-MgO-Al_2O_3-SiO_2-CO_2-H_2O$ for metabasites similar in composition to those found in the Jasper Lake greenstone (Fig. 13). The mineral assemblage represented in the veins intruding the Jasper Lake greenstone is represented by the following reaction:

Prehnite + CO_2 = Calcite + Zoisite + Quartz + H_2O

Glassley's results indicate that at 2 kb this assemblage is stable when X_{CO_2} ranges roughly from 0.06 to 0.1 and approximately 215-410°C, which, within a limited range of oxygen fugacity, represents conditions of prehnite-pumpellyite facies retrograde metasomatism of the greenstone unit at Jasper Lake.

The observed carbonate mineral assemblages in and around fault zones within the Jasper Lake units can, therefore, be explained as the result of the influence of H_2O and CO_2 in the fluid phase during greenschist



MINERAL SYMBOLS

cl = Chlorite
gr = Grossularite
zo = Zoisite
q = Quartz
H = Water

cc = Calcite
C = CO_2
pr = Prehnite
pu = Pumpellyite

FIGURE 13--PHASE DIAGRAM OF THE SYSTEM $CaO-MgO-Al_2O_3-SiO_2-CO_2-H_2O$ AT 2 KB (after Glassley, 1974)

and amphibolite facies metamorphism of these rocks. Harte and Graham (1975) studied such effects in metabasites. They suggest that reactions involving both H_2O and CO_2 will often involve formation of carbonates at the expense of silicates, especially Ca-silicates, producing the mineral assemblages observed above. The following reactions are suggested to illustrate this effect:

Calciferous amphibole + CO_2 + H_2O =
Calcite + Chlorite + Quartz

Actinolite + Calcite + CO_2 =
Ankerite + Quartz + H_2O

Using available data on greenschist facies metabasites of Billings and White (1950), Harte and Graham (1975) constructed a schematic T-X_{CO_2} diagram (Fig. 14) to illustrate the effect of increased X_{CO_2}, which can also be applied to the rocks at Jasper Lake. Five principal assemblages, denoted by roman numerals in Figures 14 and 15, can be recognized. Zone I consists of the typical greenschist facies assemblage observed throughout most of the Jasper Lake area. Zone II represents the addition of calcite to the greenschist assemblage, such as is observed approximately 20-100 meters from the faults, and in scattered areas throughout the area. Zone III corresponds to the albite-chlorite-calcite-quartz assemblage found dominantly within 10-20 meters of the faults. Calciferous amphibole

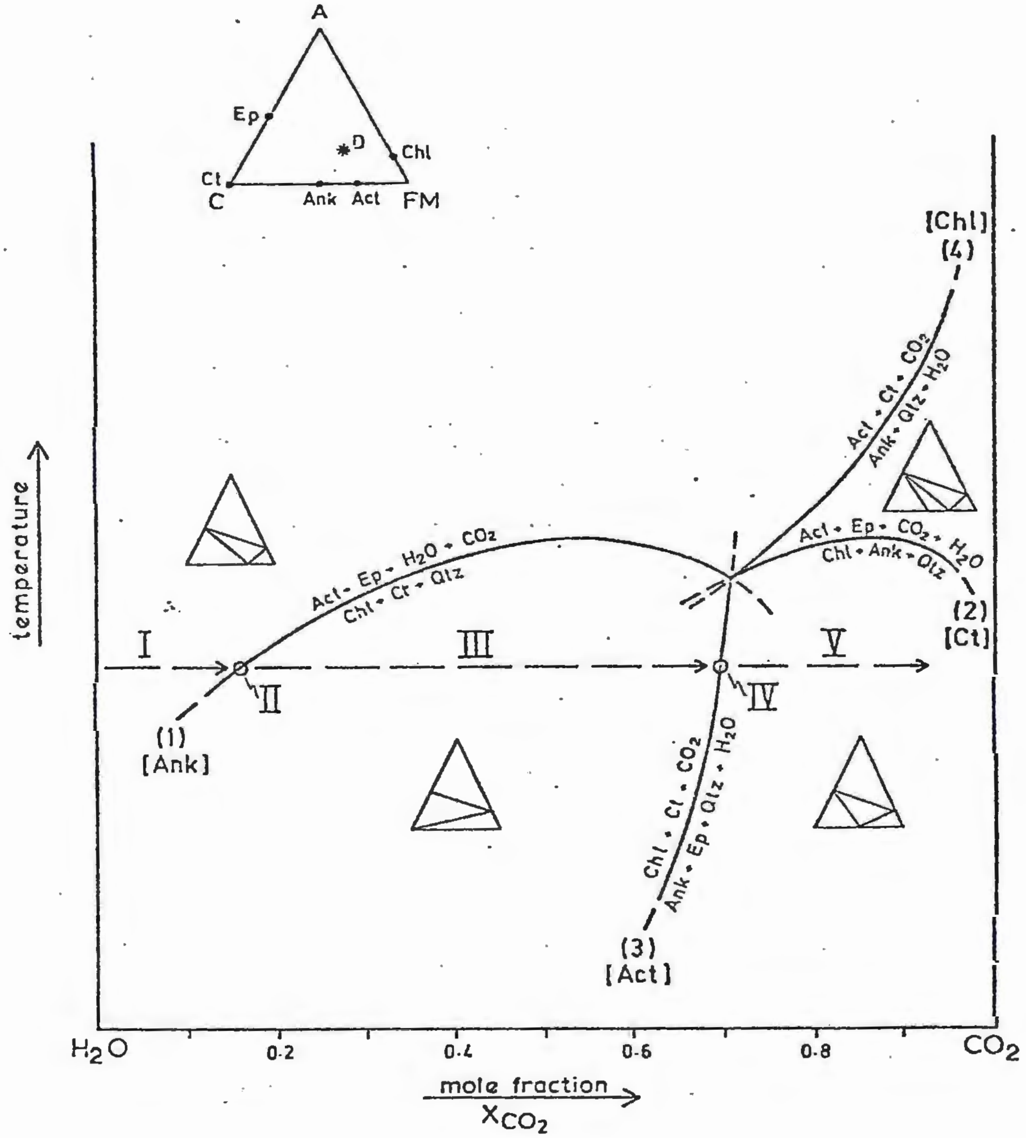


FIGURE 14--SCHEMATIC ANALYSIS OF RELATIONSHIPS IN T-X_{CO_2} ISOBARIC SECTION OF QUARTZ-, EPIDOTE-, AND FLUID BEARING GREENSCHIST FACIES METABASITE ASSEMBLAGES IN THE SYSTEM CaO-Al_2O_3-$(Fe,Mg)O$-SiO_2-H_2O-CO_2 (after Harte and Graham, 1975)

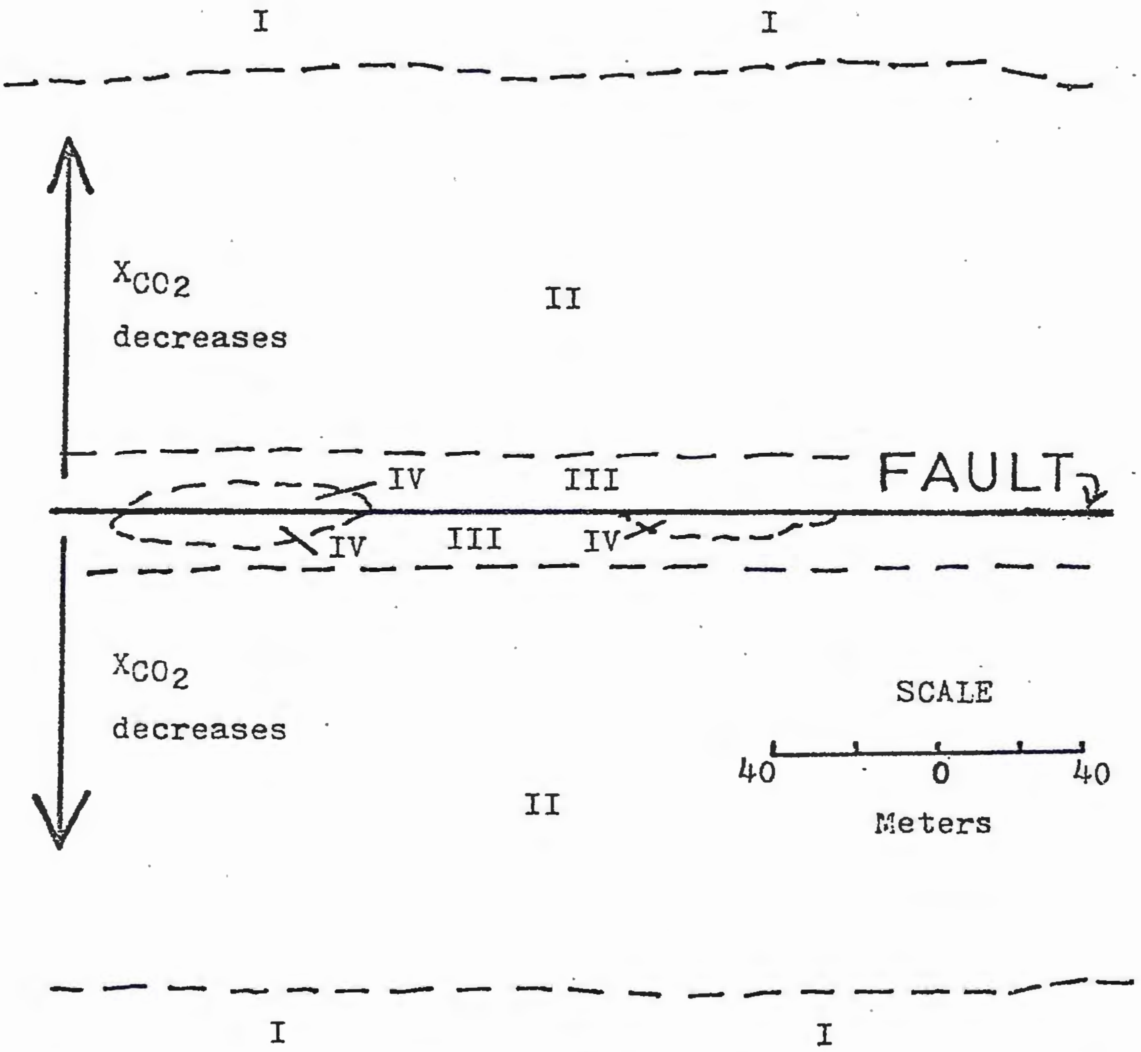
FIGURE 14--Continued

ASSEMBLAGE TYPES

I Low and unbuffered X_{CO_2} assemblages w/o carbonate
II Low-intermediate and buffered X_{CO_2} assemblages
III Intermediate and unbuffered X_{CO_2} assemblages
IV High-intermediate and buffered X_{CO_2} assemblages
V High and unbuffered X_{CO_2} assemblages

MINERAL SYMBOLS

Act = Actinolite
Ep = Epidote
Chl = Chlorite
Ct = Calcite
Ank = Ankerite
Qtz = Quartz



MINERAL ASSEMBLAGES

I albite - chlorite - epidote - actinolite

II albite - chlorite - epidote - actinolite - calcite

III albite - chlorite - calcite - quartz

IV albite - chlorite - calcite - quartz - ankerite

V albite - chlorite - ankerite

FIGURE 15--SCHEMATIC DIAGRAM OF TYPICAL ZONING OF METAMORPHIC MINERAL ASSEMBLAGES ADJACENT TO FAULTS WITHIN THE JASPER LAKE AREA

(actinolite, usually) is absent and calcite is the principal CaO-bearing phase. In Zone IV, FeO- and MgO-bearing carbonate (principally ankerite) is an additional phase of the assemblage of the previous zone. It is characterized by minor, small areas immediately adjacent to the faults. Zone V assemblages are not observed in the Jasper Lake area.

In general, evidence of carbonate-bearing mineral assemblages in the Jasper Lake area associated with shear zones indicates some initial fault movement and the presence of CO_2-rich fluids along these faults to produce these assemblages. The observed mineral assemblage zonation next to these faults suggest X_{CO_2} reached approximately 0.5 (Harte and Graham, 1975). This X_{CO_2} value is located schematically, since the values of P and T are not known in Figure 14.

STRUCTURE OF THE JASPER LAKE AREA

General Statement

In the Jasper Lake area, as well as in the rest of the Vermilion district, structural relationships must be considered together with stratigraphic relations to gain a reasonable understanding of the area. The structures of most importance are the following: (1) primary depositional structures such as described above, (2) intrusive relationships of hypabyssal and plutonic rocks, also discussed above, (3) faulting, (4) folding, and (5) jointing.

Faults

Gruner (1941) first recognized the significance of faulting in the eastern Vermilion district. It is considered of prime importance in reconstructing geologic relationships within the Jasper Lake area.

The most commonly observed evidence of faulting is the physical condition of the rock. For instance, within all fault zones in the area the rocks exhibit varying degrees of schistosity or shearing producing a fissile fabric.

Primary textural features are usually destroyed within fault zones and owing to their greater susceptibility to erosion, actual faulted contacts are rarely observed, but are commonly expressed as topographically low, trench-like lineaments, which are visible both on the ground and on aerial photographs.

These lineaments, together with the displacement of the contacts between rock units, imply faulting has occurred (Plate 2). Unfortunately, the amount of vegetation, lake, bog, and minor glacial drift cover make direct recognition of even weathered fault surfaces or zones difficult.

There are strongly developed lineaments in some areas which show no discernible offset of rock units. The absence of offset may result from: (1) the lack of mappable contacts between the structural units which would demonstrate displacement, (2) displacement may be mainly vertical, thus exhibiting no visible offset in vertical beds, (3) the fact that only minor displacement has occurred.

Faults within the Jasper Lake area are generally believed to have near-vertical dips. Although extensive fault planes were not observed, slickensided surfaces were noted which may represent a fault surface in a few localities. These surfaces display near-vertical dips.

Shear zones are common throughout the Jasper Lake area, many of which are associated with mappable faults. They are defined as zones of intense cataclasis with observable offset not necessarily noted of the rock units, and range in width up to 200 meters. They display gradational contacts and much iron-staining and pyrite. Most shear zones tend to obliterate matrix or groundmass textures and structures and form a foliation around clasts and fragments, if present.

Many of the faults in the area probably continue beyond the limits shown on Plate 2, but they were not extended because of the absence of direct evidence.

The east shore of Ogishkemuncie Lake is defined by a large northeast-trending, high-angle fault (Gruner, 1941). The fault extends from the southern part of Sec. 7, T.65N., R.5W., southwestward, to the northern part of Sec. 26, T.65N., R.6W., and truncates structural trends of the Jasper Lake area. The fault appears to terminate or die out just west of Redpoll Lake in Sec. 7, T.65N., R.5W., within the northeast-trending, vertical beds of the Ogishke conglomerate of the Knife Lake Group. However, it may be an intraformational fault which continues to the northeast within the conglomerate, but is not readily observable on the surface. This fault is characterized mainly by shearing and vertical foliation within a zone 150 meters wide. Clasts and fragments within both the Ogishke conglomerate to the west, and the pyroclastic unit to the east are intensely fractured and mylonitized. In addition, vertical lineations of a few stretched clasts are also observed, notably north of Kingfisher Lake in the NW$\frac{1}{4}$, Sec. 18, T.65N., R.5W., within the fault zone. The lineations are probably related to vertical displacement of the fault.

The extent of horizontal separation along the right lateral displacement of this fault is unknown. Vertical displacement was estimated as 3-4 km by Gruner (1941) on the basis of displacement of large thicknesses of the juxtaposed units.

A major west-northwest-trending curvilinear fault was also observed along the north shore of Jasper Lake. It extends from the NW$\frac{1}{4}$, Sec. 18, T.65N., R.5W., at Kingfisher Lake, where it trends N90°W, to the central part of Sec. 17, T.65N., R.5W., just west of Tern Lake, where it trends N65°W. The fault zone is 5-10 meters wide and is characterized by a large amount of carbonate and intense shearing. Iron-staining, abundant pyrite, and slickenside surfaces were also observed. This fault is truncated and displaced at its eastern extent by a N35°W-trending fault. Horizontal separation of the main fault surface along this fault is at least 1000-1500 meters. The displaced portion of the fault probably continues 20 km to the east and connects with the Lookout Fault described by Morey (personal communication, 1977) in the Long Island Lake quadrangle.

The N35°W-trending fault, mentioned above, stretches from the central part to the SE$\frac{1}{4}$, Sec. 17, T.65N., R.5W., and probably continues beyond the limits indicated on Plate 2. It continues north to N10°W from a point just south of the Jasper-Tern Lakes portage, about

700 meters through a portion of Jasper Lake as suggested by shearing and carbonate in these areas. The southern extent of this fault may continue southeastward approximately 0.5 km, cross-cutting the Jasper Lake andesite and accounting for the sudden change in thickness of the andesite in the NW½, Sec. 21, T.65N., R.5W.

Two smaller faults are also observed in the area: one, trends N30°W, and extends from east central Sec. 18, at Jasper Lake, to NW¼, Sec. 20, T.65N., R.5W., at Ray Lake, and the second, trends N35°E, and is located just south of Jasper Lake in the NE¼, Sec. 19, T.65N., R.5W. These fault zones are characterized by a high degree of shearing and carbonate, together with pyrite.

The northwest-trending fault from Jasper to Ray Lakes is right lateral with an approximate horizontal separation of 200 meters. Likewise, the fault south of Jasper Lake is left lateral, with at least 50 meters of horizontal separation.

The N30°W-trending fault, cutting Jasper and Ray Lakes, as mentioned above, probably continues to the southeast as suggested by the abrupt thickening of the andesite unit within the central part of Sec. 20, T.65N., R.5W., although no direct evidence for the existence of such a fault was observed. The relationship of this fault with the major west-northwest-trending fault is unknown.

The small N35°E-trending fault, south of Jasper

Lake, may continue a short distance to the southwest as suggested by intense shear zones across a small lake in the area.

Folds

On a broad scale, the entire sequence at Jasper Lake faces southwest, and thus forms a homoclinal, vertical sequence. To some extent, only local secondary folding is exhibited about fold axes of unknown plunges with amplitudes up to 0.5 km wide. This is in contrast to the rest of the eastern Vermilion district in which most fold axes are steep (Gruner, 1941).

The Jasper Lake greenstone unit exhibits little evidence of folding. Top directions from relatively few (5 localities) pillow structures are consistently to the southwest except for one northeast-trending reading. No marker beds were traced laterally because of the lack of exposure and irregularity in thickness of the units.

In the southwestern portion of the area, within the pyroclastic unit, top directions alternate from generally southwest to northeast, indicating folding with vertical (isoclinal) limbs. These folds have a west-northwest (N60-80°W) trend with amplitudes up to 800 meters. Whether the fold axes are shallow or steep in this area is unknown as collected data in the area do not allow distinction between these two choices.

Depositional structures that indicate stratigraphic younging directions were found in few exposures (11 localities) within the pyroclastic unit. Therefore, few folds are indicated directly on the geologic map (Plate 2).

Phenocryst lineations within the Jasper Lake andesite are also scant, but are always subhorizontal and parallel to the outline of the unit.

Joints

Vertical jointing is common in the Jasper Lake area, especially near contacts between rock units. They are usually best developed within the pyroclastic unit, and typically parallel rock unit contacts or fault traces.

Thirty-eight trends of vertical joints were measured and plotted on a rose diagram in Figure 16, and produce a preferred, roughly east-west direction. A minor set of joints trending approximately N40°W is also noted.

Interpretation

The Jasper Lake area is a structurally complex segment of the eastern Vermilion district. The scarcity of well exposed structural indicators within the area makes interpretation difficult.

From the observations and data collected in this

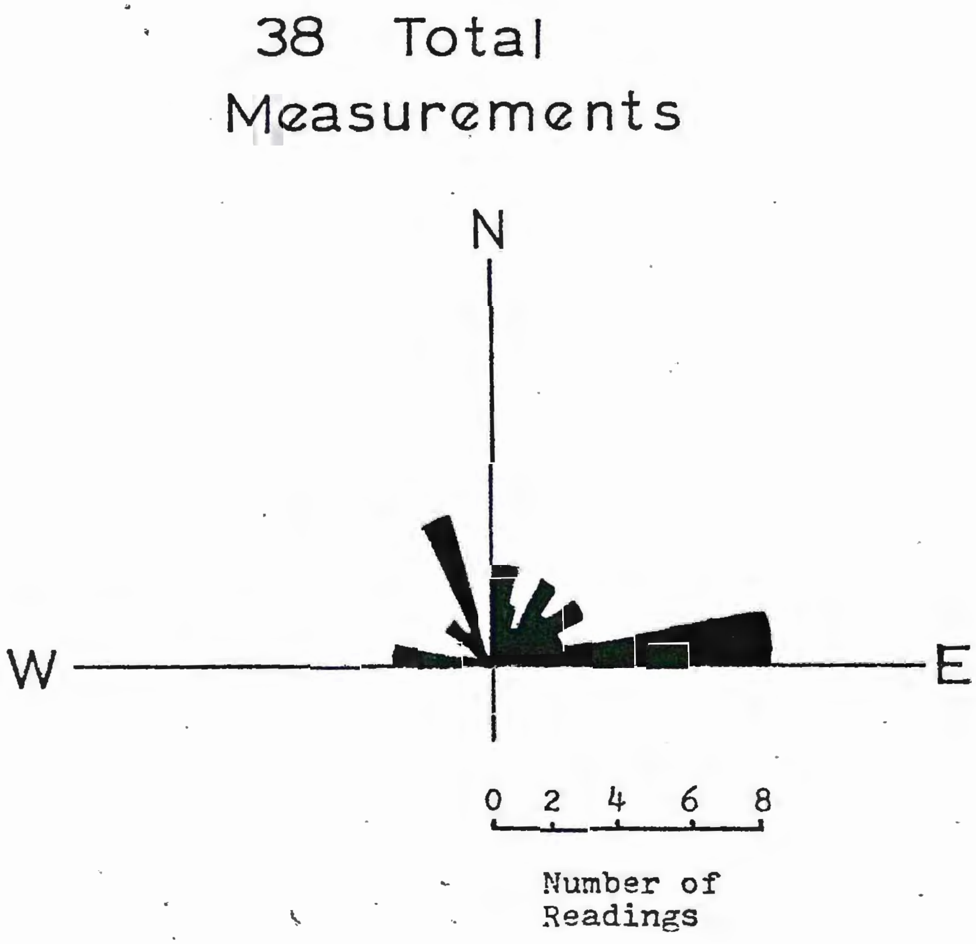


FIGURE 16--ROSE DIAGRAM OF ALL VERTICAL JOINT TRENDS IN THE JASPER LAKE AREA.

study, three structural interpretations of the Jasper Lake area are proposed. These three interpretations are based upon two important assumptions: (1) the Jasper Lake greenstone is the oldest unit in the area, and is conformable with the overlying pyroclastic unit, and (2) the Jasper Lake andesite was intruded prior to faulting of the Jasper Lake units.

The first interpretation assumes that east-west faulting within the Jasper Lake area occurred before folding. Subsequently, isoclinal folding took place along essentially east-west-trending fold axes. In this model, the arcuate structure formed by the Jasper Lake andesite and pyroclastic units, which is convex to the west, would represent an antiform with an axis that plunges gently to the west. Scant bedding indications within the pyroclastic unit show topping directions which radiate from the andesite intrusive on the west, and support an antiformal interpretation.

However, this interpretation introduces several problems. One is the proposed conformable relationship observed in one locality on the north shore of Jasper Lake between a fault sliver of greenstone and vague bedding in the pyroclastic unit discussed above. Serious stratigraphic problems arise since unfolding of the proposed antiform would indicate that the greenstone sliver occurs stratigraphically within the pyroclastic unit instead of underneath it. This assumes no vertical motion on the main east-west fault occurred. Another problem is the mechanical feasibility of faulting the area before folding to produce the observed outcrop pattern. One would expect faulting followed by folding to produce a displacement of fault traces and fault relationships, and uniformly affect the rocks on either side of the faults. These conditions were not observed in the Jasper Lake area.

A second interpretation assumes that folding in the area preceded faulting, and that in most places, two episodes of folding must have occurred to produce the observed structural pattern.

The arcuate structure of the andesite and pyroclastic units, described above, therefore, may represent a fold with either a horizontal or vertical fold axis. If the axis is horizontal, the structure is probably a synform, in which the (older) greenstone unit, at one time, wrapped around this arcuate structure to the west, but is now cut by the N35°W-trending longitudinal fault. This implies only one period of folding (isoclinal) is necessary to explain the observed pattern. If the axis is vertical, the fold could be interpreted as either a synform or an antiform. In this case, these rocks were probably initially folded isoclinally, and then subjected to an additional folding which tilted the fold axes.

A synformal structure is more mechanically feasible than an antiform in that, the older greenstone unit in the area lies spatially outside of this structure. Antiform formation with the observed spatial pattern of rock units is stratigraphically untenable.

This second interpretation also raises many problems. Top directions west of Tickle Lake suggest an antiformal structure rather than a synform for the arcuate pattern observed. The top direction indicators in this area, however, may have been disrupted by net slip (left lateral) along the main northeast-trending fault to the west, incorrectly recording top directions. The stratigraphic position of the greenstone fault sliver and conformable pyroclastic unit also negates this interpretation.

The third interpretation assumes that the andesite intrusive is essentially unfolded. Thus, the intrusive represents an irregular, subconcordant, possibly flattened, intrusive body. Therefore, this implies the Jasper Lake sequence represents a N65-75°W-trending, homoclinal sequence in which isoclinal folding occurred, followed by faulting.

This interpretation raises fewer problems than the previously mentioned interpretations. The stratigraphic problem is avoided since the greenstone sliver can be interpreted as occurring at the bottom of the sequence. This interpretation is mechanically feasible and requires only one deformational period.

A hypothetical structure section is illustrated in Figure 17 according to the third interpretation.

The age of faulting is known only within very wide limits. Since no faulting was observed in this study cutting the Saganaga batholith, it is difficult to relate it temporally with the intrusion of the batholith.

The faults within the Jasper Lake volcanic units occurred prior to Ogishke conglomerate deposition and faulting along the N35°E (Ogishkemuncie) trend, as they are truncated to the west by this northeast-trending fault and the units of the Knife Lake Group.

This northeast-trending fault cuts, but apparently dies out within units of the Ogishke conglomerate which contains Saganaga detritus, therefore dating it as at least post-Saganaga intrusion and post-deposition of the Knife Lake Group (specifically the Ogishke conglomerate) in age. The fault may continue to the northeast as an intraformational fault within the Ogishke conglomerate, which is not expressed or observable directly on the surface. This fault does not cut the Duluth complex to the south, and therefore, is older than Keweenawan (1.1 billion years old) (Gruner, 1941).

The age of folding in the area is assumed to be early Precambrian in age since no other evidence is found in the region for major crustal instability between Algoman and Animikie sedimentation. The faults within the Jasper Lake units probably occurred during

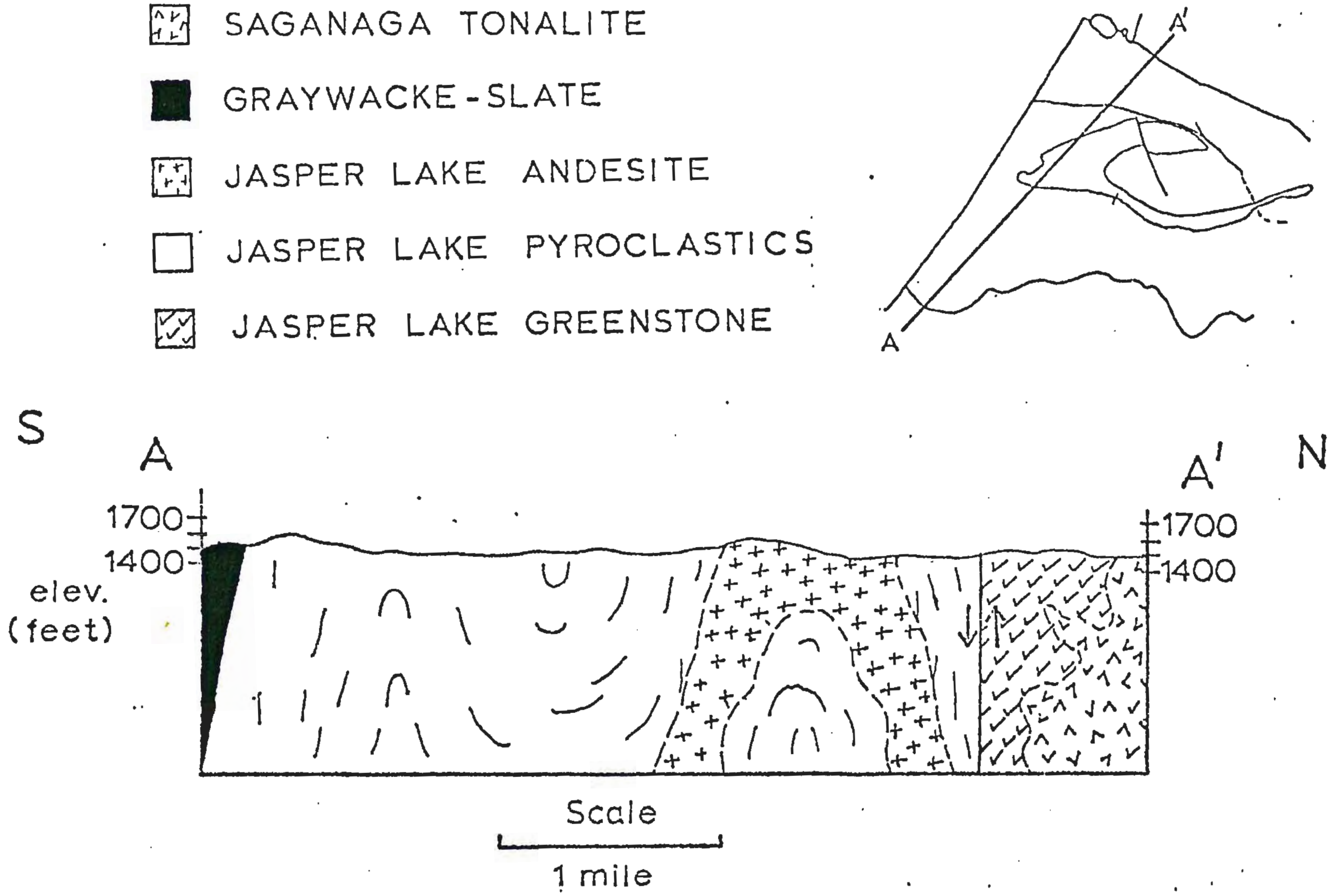


FIGURE 17--HYPOTHETICAL STRUCTURE SECTION ACROSS A-A' IN THE JASPER LAKE AREA.

or slightly later than intrusion of the Saganaga batholith. If, indeed, folding in the area was the result of Saganaga intrusion, faulting probably occurred shortly after, during the intrusive event.

A second folding event affected the major portions of the eastern Vermilion district exclusive of the Jasper Lake area including the Ogishke conglomerate, and folded these rocks on northeast-trending fold axes.

Jointing in the area occurred after Saganaga tonalite intrusion and affected all of the Jasper Lake units. They may have occurred as a result of cooling and contraction affects of the Saganaga intrusion, renewed movement in the area from other sources, or reflect affects of glacial unloading and isostatic rebound of the bedrock in the area.

SUMMARY AND CONCLUSIONS

Geologic History of the Jasper Lake Area

The Jasper Lake area developed within a tectonic environment similar to modern island arcs, commencing with an episode of mafic volcanism. The nature of the basement rocks on which these volcanic rocks were deposited is unknown. It was accompanied by intrusion of synvolcanic hypabyssal rocks such as diabase and andesite-dacite, which never reached the surface. Volcanism was mostly subaqueous and magmas were mainly a basaltic composition, building up a sequence to at least 1000-1500 meters thick as presently preserved. Minor interruptions in volcanic activity resulted in local deposition of tuffaceous sediments.

Volcanism continued with deposition of dominantly andesitic and lesser dacitic pyroclastics (breccias, tuffs). The pyroclastic debris was deposited largely as volcanic mudflows or lahars. Locally, stable conditions prevailed allowing deposition of interbedded tuffs, conglomerates, and graywacke-argillites derived from erosion of the upper part of the volcanic edifice. Hypabyssal intrusives, such as the Jasper Lake andesite were intruded into the pile penecontemporaneously with pyroclastic activity. The andesite is also consanguineous with the pyroclastic debris.

Further crustal instability, erosion, and deposition produced a thick (at least 1.6 km) sequence of graywacke-slates. These rocks were deposited in a deep ocean basin next to the volcanic center.

After an unknown period of time, this sequence was intruded by the Saganaga tonalite batholith which both deformed and metamorphosed the Jasper Lake rocks. The batholith was intruded during the Algoman orogeny and is dated at 2.7-2.75 billion years old (Goldich, 1968). The intrusion folded the Jasper Lake strata isoclinally along west-northwest-trending fold axes. It also raised the grade of metamorphism from previous regional greenschist facies to amphibolite facies within the mafic volcanics along the intrusive contact. Late retrograde prehnite-pumpellyite facies metamorphism, largely within veins along the contact, also affected the mafic volcanics and was possibly associated with Saganaga intrusion or regional metamorphism.

The basaltic rocks of komatiitic composition, found almost exclusively within the Archean, together with the Saganaga tonalite are thought to have been mantle derived (Brooks and Hart, 1974, and Goldich, 1968).

After, or during the later stages of intrusion of the batholith, and after folding, the Jasper Lake units were faulted on predominantly east-west to northwest trends.

Uplift and unroofing of the Saganaga batholith provided a large portion of the detritus for deposition of the Ogishke conglomerate of the Knife Lake Group.

As the Saganaga tonalite continued to rise, the Ogishke conglomerate and younger units were deformed and folded isoclinally along steep northeast-trending fold axes. Jasper Lake volcanic units were unaffected by this later stage of deformation because of their higher competency than Knife Lake conglomerates, graywackes, and slates.

A second episode of faulting, along a northeast-trend, affected the eastern Vermilion district. This episode produced a major N35°E-trending fault which truncated the Jasper Lake area on the west, and cut both the Jasper Lake units and the Ogishke conglomerate of the Knife Lake Group. The fault apparently dies out within the Ogishke conglomerate at the northern extent of the area where these rocks trend northeastward and unconformably overly the west-northwest-trending mafic volcanics of the Jasper Lake area. The fault may continue northeastward within the conglomerate as an intraformational fault.

The effects of the Keweenawan intrusions and extrusions to the south of the area on the Jasper Lake units are unknown.

A large interval of time, up until the Pleistocene, was characterized by erosion and lowering of topography in the Jasper Lake area.

During Pleistocene time, ice sheets of the Rainy Lobe (15,000 years ago) scoured off the rock surfaces and deposited a thin, patchy veneer of glacial drift.

Conclusions

Significant conclusions which can be drawn from this study are:

(1) The Jasper Lake area represents the basal portion of the regional lower Precambrian metavolcanic-metasedimentary pile of the eastern Vermilion district.

(2) The rocks of the Jasper Lake area have been isoclinally folded as well as faulted. The main N35°E-trending fault, truncating the area on the west, continues to the northeast from its extent drawn previously (Gruner, 1941), and cuts the Jasper Lake greenstone. It may die out within the Ogishke conglomerate of the Knife Lake Group to the north. The Jasper Lake greenstone and pyroclastic units are largely separated by high-angle faults. Similar left and right lateral faults, with up to 200 meters of horizontal separation, also occur within the area.

(3) The contact between the Jasper Lake greenstone and the Saganaga tonalite batholith is not faulted, as previously assumed (Gruner, 1941, Clements, 1903), but represents a gradational metamorphic contact

of branching network-like tonalitic and quartz-rich veins within the greenstone unit.

(4) The Saganaga batholith raised the metamorphic grade of the Jasper Lake greenstone to amphibolite facies within a 30-60 meter wide zone along the contact. A late, retrograde prehnite-pumpellyite facies metasomatism within the greenstone also occurred. Retrograde effects are largely apparent within the tonalitic and quartz-rich veins intruding the greenstone along the contact zone.

(5) The Jasper Lake andesite is an unfolded, contemporaneous, subconcordant intrusion with the Jasper Lake pyroclastic unit instead of a folded lava flow as previously assumed (Gruner, 1941).

(6) The Jasper Lake pyroclastic unit is composed dominantly of breccias and tuffs rather than agglomerate or conglomerate as previously assumed (Gruner, 1941).

REFERENCES CITED

Anderson, C.A., 1933, The Tuscan Formation of northern California: Calif. Univ. Pubs. Dept. Geol. Sci. Bull., v. 23, pp. 215-276

Anhaeusser, C.R., Mason, R., Viljoen, M.J., and Viljoen, R.P., 1969, A reppraisal of some aspects of Precambrian Shield Geology, Bull. Geol. Soc. of Amer., v. 80, pp. 2175-2200

Arth, J.G., and Hanson, G.N., 1975, Geochemistry and origin of the early Precambrian crust of northeastern Minnesota, Geochim. Cosmochim. Acta, v. 39, pp. 325-362

Baragar, W.R.A., and Goodwin, A.M., 1969, Andesites and Archean volcanism of the Canadian Shield in: Proceedings of the Andesite Conference, Oregon, Dep. Geol. Min. Industries, Bull. 65

Billings, M.P., and White, W.S., 1950, Metamorphosed mafic dikes of the Woodsville quadrangle, Vermont and New Hampshire, Am. Mineral., v. 35, pp. 629-643

Bowen, N.L., 1928, The evolution of igneous rocks: Dover Publications, 332p. (reprinted 1956)

Brooks, C., and Hart, S., 1972, An extrusive basaltic komatiite from a Canadian Archean metavolcanic belt, Can. J. Earth Sci., v. 9, pp. 1250-3

Brooks, C., and Hart, S., 1974, On significance of komatiite, Geology, v. 2, No. 2, pp. 107-110

Catanzaro, E.J., and Hanson, G.N., 1971, U-Pb ages for sphene from Early Precambrian igneous rocks in northeastern Minnesota-western Ontario: Can. J. Earth Sci., v. 8, pp. 1319-1324

Carmichael, I.S.E., Turner, F.J., and Verhoogen, J., 1974, Igneous Petrology, MacGraw-Hill, Inc., New York, 739 p.

Clarke, D.B., 1970, Tertiary basalts of Baffin Bay: possible primary magma from the mantle, Contr. Mineral. Petrol., v. 25, pp. 203-224

Clements, J.M., 1903, The Vermilion iron-bearing district of Minnesota, U.S. Geol. Survey, Mono. 45

Ernst, W.G., 1968, Minerals, rocks, and inorganic materials, v. 1, Amphiboles, New York: Springer-Verlag

Fisher, R.V., 1960, Criteria for recognition of laharic breccias, southern Cascade Mtns., Washington: Geol. Soc. Am. Bull., v. 71, pp. 127-132

Fisher, R.V., 1961, Classification of volcanic breccias, Geol. Soc. Am. Bull., v. 71, pp. 973-982

Fiske, R.S., 1963, Subaqueous pyroclastic flows in the Ohanapekosh Formation, Washington: Geol. Soc. Am. Bull., v. 74, pp. 391-406

Fiske, R.S., Hopson, C.A., and Waters, A.C., 1963, Geology of Mount Rainier National Park, Washington: U.S. Geol. Survey Prof. paper 444, 93p.

Fiske, R.S., and Matsuda, T., 1964, Submarine equivalents of ash flows in the Takiwa Formation, Japan: Am. J. Sci., v. 262, pp. 76-106.

Folinsbee, R.E., Baadsgaard, H., Cumming, G.L., and Green, D.C., 1968, A very ancient island arc, in: the crust and upper mantle of the Pacific area, Am. Geophys. Un. Mono. 12, pp. 441-8

Gale, G.H., 1973, Paleozoic basaltic komatiite and ocean-floor type basalts from northeastern Newfoundland, Earth Planet. Sci. Lett. 18, pp. 22-28

Gelinas, L., and Brooks, C., 1974, Archean quench-texture tholeiites, Can. J. Earth Sci., v. 11, pp. 324-340

Glassley, W., 1974, A model for phase equilibria in the prehnite-pumpellyite facies, Contrib. Mineral. Petrol., v. 43, pp. 317-332

Green, J.C., 1970, Lower Precambrian rocks of the Gabbro Lake quadrangle, northeastern Minnesota, Minn. Geol. Survey Spec. Pub. 13, 96p.

Green, J.C., 1972, Ultramafic rocks in the Vermilion district, pp. 76-78, in Sims, P.K., and Morey, G. B., eds., Geology of Minnesota: A Centennial Volume, Minn. Geol. Survey, 632p.

Green, J.C., and Schulz, K.J., 1977, Iron-rich basaltic komatiites in the Early Precambrian Vermilion district, Minnesota, University of Minnesota-Duluth, Geol. Dept., Univ. of Minn. Geol. and Geophys. Dept.

Goldich, S.S., 1968, Geochronology in the Lake Superior region: Can. J. Earth Sci., v. 5, pp. 715-724

Goldich, S.S., Nier, A.O., Baadsgaard, H., Hoffman, J.H., and Krueger, H.W., 1961, The Precambrian geology and geochronology of Minnesota: Minn. Geol. Survey Bull. 41, 193p.

Goldich, S.S., Hanson, G.N., Hallford, C.R., and Mudrey, M.G., 1972, Early Precambrian rocks in the Saganaga Lake-Northern Light Lake area, Minnesota-Ontario, Part I, petrology and structure: in B.R. Doe and D.K. Smith, eds., Studies in Precambrian geology and mineralogy (Gruner volume), Geol. Soc. America Mem. 135

Goodwin, A.M., 1968, Archean protocontinental growth and early crustal history of the Canadian Shield, 23rd Int. Geol. Cong., Prague, 1, pp. 69-89

Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The geology of Cook County, Minnesota, UM-Minn. Geol. Survey Bull. 39

Gruner, J.W., 1941, Structural geology of the Knife Lake area of northeastern Minnesota, Geol. Soc. Am. Bull., v. 52, pp. 1577-1642

Hanson, G.N., 1968, K-Ar ages for hornblende from granites and gneisses and for basaltic intrusions in Minnesota: Minn. Geol. Survey Rept. Inv. 8, 20p.

Hanson, G.N., and Goldich, S.S., 1972, Early Precambrian rocks in the Saganaga Lake-Northern Light Lake area, Minnesota-Ontario, Part II, petrogenesis: in B.R. Doe and D.K. Smith, eds., Studies in Precambrian geology and mineralogy (Gruner volume), Geol. Soc. Amer. Mem. 135

Hanson, G.N., Goldich, S.S., Arth, J.G., and Yardley, D. H., 1971, Age of the Early Precambrian rocks of the Saganaga Lake-Northern Light Lake area, Ontario-Minnesota, Can. J. Earth Sci., v. 8, p. 1110

Hart, S.R., and Davis, G.L., 1969, Zircon U-Pb and whole-rock Rb-Sr ages and early crustal development near Rainy Lake, Ontario: Geol. Soc. Am. Bull., v. 80, pp. 595-616

Hart, S.R., and Nalwalk, A.J., 1970, K, Rb, Cs, and Sr relationships in submarine basalts from the Puerto Rico trench, Geochim. Cosmochim. Acta, v. 34, No. 2, pp. 145-154

Harte, B., and Graham, C.M., 1975, The graphical analysis of greenschist to amphibolite facies mineral assemblages in metabasites, J. Petrology, v. 16, pp. 347-370

Irvine, T.N., 1973, Bridget Cove volcanics, Juneau area, Alaska: possible parental magma of Alaskan-type ultramafic complexes, Carnegie Inst. Yearbook 72, pp. 478-491

Jaggar, T.A., 1908, Evolution of Bogoslof volcano: Am. Geog. Soc. Bull., v. 49, pp. 1829-1862

Jahn, Bor-ming, and Murthy, V.R., 1971, Isotopic studies of the Vermilion greenstone belt, northeastern Minnesota (abs.): Geol. Soc. Am. Abs. with Programs, v. 3, p. 611

Jakes, P., and Smith, I.E., 1970, High potassium calc-alkaline rocks from Cape Nelson, eastern Papua, Contrib. Mineral. Petrol., v. 28, pp. 887-902

Kuniyoshi, S., 1972, Petrology of the Karmutsen Group, northeastern Vancouver Island, British Columbia, Ph.D. Thesis, Univ. of Calif., Los Angeles

Kuniyoshi, S., and Liou, J.G., 1976, Contact metamorphism of the Karmutsen volcanics, Vancouver Island, British Columbia, J. Petrology, v. 17, pp. 73-99

Liou, J.G., Kuniyoshi, S., and Ito, K., 1974, Experimental studies of the phase relations between greenschist and amphibolite facies in a basaltic system, Am. J. Sci., v. 274, pp. 613-632

Lowder, G.G., 1970, The volcanoes and caldera of Talasea, New Britain: mineralogy, Contrib. Mineral. Petrol., v. 26, pp. 324-340

Lowder, G.G., and Carmichael, I.S.E., 1970, The volcanoes and caldera of Talasea, New Britain: geology and petrology, Bull. Geol. Soc. Am., v. 81, pp. 17-38

Lydon, P.A., 1968, Geology and lahars of the Tuscan Formation, northern California, Geol. Soc. Am. Mem. 116, pp. 441-475

Macdonald, G.A., 1972, Volcanoes, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 510p.

McBirney, A.R., and Williams, H., 1969, Geology and petrology of the Galapagos Islands, Geol. Soc. Am. Mem. 118

McGlynn, J.C., 1970, Geology of the Canadian Shield: In R.W. Douglas, editor, Geology and Economic Minerals of Canada, Can. Geol. Survey Econ. Geol. Rept. 1, pp. 45-71 (5th edition)

Miyashiro, A., 1973, Metamorphism and metamorphic belts, New York: John Wiley and Sons.

Morey, G.B., Green, J.C., Ojakangas, R.W., and Sims, P.K., 1970, Stratigraphy of the Lower Precambrian rocks in the Vermilion district, northeastern Minnesota, Minn. Geol. Survey Rept. of Inv. 14, 33p.

Morey, G.B., Davidson, Jr., D.M., Weiblen, P.W., and Mudrey, M.G., 1971, Guide to the Precambrian rocks of northwestern Cook County as exposed along the Gunflint Trail, In: 17th Ann. Inst. Lake Superior Geol. (Duluth, Minnesota), 162p.

Morey, G.B., Weiblen, P.W., Papike, J.J., and Anderson, D.H., 1968, Geologic map of the Long Island Lake quadrangle, Cook County, northeastern Minnesota - open file map - Minn. Geol. Survey

Morimoto, R., and Ossaka, J., 1955, The 1952-53 submarine eruption of the Myojin reef near the Bayonnaise rocks, Japan (1): Earthquake Research Inst. Bull., v. 33, pp. 221-250

Mullineaux, D.R., and Crandell, D.R., 1962, Recent lahars from Mt. St. Helens: Geol. Soc. Am. Bull., v.73, pp. 855-870

Naldrett, A.J., and Arndt, N.T., 1975, Volcanogenic nickel deposits with some guides for exploration, AIME Transactions.

Naldrett, A.J., and Mason, G.D., 1968, Contrasting Archean ultramafic igneous bodies in Dundonald and Clergue townships, Ontario, Can. J. Earth Sci., v. 5, pp. 111-143

Nesbitt, R.W., 1970, Skeletal crystal forms in the ultramafic rocks of the Yilgarn Block, western Australia: Evidence for an Archean ultramafic liquid, Geol. Soc. Australia Spec. Pub. 3, pp. 331-347

Nitsch, K.H., 1970, Stabilitatsbeziehungen von Prehnit- und Pumpellyithaltigen Paragenesen, Contrib. Mineral. Petrol., v. 30, pp. 240-260

Ojakangas, R.W., 1972, Archean volcanogenic graywackes of the Vermilion district, northeastern Minnesota: Geol. Soc. Am. Bull., v. 83, pp. 429-442

Pyke, D.R., Naldrett, A.J., and Eckstrand, O.R., 1973, Archean ultramafic flows in Munro Township, Ontario, Geol. Soc. Amer. Bull., v. 84, pp. 955-978

Schmincke, Hans-Ulrich, 1967, Graded lahars in the type sections of the Ellensbury Formation, south-central Washington, Jour. of Sed. Pet., v. 37, No. 2, pp. 438-448

Schulz, K.J., and Ripley, E.M., 1973, Petrology of some Early Precambrian differentiated ultramafic bodies in northeastern Minnesota (abs.), 19th Ann. Inst. Lake Superior Geol. (Madison, Wisconsin) Program, pp. 32-33

Seki, Y., 1969, Facies series in low-grade metamorphism, J. Geol. Soc. of Japan, v. 75, pp. 255-266

Sims, P.K., 1972, Early Precambrian - Northern Minnesota, General Geologic Features, in Geol. of Minn.: A Centennial Volume, Sims, P.K., and Morey, G.B., (eds.) Minn. Geol. Survey, Ch. III, pp. 41-62

Sims, P.K., and Morey, G.B., editors, 1972, Geology of Minnesota: A Centennial Volume, Minn. Geol. Survey, Univ. of Minnesota, 632p.

Sims, P.K., Morey, G.B., Ojakangas, R.W., Griffin, W.L., 1968, Stratigraphic and structural framework of the Vermilion district and adjacent areas, northeastern Minnesota (abs.): Ann. Inst. Lake Superior Geol., 14th, (Superior, Wisconsin), pp. 19-20

Taylor, G.A., 1958, The 1951 eruption of Mt. Lamington, Papua, Bur. Min. Res. (Australia) Bull. 38

Tilton, G.R., and Gruenfelder, M.H., 1968, Sphene: lead-uranium ages; Science, v. 59, pp. 1458-1461

Turner, F.J., 1968, Metamorphic Petrology: Mineralogical and field aspects: New York: McGraw-Hill Book Co., 403p.

Viljoen, M.J., and Viljoen, R.D., 1969, The geology and geochemistry of the Lower ultramafic unit of the Onverwacht Group and a proposed new class of igneous rock, Geol. Soc. So. Africa Spec. Pub. No. 2, pp. 55-85

Weiblen, P.W., Davidson Jr., D.M., Morey, G.B., and Mudrey, M.G., 1971, Guide to the Precambrian rocks of northwestern Cook County as exposed along the Gunflint Trail: Ann. Inst. Lake Superior Geol., 17th Proc., (Duluth, Minnesota), pp. 97-127

Williams, H., 1949, Geology of the Mac doel quadrangle: Calif. Dept. Nat. Res., Dir. Mines Bull. 151, 78p.

Williams, H., 1956, Glowing avalanche deposits in the Sudbury basin: Ontario Dept. Mines, 65th Ann. Rept., v. 65, Pt. 3. pp. 57-89

Wilson, H.D., Andrews, P., Maxham, R.L., and Ramlal, K., 1965, Archean volcanism in the Canadian Shield, Can. J. Earth Sci., v. 2, p. 161

Winchell, N.H., 1899, The Geology of Minnesota, Geol. Nat. Hist. Survey Minn., Final Rept., v. 4, pp. 313-345

Winchell, N.H., 1900, The Geology of Minnesota, Structural Geology; Minn. Geol. and Nat. Hist. Survey, Final Rept., v. 5.