Geology of the Cypress, Hanson and South Arm of Knife Lake Area, Boundary Waters Canoe Area: Eastern Vermilion District, Northeastern Minnesota

A Thesis
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By
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This thesis is dedicated to my family, particularly my father, Frank, and my mother, Florence. This thesis is also dedicated to Dr. John Tinker who sparked my interest in geology, and Dr. Gene LaBerge and Dr. Richard Ojakangas who kindled that interest.

ABSTRACT

Archean volcanic and volcanogenic sedimentary rocks of the Cypress, Hanson and South Arm of Knife Lake Area are located within the eastern Vermilion district and lie in three of Gruner's (1941) structural segments.

The dominant lithology within the Spoon Lake segment is dacite porphyry conglomerate, derived from a small lens of dacite porphyry. The dacite porphyry conglomerate is composed of dacite porphyry detritus and is interbedded with sequences of graywacke-argillite. The graywacke is of both the feldspathic and lithic type. Two small outcrops of greenstone, one of which is pillowed, occur within the segment and may be fault slices. Keweenawan diabasic dikes intrude both the igneous and the sedimentary rocks. Bedding within the sedimentary rocks indicates that the rocks within the Spoon Lake segment strike N 45°E and dip steeply to the southeast and northwest.

The dominant lithology within the Knife Lake Greenstone segment is greenstone which is texturally and compositionally similar to the Ely Greenstone. Overlying the greenstone and containing abundant clasts of greenstone, is a greenstone pebble conglomerate. This is a thin unit and grades laterally into graywacke-argillite. Bedding within the graywacke-argillite sequences indicates the rocks within the Knife Lake Greenstone

segment strike N 45°E and dip steeply to the southeast and northwest.

The rocks within the Knife Lake Synclinorium segment are divided into two units; a tuff-mafic conglomerate-mixed conglomerate unit, and a younger graywacke unit. These two units are interbedded and gradational into one another. The graywacke of the Knife Lake Synclinorium segment is similar to the graywacke of the Spoon Lake segment and the Knife Lake Greenstone segment, but can be distinguished from them by a greater diversity of volcanic rock fragments. One Keweenawan diabasic dike is present in the segment. The rocks within this segment strike predominantly northeast and dip steeply to the northwest. The northern part of the segment is part of a large overturned syncline, the axis of which trends N 45°E and plunges 30° to the northeast. The southern part of the segment lies on the limbs of folds whose axes trend N 25°E and plunges 75° to the northeast. Longitudinal faulting has removed the axes of the folds from this part of the segment.

Turbidite sequences within the Spoon Lake segment and the Knife Lake Greenstone segment are characteristic turbidites corresponding to the depositional lobe of the inner to middle portion of a submarine fan. Turbidite sequences within the Knife Lake Synclinorium segment are characteristic of proximal turbidites,

and correspond to facies associated with the inner fan of the slope-fan-basin system of a turbidite basin.

The structural information obtained from the Knife Lake Greenstone segment and the Spoon Lake segment is minimal, and few interpretations could be made. The structure of the Knife Lake Synclinorium segment however, can be accounted for in terms of three tectonic deformations. The first period of deformation produced isoclinal folds, which trend N 40° to 50°E and plunge 30° to the northeast. The second period of deformation produced a N 54° to 62° W cleavage throughout the segment. The third period of deformation occurred on a regional scale and produced major longitudinal faults which has divided the present area of study into discrete structural blocks. Transverse faulting of smaller dimensions transect the trend of the longitudinal faults and may have formed as a consequence of movements on the longitudinal faults.

The volcanic and sedimentary rocks of the Cypress, Hanson and South Arm of Knife Lake Area belong to the basalt-andesite-rhyolite association found in all of the greenstone belts of the Canadian Shield, which is also typical of continental orogenic belts or island arc systems.

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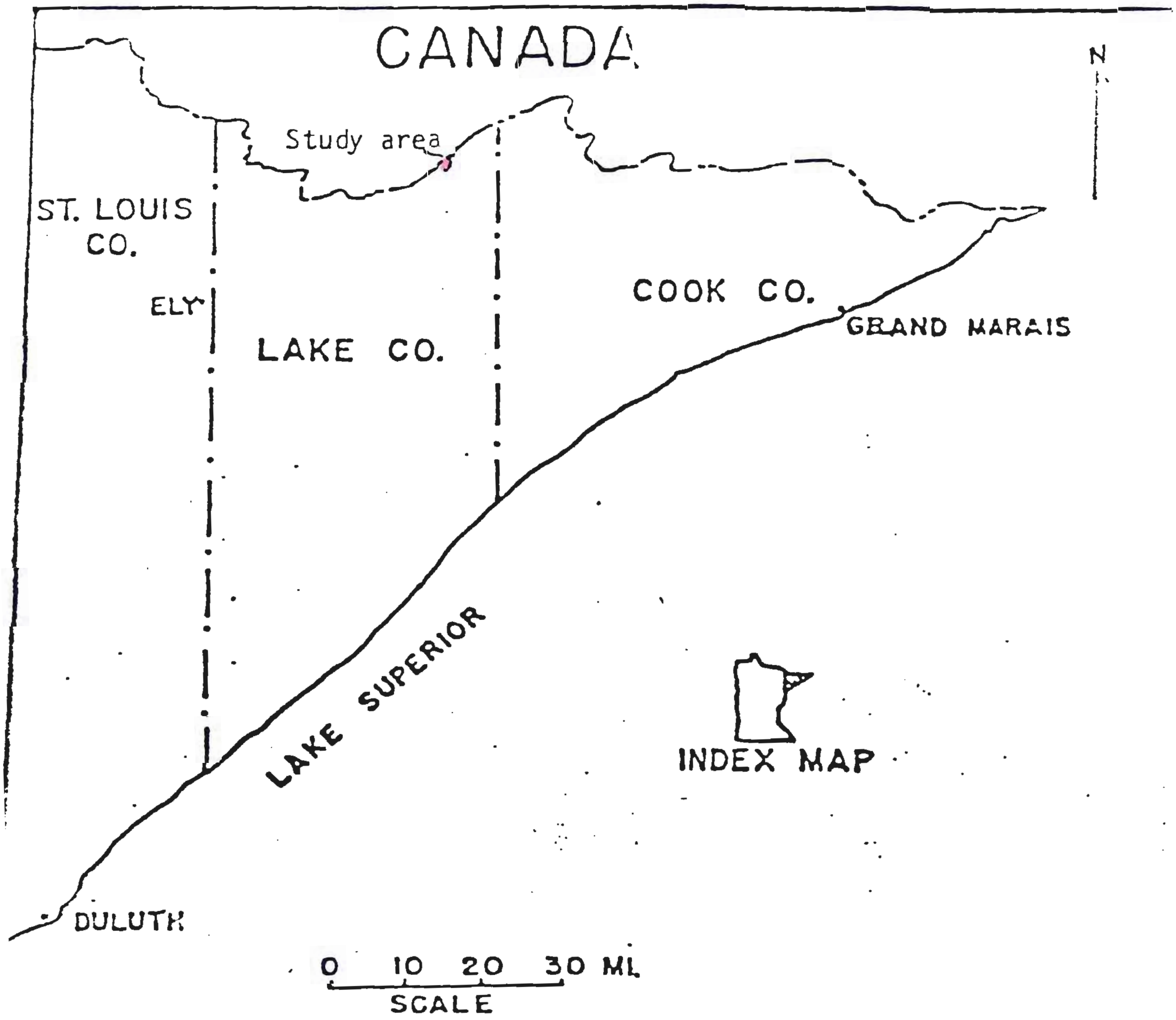
Location

The area of study is located in the Boundary Waters Canoe Area of the Superior National Forest, Lake County, Minnesota, approximately 70 kilometers northwest of Grand Marais, Minnesota (Figure 1). The area consists of about 25.6 square kilometers between Cypress Lake to the north, the South Arm of Knife Lake to the south, a western boundary determined by an imaginary line connecting Cedar and Cherry Lakes, and an eastern boundary which includes Rabbit Lake, Link Lake and Bullfrog Lake. The area, approximately wedge-shaped, lies mostly within T. 66N., T. 65N., and R. 6W. of the Ester Lake 7.5 minute quadrangle, with a small portion in T. 65N., R. 6W. of the Ogishkemuncie Lake quadrangle to the south.

The area is most readily accessible via the Saganaga Lake port of entry at the end of the Gunflint Trail. The northeast edge of the map area, located on Cypress Lake,is approximately 22 kilometers from the Saganaga Lake landing. The southeast edge of the map area, located on the South Arm of Knife Lake, has been reached using the Seagull Lake port of entry, also at the end of the Gunflint Trail.

Statement of Problem

The Cypress Lake, Hanson Lake, and South Arm of Knife Lake



igure 1: Location map of the Cypress, Hanson and South Arm of Knife Lake Area, Lake County, Northeastern Minnesota.

area contains several complexly interelated Lower Precambrian lithologic units, contained within three of Gruner's (1941) structural blocks (Figure 2). Volcanic and volcanogenic sedimentary rocks dominate in the area. The southern structural block, the Spoon Lake segment, is composed of dacite porphyry, dacite porphyry conglomerate, argillite, graywacke, minor greenstone, and mafic dikes. The central structural block, the Knife Lake Greenstone segment, is composed dominantly of greenstone, but also contains a greenstone pebble conglomerate, some graywacke, and minor mafic dikes. The northernmost structural block, the Knife Lake Synclinorium segment, is composed of argillite, graywacke, tuff, mixed conglomerate and mafic conglomerate. A cursory examination was given greenstones and banded iron-formation in the Canadian Greenstone segment to the north of the Knife Lake Synclinorium segment. The area is both stratigraphically and structurally complex. Gruner's (1941) geologic map indicated two periods of folding, along with major longitudinal faulting. This faulting separated the area into discrete segments.

The objectives of this thesis were: (1) to examine in detail the petrographic and structural relationships between the volcanic rocks and the volcanogenically derived sediments within a portion of the Knife Lake Group, (2) to determine if tonalitic clasts derived from the Saganaga batholith to the east are present within or interfingered with rocks within the study area.

The presence of such clasts would aid in age relationships and further indicate whether there was penecontemporaneous volcanism and unroofing of the Saganaga Tonalite as proposed by Ojakangas (1972), and (3) to produce a detailed geologic map of the area which lies within three of Gruner's (1941) structural blocks.

Previous Work

The first published reports of the Cypress Lake, Hanson Lake and South Arm of Knife Lake area were done by Grant (1892) while he was a member of the Geological and Natural History Survey of Minnesota. As part of a continued examination of the Kekekabic Lake area, he extended his field studies to the eastern end of Otter Track Lake, later renamed Cypress Lake, and southward beyond Little Saganaga Lake. He provided a description of rock units which included slate, graywacke, grit, greenschist, volcanic tuff, conglomerate, diabase, gabbro and drift deposits.

Winchell, in the Geology of Minnesota, Volume IV of the Final Report (1899), briefly discussed the rock units within the area of study, giving brief rock descriptions and their gross relationships. This was part of a county-by-county geologic map of Minnesota which the survey subsequently completed.

Clements (1903) summarized the complete stratigraphic, petrographic and structural knowledge of the Vermilion iron-bearing district of Northern Minnesota. The Knife Lake and Otter Track (Cypress) Lake areas were interpreted as consisting chiefly of slate and graywacke with occasional fine interstratified conglomerate. Clements decided that the Knife Lake Slates were younger than the Ely Greenstone, Soudan Iron-formation and Saganaga granite, and unconformably overlies them.

Van Hise and Leith (1911), working for the United States Geological Survey, prepared a regional review of the Lake Superior geology. They incorporated Clements earlier work on the Vermilion district in conjunction with other reports dealing with iron-bearing districts in Wisconsin and Michigan.

Leith, Lund and Leith (1935) portrayed the rocks of the Vermilion district on a map as the "Knife Lake Series" without a definite age assignment. This was done due to an absence of proved age relations. The Knife Lake Series was given a relative position on the time scale as older than Huronian and younger than the Saganaga batholith. Stark and Sleight (1939) in "The Stratigraphy of the Knife Lake Series in the Kekekabic-Ogishkemuncie Area", reviewed the stratigraphy of the Knife Lake Group, and placed the formation in the Lower Algonkian System.

Gruner (1941) studied the rocks of the eastern part of the Vermilion district, with the objective of investigating in great structural detail typical Precambrian rocks ranging in age from Keewatin to Keweenawan. Starting in 1928, he mapped for 13 summers at a scale of 1 inch to 3,520 feet. During this time, he determined that major longitudinal faults divide the district, as a whole, into fault-bounded structural segments (Figure 2). Three of these segments, the Spoon Lake, Knife Lake Greenstone, and Knife Lake Synclinorium, lie in the present area of study. He was also able to divide the Knife Lake Group into 21 separate lithologic units. Seven of these units are found within the present study area.

Grout and others (1951) officially termed these rocks the Knife Lake Group, and Goldich (1961) reassigned them from Middle to Early Precambrian.

Ojakangas (1972a, 1972b), made a general study of the volcanogenic sediments of the Vermilion district while working for the Minnesota Geological Survey. He determined that the sediments are dominantly graywackes which were derived by reworking of pyroclastics, and deposited via turbidity currents.

The "Geology of Minnesota: A Centennial Volume" (1972) provides a summary of current geologic knowledge of Minnesota, including an excellent section on the Vermilion district.

Other work within the area has been contributed as part of Master's thesis work at the University of Minnesota-Duluth by McLimans (1972), Feirn (1977), Severson (1978), Vinje (1978) and Duex (pending).

Methods of Study

Approximately forty-five days during the summer of 1979 and thirty days during the summer of 1980 were spent in the field.

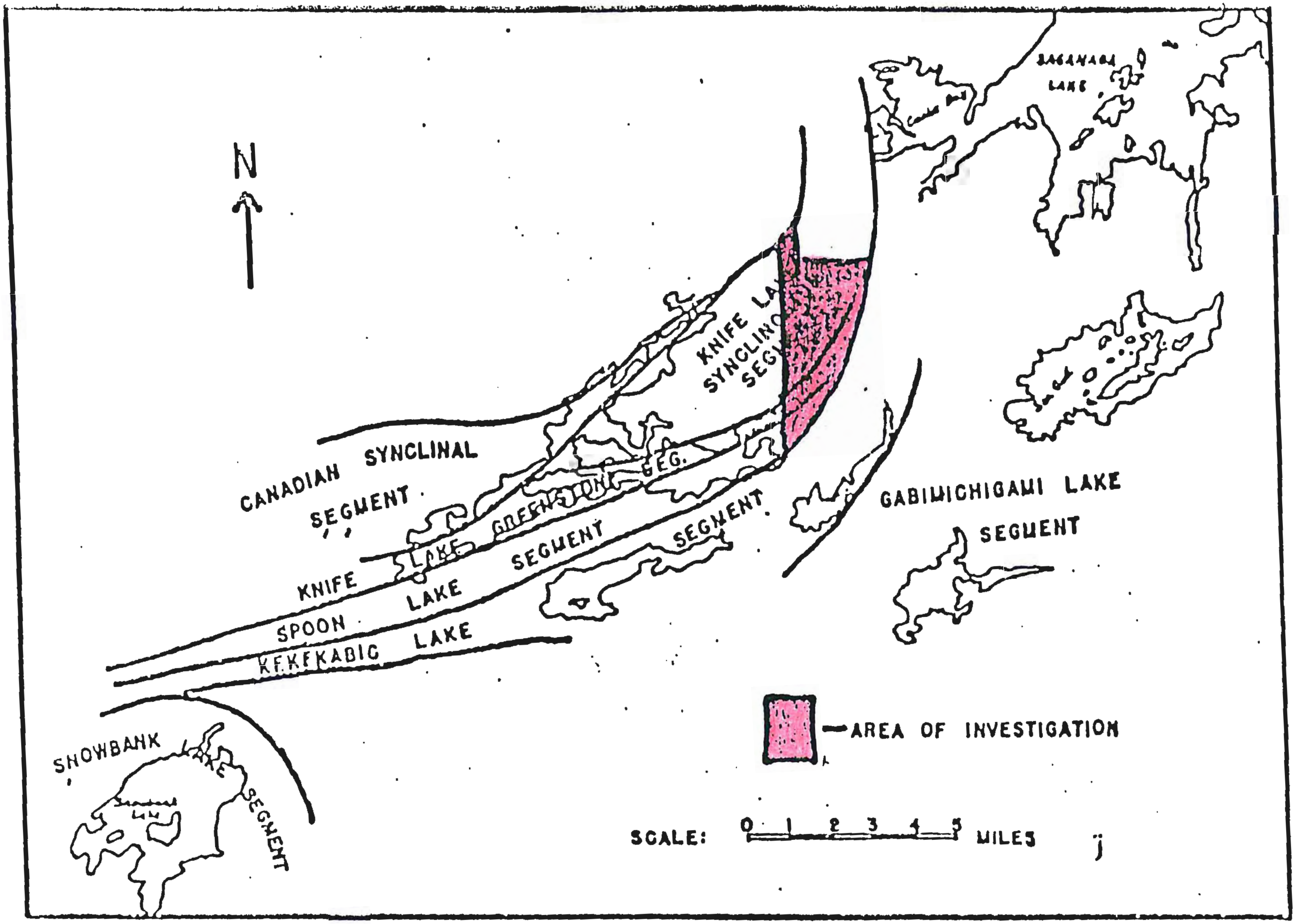


Figure 2: Structural segments of the Knife Lake Group (after Gruner, 1941).

Field work consisted of mapping on a scale of 1/12,000 using the Ogishkemuncie and Ester Lake 7.5 minute quadrangles as base maps. Additionally, Gruner's (1941) map was used as a reference. Shoreline areas were best suited for mapping and were mapped by canoe, inland areas were mapped by pace and compass. The objectives of the field mapping were to examine all the outcrops in the area, collect appropriate rock samples to be used for thin section, to take strike and dip, cleavage, lineation and cross-bedding measurements and determine Bouma sequences and topping where possible. Plate 1 is a geologic map of the area.

A total of 160 rock samples were collected, with 123 studied petrographically. Modal analyses were compiled for 77 thin sections by counting 600 points per thin section. All 123 slabs were stained for potassium using sodium-cobaltinitrate. Strike and dip and cleavage measurements were computer contoured on stereonets, while cross-beds and lineations were hand rotated on stereonets.

Acknowledgements

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Appreciation is also given to the Minnesota Geological Survey who provided financial support for this project.

REGIONAL GEOLOGY

Introduction

The Cypress Lake, Hanson Lake and South Arm of Knife Lake area of Northeastern Minnesota lies in the eastern portion of the Vermilion district, the eastern portion being defined here as east of Knife Lake. Clements (1903) originally defined the Vermilion district as a narrow belt, 160 kilometers by 5 to 10 kilometers, of metavolcanic and metasedimentary rocks that extend from the vicinity of Tower, near Lake Vermilion, northeastward to the international boundary in the vicinity of Saganaga Lake (Figure 3). The metavolcanic and metasedimentary sequence is bounded on the north by the Vermilion granite-migmatite massif, on the south by the Giants Range batholith, and on the east by the Saganaga batholith. The surrounding granites are contemporaneous with the Algoman orogeny, in the range of 2.4 to 2.75 billion years (Goldich, 1968). The Duluth Complex of Keweenawan age, 1.1 billion years, truncated much of the eastern part of the district.

The metavolcanic-metasedimentary sequence in the district typifies the Early Precambrian greenstone-granite complexes of the Canadian Shield (Goodwin, 1968). It is a complex volcanic pile, deposited mainly in a subaqueous environment. The attitude of the rocks within the district varies in trend from east to

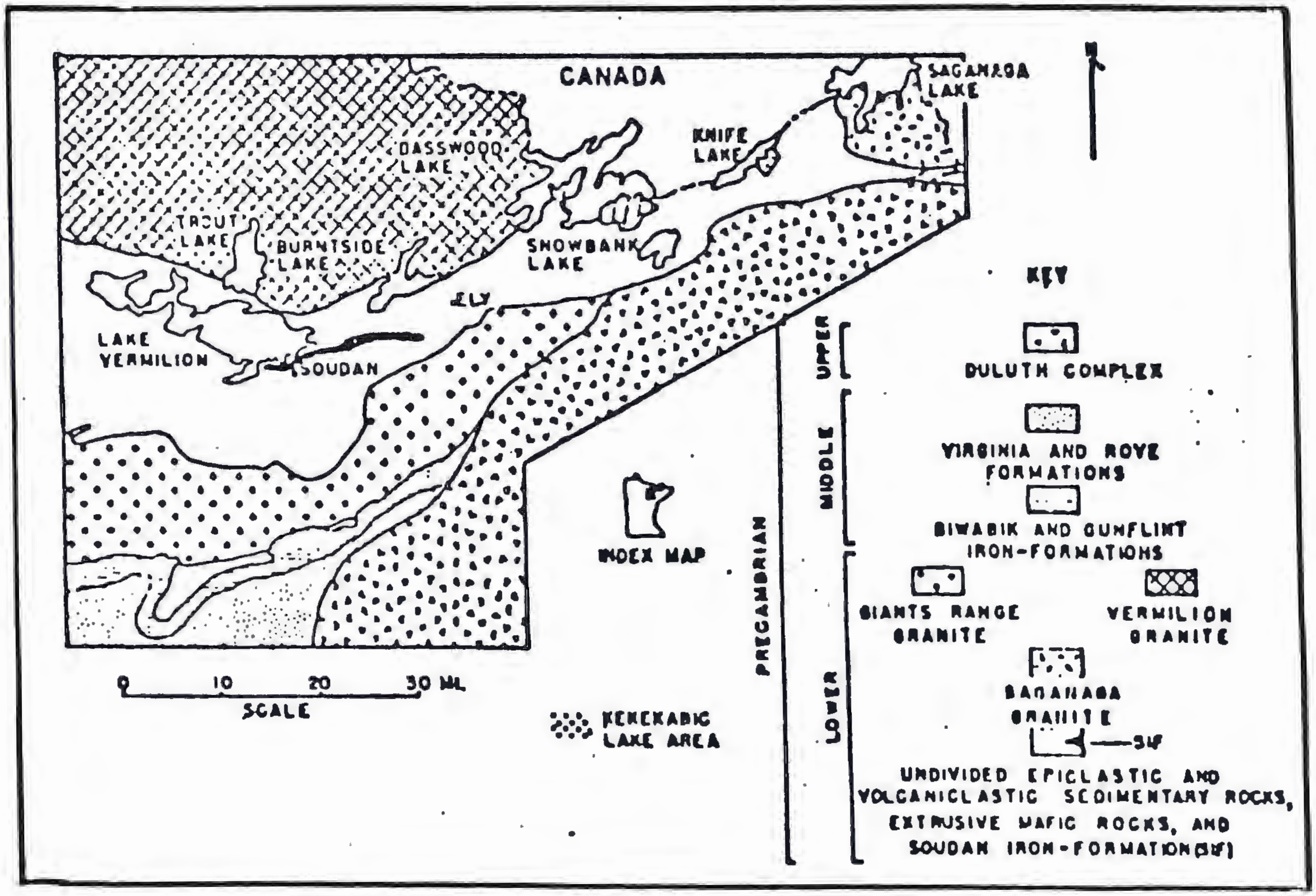


Figure 3: General geologic map of the Vermilion district (after Sims, 1972).

northeast with generally steep dips. Folding of at least two generations was broadly contemporaneous with emplacement of the surrounding batholiths and was followed by a major period of regional faulting (Sims, 1972).

Stratigraphy

The original stratigraphic nomenclature for the Vermilion district was established by Van Hise and Clements (1901) and Clements (1903). Several modifications were added by later work. Grout (1933) substituted the Knife Lake Series for the previously termed Knife Lake Slates. Grout and others (1951) later renamed this series the Knife Lake Group. Other developments included: (1) the determination (Grout and others, 1951) that the Coutchiching does not exist beneath the Ely Greenstone in Minnesota, (2) the determination by Gruner (1941) that neither the Agawa Iron-formation nor the Ogishkemuncie Conglomerate were widespread mappable units and hence not deserving of formational status, (3) a revised Precambrian summary based on radiometric age determinations (Goldich and others, 1961), (4) the formal establishment of the Lake Vermilion formation in the western Vermilion district (Morey and others, 1970) due to lack of continuity with the type section of the Knife Lake Group in the eastern Vermilion district and because it differs lithologically somewhat from the Knife Lake Group. The most recent stratigraphic summary of the Vermilion district is summarized in "Geology of Minnesota: A

Centennial Volume" (1972).

The metavolcanic and metasedimentary rocks of the Vermilion district are assigned to five formations (Morey and others, 1970). The oldest formation exposed within the district is the Ely Greenstone. The unit consists of mafic metavolcanic rocks, and the presence of pillowed structures indicate subaqueous deposition. In the western part of the district the Ely Greenstone is stratigraphically overlain by the Lake Vermilion Formation and, locally, the Soudan Iron-formation. In the central part of the district the Ely Greenstone is overlain by the Knife Lake Group. The Lake Vermilion Formation and the Knife Lake Group consist primarily of metasedimentary rocks, dominantly graywacke and slate, but also substantial amounts of felsic volcanoclastic rocks, local mafic flows, and some conglomerate and iron-formation (Sims, 1972). The Newton Lake Formation overlies the Knife Lake Group in the central part of the district and perhaps intertongues with it further eastward. The Newton Lake Formation consists of mixed felsic and mafic metavolcanic rocks. The eastern part of the Vermilion district, including the present area of study, is underlain mainly by the Knife Lake Group, although uncertainty exists regarding the position of the mafic metavolcanic rocks (Gruner, 1941).

The stratigraphy of the Vermilion district closely parallels other Archean volcanic-sedimentary greenstone belts of the

Canadian Shield as described by Goodwin (1968). The typical volcanic-sedimentary pile in a greenstone belt developed in three main stages. The first stage was the construction of a large (Figure 4) mafic platform by widespread effusion of predominantly tholeiitic basalt. This was followed by the eruption of dominantly calc-alkaline pyroclastics which resulted in the erection of high-rising piles upon the mafic platform. The final stage was marked by the denundation of the volcanic piles and construction of sedimentary blankets.

According to Gruner (1941) the rocks on the south side of the Saganaga batholith are clearly older than the Saganaga Tonalite itself. A mafic volcanic unit adjacent to the batholith is intruded and metamorphosed by the tonalite, and the overlying rocks are conformable with it. The presence of distinct Saganaga tonalite clasts in the conglomerate units interbedded with the tuffs and graywackes of the Knife Lake Group also suggest that unroofing and erosion occurred during Knife Lake Time (McLimans, 1972; Ojakangas, 1972b). The Vermilion granite-migmatite massif to the north of the district and the Giants Range batholith to the south were also emplaced penecontemporaneous with the Saganaga Tonalite, but were apparently not unroofed (Sims, 1972). Emplacement of all three batholiths probably occurred at shallow depths. This is indicated by: (1) narrow thermal aureoles; (2) geophysical evidence; and (3) unroofing of the Saganaga batholith.

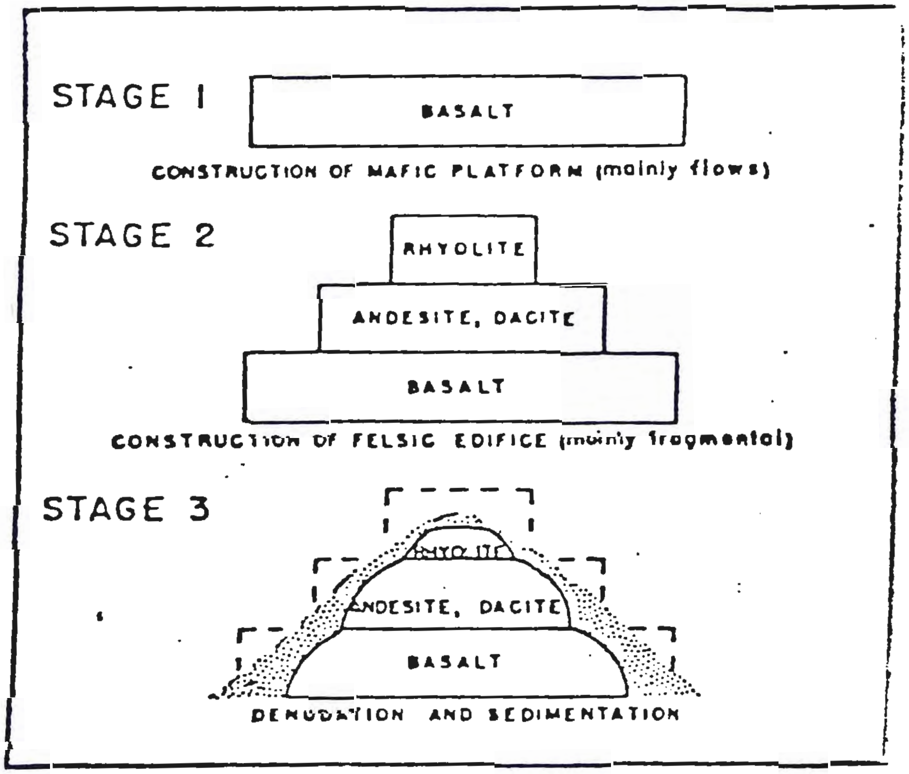


Figure 4: Evolution of an Archean volcanic-sedimentary pile (after Goodwin, 1968).

The Giants Range batholith and the volcanic and sedimentary rocks were metamorphosed during late Precambrian time by the Duluth Complex.

In the Cypress, Hanson and South Arm of Knife Lake area, the oldest rocks occur within the Knife Lake Greenstone structural segment (Gruner, 1941). This segment consists mostly of pillowed greenstones and coarser diabasic rocks although a 240 meter thickness of greenstone pebble conglomerate and graywacke is found. The Spoon Lake segment consists of a quartz porphyry and quartz porphyry conglomerate. The conglomerate is composed almost entirely of quartz porphyry or felsite fragments. This is overlain by well-bedded and banded slate and graywacke. In the Knife Lake Synclinorium segment, Amoeba Lake graywacke, slate and tuff is found. These are overlain by the Kekekabic tuff, agglomerate, slate and andesite porphyry. These in turn are overlain by Ester Lake graywacke, slate and tuff (Gruner, 1941).

Lithologies

Ely Greenstone

The Ely Greenstone was named by Van Hise and Clements (1901) from exposures at and near Ely. These include extrusive, intrusive and fragmental rocks that are various shades of green due to contained chlorite, amphibole and epidote. The name Ely Greenstone was applied by subsequent workers to include all the major bodies of greenstone in the area, especially pillowed metabasalts.

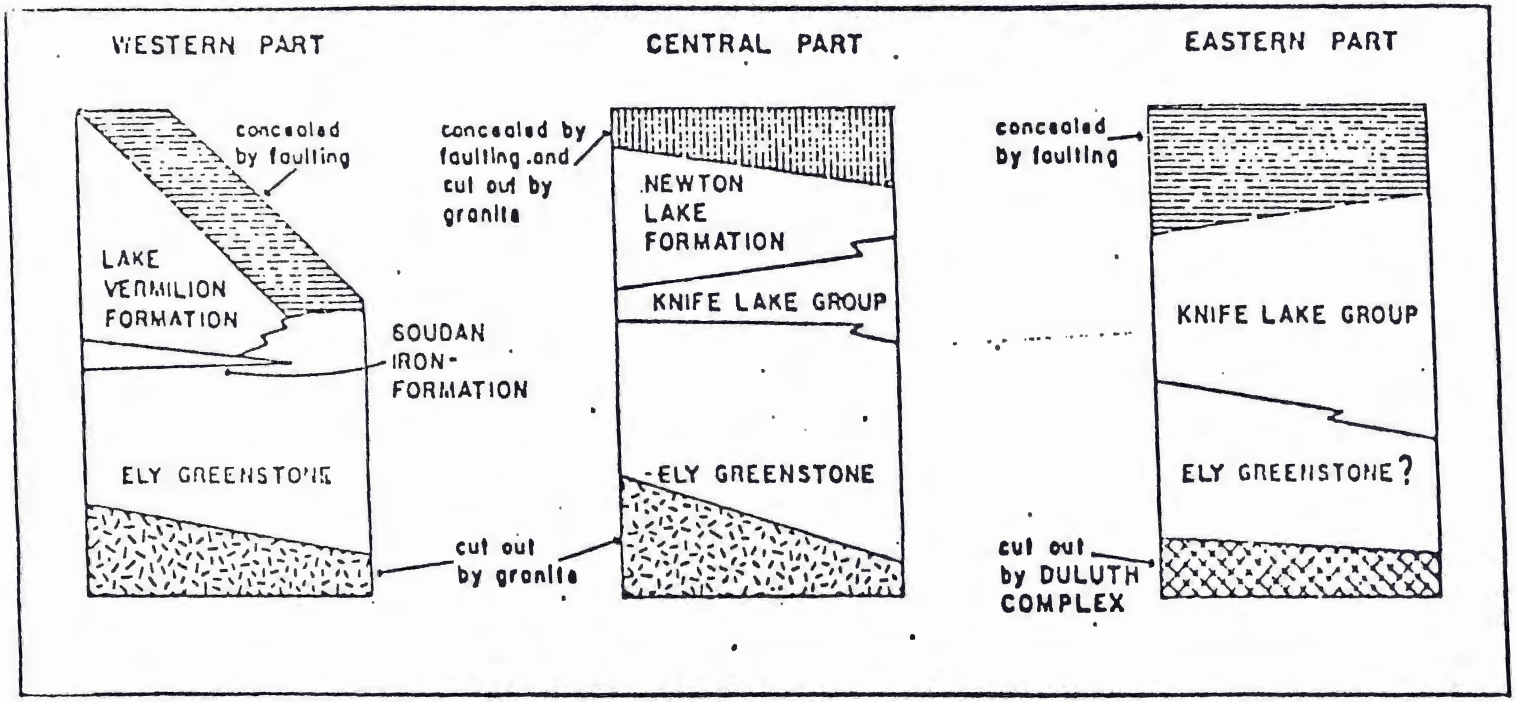


Figure 5: Principal lithologies of the Vermilion district (after Sims, 1972).

This was done regardless of stratigraphic position. The lower part of the Ely Greenstone is poorly exposed, but appears to consist mostly of metabasalt, much of which is pillowed, and metadiabase. The upper part consists of metabasaltic flows, felsic volcanic rocks, chert, banded iron-formation and metaclastic rocks. The total thickness of the Ely Greenstone exceeds 6,000 meters (Sims, 1972).

Soudan Iron-Formation

Van Hise and Clements (1901) named the Soudan Iron-formation from exposures on Soudan Hill, near the town of Soudan. It was originally presumed (Grout and others, 1951) that the distribution of banded iron-formation could be accounted for by complex folding of a single, major, continuous unit. Later work (Sims and others, 1968; Green and others, 1966) has shown that iron-formations occur at several stratigraphic positions in the greenstone belt. The Soudan consists of fine-grained ferruginous chert that is interbedded with fine-grained tuffaceous rock and rarely, mafic flows.

Knife Lake Group

The rock group known as the Knife Lake Slates were first introduced by Clements (1903). This was subsequently modified by Grout in 1926 (in Sims, 1972) to include similar-appearing rocks within the region. In 1933 Grout substituted Knife Lake Series for Knife Lake Slates. Later (Grout and others, 1951) the succession was called the Knife Lake Group.

The Knife Lake Group is composed dominantly of graywacke and other clastic rock (Ojakangas, 1972), although it contains substantial amounts of metavolcanic rock. These volcanic rocks, which are interpreted to be the products of submarine eruption, grade into clastic debris derived from them. Mafic pillowed lavas also occur sporadically (Sims, 1972).

In the central part of the Vermilion district, dacitic or andesitic tuff and tuff-breccia constitutes the dominant facies of the Knife Lake Group. In the Knife Lake area, agglomerate and conglomerate comprise a substantial portion of the stratigraphic column.

Quartz Porphyry Conglomerate Member

This member consists of quartz porphyry and quartz porphyry conglomerate derived therefrom. The exact contact between porphyry and conglomerate is difficult to determine in most places even where good outcrop is available. The conglomerate grades from a boulder conglomerate with well-rounded clasts a foot or more in diameter to an arkose (Gruner, 1941).

Well Banded Slate and Graywacke Member

This member is bedded and banded and shows considerable gradational bedding. The rocks are gray to greenish on fresh surface, brownish gray on weathered surfaces. In the South Arm of Knife Lake area, this member overlies the quartz porphyry and arkose beds (Gruner, 1941).

Ogishke Granite Pebble Conglomerate Member

This unit is located just east of Hanson Lake, and was originally called the Grant Conglomerate by Gruner (1941). This member contains all the kinds of pebbles found for the other belts, which includes granite, volcanics, jasper, green hornblendite and gray chert pebbles. Its thickness does not exceed 240 meters, and the transition to graywacke and slate is gradual.

Amoeba Lake Graywacke, Slate and Tuff Member

These sediments have been named after Amoeba Lake, where they are best exposed. They consist of well banded slate and graywacke. They also contain considerable tuffaceous material and interstratified lenses of conglomerate. Gradational bedding is common. The maximum thickness of this member is about 1,200 or 1,600 meters.

Kekekabic Tuff, Agglomerate, Slate and Andesite Porphyry Member

These sediments lie on the Amoeba Lake Member. The tuff and agglomerate of this member are green and on weathering disintegrate to a light-green sandy material consisting chiefly of hornblende. These tuffs and agglomerates surround the andesite porphyry which lies in a syncline. The andesite fragments are high in carbonates and on weathering leave hollows and unusual channeled surfaces. The gradual transition from the Amoeba Lake Member makes delineation of this member difficult.

Ester Lake Graywacke, Slate and Tuff Member

A great thickness of graywacke, slate, tuff and minor conglomerate and agglomerate lenses overlies the Kekekabic tuffs and agglomerates. The typical slates are dark gray on fresh fracture and break with conchoidal fracture. Lenses of conglomerate are numerous and may be as thick as 8 meters, although they are usually much thinner. The average pebble is less than 3 centimeters and is commonly graywacke or greenstone, although some are slate and granite.

Saganaga Batholith

The Saganaga batholith is a rather homogeneous intrusive body that has maximum surface dimensions of about 22 by 32 kilometers. It is located along the International Boundary in the vicinity of Saganaga Lake. The Saganaga batholith is a composite intrusion containing several rock types, the most common of which is a gray, medium-to coarse-grained tonalite characterized by large quartz eyes. These quartz aggregates, which resemble phenocrysts, are commonly about 1 centimeter across and have differing optical orientations. About 60% of the rock is composed of non-perthitic, unaltered, weakly zoned and poorly twinned plagioclase (An 20-28). Antiperthite is well developed in the more highly sheared parts, but otherwise constitutes a minor part. Microcline is sparse, and occurs as small, antiperthitic anhedral grains. Hornblende is the dominant ferromagnesian mineral. It forms euhedral or subhedral grains that are altered slightly to chlorite and epidote or occurs as aggregates with biotite, epidote and chlorite. Augite is minor and apatite, epidote, sphene and opaque oxides are common accessory minerals. The tonalite intrudes greenstone and gneiss on the south, north and east, and is overlain unconformably along the western margin by metaconglomerate and associated metasedimentary rocks of the Knife Lake Group (Hanson, 1972).

Duluth Complex

Anorthositic, troctolitic, gabbroic and granodioritic intrusive rocks assigned to the Upper Precambrian Duluth Complex cover about 6,250 square kilometers in northeastern Minnesota. The complex was intruded along an unconformity between overlying volcanics and underlying rocks of Early and Middle Precambrian Age. At Duluth, however, the complex is underlain and overlain by the Upper Precambrian North Shore Volcanic Group. Radiometric dating of zircons from the North Shore Volcanic Group and the Duluth Complex suggest similar ages in the range of 1-1.2 billion years old.

Glacial Deposits

Glacial drift is minor to absent in the eastern part of the Vermilion district. In the present area of study minor glacial debris is found; however, glacially polished and striated surfaces are common. A dozen measured striations had a span of N 0°E to N 30°E.

Structure

Folds

Two generations of folding and a younger generation of deformation have been recognized in the western Vermilion district (Hooper and Ojakangas, 1971). Gruner (1941) suggested at least two generations of folding in the eastern Vermilion district. Correlation of the fold age relations between the two areas is difficult. In the eastern part of the district, the folds within the metavolcanic-metasedimentary sequence trend either northwest or east to northeast. The northwest-trending generation is older, while the northeast-trending generation is younger. Many of the folds are isoclinal, while some are tight to closed. The northeast-trending folds have been collectively referred to as comprising the Knife Lake Synclinorium and are interpreted as having been folded during or after emplacement of the Saganaga batholith (Sims, 1972).

Faults

The rocks of the Vermilion district were profoundly affected by faulting. The supracrustal sequence has been cut into several separate segments by longitudinal faults that have locally cut out substantial amounts of both the upper and lower parts of the sequence. The distribution of nearby granitic bodies may be controlled by these faults. Transverse faulting within the district was of a smaller order than the longitudinal faulting and mainly produced small or moderate offsets of rock contacts (Sims, 1972). Gruner (1941) has estimated fault displacement on some of the longitudinal faults to be up to 5 kilometers horizontally and up to 3,000 meters vertically. Correlation between segments is nearly impossible due to these large displacements which commonly parallel bedding, but also due to rapid lateral facies change. The pattern of the longitudinal faults in the Vermilion district is remarkably similar to younger island arc-trench environments (Sims, 1972).

Metamorphism

The supracrustal rocks of the Vermilion district contain mineral assemblages characteristic of the greenschist facies metamorphism. Adjacent to major granite bodies and some faults, mineral assemblages characteristic of amphibolite grade metamorphism are found.

PETROLOGY

Introduction

The volcanogenic rocks of the eastern Vermilion district have only recently begun to be scrutinized in petrographic detail. The first petrography was done by Clements (1903) who summarized the petrographic and structural knowledge of the Vermilion iron-bearing district in northern Minnesota. Gruner (1941), as part of his structural analysis of part of the eastern Vermilion district gave detailed megascopic descriptions of the rocks, but included no petrography in his report. The first noteworthy petrography was done by Ojakangas (1972a, 1972b) as part of an encompassing study of the Vermilion district volcanogenic sediments. Several M.S. candidates at the University of Minnesota, Duluth, working closely with Ojakangas, have contributed petrographic information on Archean rocks as part of thesis-related problems undertaken in the Boundary Waters Canoe Area, in the eastern Vermilion district. McLimans (1971) studied four granite-bearing conglomerate units within the Knife Lake Group. Feirn (1977) studied metavolcanic and metasedimentary rocks within the Jasper Lake area. Severson (1978) studied graywacke and conglomerate units in the Ogishkemuncie Lake area. Vinje (1978) studied the volcanogenic rocks between Knife Lake and Kekekabic Lake, and Duex (pending) is studying graywackes and sediments in the Ester Lake area, which are related to the unroofing of the Saganaga batholith. These previous studies are in close proximity and generally peripheral to the present area of study, and the present study will add one more piece of information to the petrographic puzzle of the eastern Vermilion district.

The petrography presented in this paper will be divided into three major parts and a minor part, each part corresponding to one of Gruner's (1941) structural blocks. Gruner believed each of these blocks to be structurally separated from the others, and therefore distinct in itself. They will be so considered in this paper.

Problems

Poor outcrop and a lack of traceable marker beds are the major problems confronting one who studies the Archean rocks in the Boundary Waters Canoe Area in Northeastern Minnesota. The best outcrops occur along lakeshores, with the inland areas blanketed by a wide variety of flora, ranging from dense deciduous and coniferous forests to swampy herbaceous lowlands. Outcrops within the inland areas occur as isolated bedrock knobs surrounded by biota, making lithologic and stratigraphic correlations between outcrops very difficult. Field measurements of stratigraphic thicknesses are virtually impossible due to a lack of traceable marker beds. Field recognition of the various lithologies can be very difficult because the rocks of the entire eastern Vermilion district, including the present area of study, have been metamorphosed and deformed, and are frequently covered with moss or lichen.

Techniques

Field techniques used in this study of the rocks in the Cypress, Hanson and South Arm of Knife Lakes Area included: (1) outcrop location, (2) examination of outcrop to determine the lithology, (3) measurement of structural features including strikes and dips, cleavages, lineations and fold attitudes, (4) examination and measurement of sedimentary features, including graded bedding, cross-bedding, flame structures, and sole marks, and (5) detailed examination of several well-exposed graywacke units, to determine individual bed thicknesses, possible Bouma intervals in turbidite beds, and bed sequences.

Lab techniques used in this study included: (1) detailed petrographic examination of 123 selected samples, representing all the lithologies encountered. Of these, 77 were point counted to obtain modal analyses, using a minimum of 600 points per thin section. The remaining 46 thin sections were either too fine-grained or too altered to yield reliable results. (2) All 123 thin section heels were stained for both plagioclase and k-feldspar.

Operational Definitions, Igneous Rocks

Igneous rocks within the present study area were classified according to Travis' "Classification of Igneous Rocks" (1955) Figure 6.

Dacite Porphyry

Dacite porphyry is characterized by medium-to coarse-grained phenocrysts of plagioclase and quartz in a fine-grained, plagioclase-rich groundmass. The plagioclase is commonly tabular to lathy, polysynthetically twinned, rarely zoned, and moderately to strongly altered to sericite and saussurite. The quartz is commonly rounded to subrounded because of magmatic resorption. Mafic minerals are conspicuous by their absence, with opaques being minor. Modal analyses indicate a composition of approximately 15% plagioclase phenocrysts, 10% quartz phenocrysts, and 70% groundmass.

Greenstone

Greenstones are characterized by fine-to medium-grained phenocrysts, commonly plagioclase and augite, in a fine-grained dark groundmass. Alteration is moderate to severe, and only remnant ophitic textures remain. Medium-to fine-grained, subhedral augite, altered in varying degrees to epidote, is the common mafic mineral. Plagioclase is fine-to medium-grained and commonly altered to saussurite which commonly forms pseudomorphs

ESSENTIAL MINERALS	POTASH FELDSPAR 2/3 TOTAL FELDSPAR		POTASH FELDSPAR 1/3-2/3 TOTAL FELDSPAR		PLAGIOCLASE POTASH FELDSPAR 10%TOTAL FELDSPAR	2/3 TOTAL FELDSPAR POTASH FELDSPAR 10% TOTAL FELDSPAR		
						SODIC		CALCIC
	QUARTZ 10%	QUARTZ 10%	QUARTZ 10%	QUARTZ 10%	QUARTZ 10%	QUARTZ 10%	QUARTZ 10%	QUARTZ 10%
CHARACTERIZING ACCESSORY MINERALS	HORNBLENDE BIOTITE MUSCOVITE PYROXENE		HORNBLENDE BIOTITE PYROXENE		HORNBLENDE BIOTITE PYROXENE (in andesite)			PYROXENE OLIVINE
PHANERITIC	GRANITE	SYENITE	QUARTZ MONZONITE	MONZONITE	GRANODIORITE	QUARTZ DIORITE	DIORITE	GABBRO
PORPHYRITIC	RHYOLITE PORPHYRY	TRACHYTE PORPHYRY	QUARTZ LATITE PORPHYRY	LATITE PORPHYRY	DACITE PORPHYRY		ANDESITE PORPHYRY	BASALT PORPHYRY
APHANITIC	RHYOLITE	TRACHYTE	QUARTZ LATITE	LATITE	DACITE		ANDESITE	BASALT

Figure 6: Classification of Igneous rocks used in this study (after Travis, 1955).

after plagioclase. Olivine and quartz grains are rare, generally fine-grained and moderately altered. The groundmass has a dark, nearly opaque appearance, and is dominated by epidote with minor fine-grained plagioclase, saussurite, opaques and some carbonate. Opaques are minor and generally anhedral. Vein replacements are common, and consist chiefly of epidote, carbonate, and recrystallized quartz, with chlorite and serpentine. Visual estimates of greenstone compositions indicate approximately 6% augite, 4% plagioclase, 80% groundmass and 10% vein material.

Tuff

Tuff is defined as a rock formed of compacted volcanic fragments, generally smaller than 4 mm in diameter (Glossary of Geology, 1974). Tuffs within the present area of study are characterized by medium-grained, subhedral, occasionally twinned and rarely zoned augite, hornblende, and minor plagioclase in an aphanitic groundmass composed of chlorite, epidote, hornblende, plagioclase, augite and quartz. Remnant ghosts of shards are present but not common within the matrix. Tuffs within the present area of study should correctly be called crystal tuffs. Modal analyses indicate a composition of approximately 20% augite crystals, 10% hornblende crystals, 5% plagioclase crystals, and 65% chlorite matrix.

Keweenawan Diabasic Dikes

Diabasic dikes, fine-to medium-grained, holocrystalline, hypidiomorphic, and ophitic with a felty groundmass, are found within the present area of study, and are petrographically distinct because they are remarkably fresh. Slightly altered lathy plagioclase is the dominant mineral, with moderately altered anhedral augite being common. The groundmass is composed of fine-grained plagioclase, augite, epidote, calcite, opaques and saussurite. Modal analyses indicate a composition of approximately 50% plagioclase, 35% augite and 15% groundmass.

Igneous Clasts

Several igneous lithologies are found within the present area of study, not as separate units, but as clasts in other units.

Hornblende Andesite

Hornblende andesite is a common clast within several units. The hornblende andesite is characterized by euhedral, medium-grained hornblende phenocrysts and fine-grained polysynthetically twinned lathy plagioclase in an aphanitic felty plagioclase groundmass. Quartz is absent. Visual estimation indicates a composition of approximately 10% hornblende, 20% plagioclase and 70% groundmass.

Augite Andesite

Augite andesite is a common clast within the tuffs and conglomerates, and is characterized by unaltered, euhedral, medium-to coarse-grained augite phenocrysts and fine-grained lathy plagioclase in an aphanitic groundmass. Visual estimations indicate a composition of approximately 10% augite, 10% plagioclase and 80% groundmass.

Lamprophyre

Lamprophyre is defined as a dark colored, porphyritic, hypabyssal igneous rock characterized by a panidiomorphic texture and mafic phenocrysts in an aphanitic groundmass composed of mafic minerals and feldspars (Glossary of Geology, 1974). One clast of lamprophyre approximately 5 mm in diameter was found within a conglomerate unit, and is characterized by kelly-green pyroxene phenocrysts and a fine-grained groundmass which includes sodium and potassium feldspars.

Mafic Volcanic Rock Fragments (MVRF)

The term MVRF as used in this study includes undifferentiated clasts of mafic composition. Greenstone is the dominant MVRF, diabasic clasts are common, and gabbroic clasts are rare.

Sedimentary Rocks

The sedimentary rock classification scheme used in this paper is based on Travis' "Classification of Sedimentary Rocks" (1955), with additional classification, particularly of the graywackes, according to Pettijohn's (1957) classification of sandstones.

Conglomerate

Conglomerate is defined as a sedimentary rock which contains rounded clasts greater than 2 mm in diameter. Within the present area of study, conglomerate clasts range from very coarse sand size (2 mm) to boulder size. The average clast size is about 1.0 cm. Common clasts include dacite, andesite, MVRF and sedimentary rock fragments.

Feldspathic Graywackes

Feldspathic graywackes are defined as sedimentary rocks which contain sedimentary rock particles 0.06 mm to 2 mm in diameter, a minimum of 15% clay matrix, and a dominance of feldspar clasts over rock fragments (Pettijohn, 1957). Most graywackes within the present area of study are feldspathic graywackes. Modal analyses indicate that several of the graywackes should correctly be called lithic graywackes, while others may fall into the category of subgraywackes. However, lithic graywackes and subgraywackes are minor, and in this paper will be included with the feldspathic graywackes. Components (Framework grains >0.03 mm) found within the graywackes include dacite, andesite, MVRF, sedimentary rock fragments, plagioclase, hornblende, quartz and minor epidote, chlorite and carbonate. The matrix consists of dark interstitial material made up of chlorite, epidote, sericite and minute particles of quartz, plagioclase, hornblende and rock fragments.

Argillite

Argillite is defined as a compact, indurated rock, derived from mudstone, claystone, siltstone, or shale. Argillite within the present area of study is characterized by fine-grained quartz, plagioclase, hornblende and epidote in a dark muddy matrix. The argillites have been metamorphosed to varying degrees, and are frequently interbedded with the graywackes.

Sedimentary Rock Fragments (SRF)

SRF as used in this study includes undifferentiated clasts of sedimentary origin with a grain size of less than 0.05 mm, including siltstone, mudstone, and claystone. Many of the SRF's may have been formed by the gouging of the previously deposited fine-grained sediments. The grain size is too fine to permit modal analyses.

Mineral Components

Components found in the petrographic study of the sedimentary rocks include the previously described rock fragments and mineral grains which include:

Volcanic Quartz:	Clear unit grain characterized by sharp extinction, commonly euhedral or embayed, some rounded due to magmatic resorption and is common in the study area.
Common Quartz:	Clear monocrystalline grains, characterized by lack of sharp extinction and anhedral crystal form. Much of the common quartz is probably volcanic based on other provenance indicators, but is not classified as such because it lacks the definitive criteria of volcanic quartz.

Vein Quartz:	Polycrystalline quartz characterized by multiple extinction, anhedral, fine-grained, and most frequently found in replacement veins.
Plagioclase:	Tabular to lathy grains, moderately to highly altered to sericite and saussurite, commonly polysynthetically twinned and rarely zoned. Most plagioclase is similar to the plagioclase found in the volcanic rock fragments.
Orthoclase:	Rare component within the present area of study; very fine-grained, and detected mostly by staining for potassium using sodium-cobaltinitrate.
Hornblende:	Euhedral to subhedral grains, moderately to highly altered, pleochroic yellow to green to brown, and rarely with oxidized rims.
Augite:	Euhedral to subhedral grains, occasionally twinned and rarely zoned, moderately altered to epidote.
Chlorite:	Spotty alteration of hornblende; common in matrix, less common in veins, pleochroic in greens.
Epidote:	Dark colored alteration of mafic minerals; common in matrix, less common in veins.
Carbonate:	Fine-grained replacement in matrix and fine-grained rhombs in veins.
Saussurite:	Fine-grained alteration of calcic plagioclase consisting of epidote, sericite, and calcite.

Sericite:	Fine-grained muscovite, formed by the alteration of plagioclase, characterized by minute clear, high birefringent grains.
Opaques:	Commonly amorphous blebs of pyrite, but euhedral cubes of pyrite and magnetite are also common.
Matrix:	Aphanitic interstitial material, less than 0.03 mm in diameter, including fine-grained quartz, plagioclase, hornblende, epidote, chlorite, sericite, and carbonate.

Metamorphic Rocks

The rocks within the Cypress, Hanson and South Arm of Knife Lakes Area are all metamorphosed to varying degrees, and to simplify the presentation, the prefix "meta" will be omitted from this paper with the preceding understanding.

Petrology of the Spoon Lake Segment

The Spoon Lake segment is a knife-blade shaped area which comprises approximately 5 square kilometers of area in the south-southwest section of the present study area (Figure 2). It is broadest as it encompasses the westernmost extension of the South Arm of Knife Lake, and tapers to a point near Pitfall Lake. The northern boundary of this segment is a major longitudinal fault that separates the Spoon Lake segment from the Knife Lake Greenstone segment. The southern boundary is a major longitudinal fault that separates the Spoon Lake segment from the Kekekabic Lake segment (Gruner, 1941).

Dacite porphyry is the oldest unit with the possible exception of some pillowed greenstones within this segment. The dominant lithologies are conglomerates and graywackes in part derived from the dacite porphyry. In the southwest corner of the study area, small outcrops of pillowed greenstones lie in close proximity to the dacite porphyry conglomerate. The type of contact between the two units is unknown, but the sheared nature of the greenstones and the conglomerates suggest a fault contact. No age correlation between the two units is possible. Keweenawan diabasic dikes intrude both the igneous and the sedimentary rocks.

Structural measurements taken within this segment indicate a northeast trend and a steep, often slightly overturned, dip to the southeast. A total of 37 thin sections from this segment were studied.

Description of Rock Types

Dacite Porphyry

The dacite porphyry is white to brownish-orange on weathered surface, with much of the limonitic staining resulting from the oxidation of pyrite. On fresh surfaces, the rocks are light green in color and contain up to 2%, by visual estimation, of unaltered pyrite. Distinctive rounded gray to white quartz phenocrysts up to 0.5 cm in diameter are common, and often protrude slightly as the result of differential weathering.

A total of 6 thin sections was used for petrographic study of the dacite porphyry, including one thin section taken from a large boulder of dacite porphyry found within a dacite porphyry conglomerate. Table 1 is a summary of the modal analyses.

Microscopically, the dacite is holocrystalline, hypidiomorphic, porphyritic, medium-to coarse-grained (average 3 mm to 0.5 cm) with a granular groundmass (Figure 7). Plagioclase, the dominant phenocryst, is equant to lathy, polysynthetically twinned and moderately to highly altered to sericite and rarely to saussurite. Unaltered rounded unit volcanic quartz phenocrysts formed by magmatic resorption, are common, and up to 0.5 cm in diameter. The groundmass is composed of aphanitic plagioclase, quartz and amorphous alteration products including sericite, calcite and saussurite. Opaques are mostly pyrite, and occur as euhedral cubes and as amorphous grains. Veining is ubiquitous, and vein minerals include calcite, recrystallized quartz and epidote. Of the 6 thin sections, 5 were moderately to highly sheared. Shearing no doubt facilitated the alteration of the plagioclase, broke the quartz phenocrysts, added to the formation of the groundmass, and was responsible for much of the veining.

Dacite Porphyry Conglomerate

Dacite porphyry conglomerate is the dominant lithology of the Spoon Lake segment (Figure 8). Megascopically, the unit is very similar to the dacite porphyry, and differentiation between

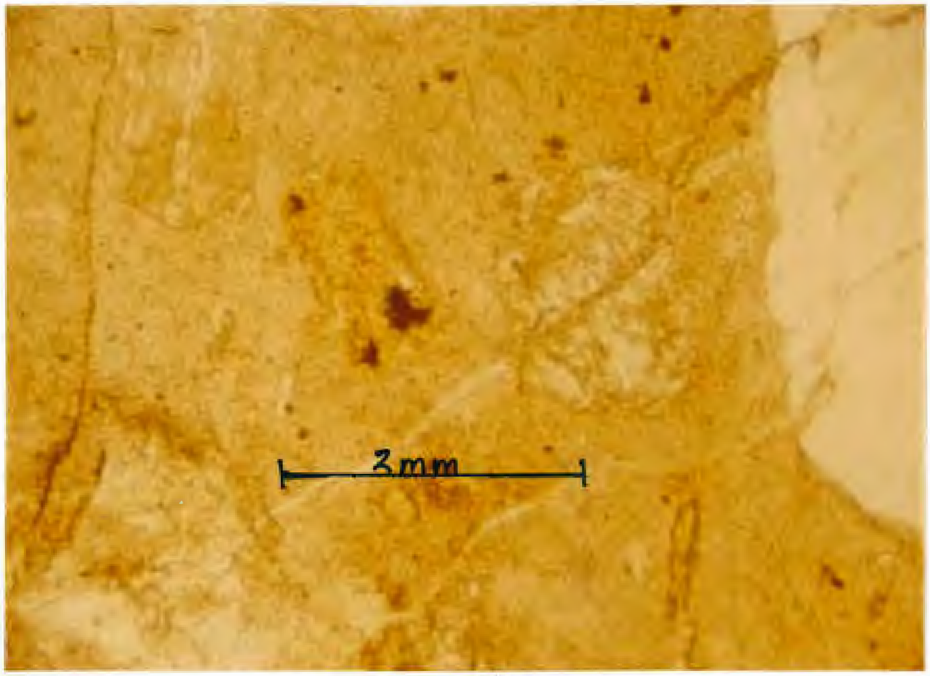


Figure 7: Photomicrograph of dacite porphyry (one polar) from the South Arm of Knife Lake. Large fragment at left is rounded quartz phenocryst. Note altered plagioclase in center.

Table 1--Modal Analyses of Dacite Porphyry From Spoon Lake Segment

	1	2	3	4	5	6
Volcanic quartz	1.3	1.2	1.6	4.7	2	1.2
Plagioclase	18.8	31.2	19	15.2	20.3	17.1
Epidote	7.8		.5	.8	1	
Carbonate	2	2.2	.7	2.3	4.7	
Sericite	6.8	2	3.8	8.7	2	
Vein Quartz	4	6.8	4.3	3.8	5.3	12.3
Opaques	.5	.2	.5	.3	.7	2
Groundmass	58.7	56.5	69.5	64.2	64	67
Others						* .3

*Zircon

Figure 8: Dacite porphyry conglomerate from the South Arm of Knife Lake, southeast of the portage to Hanson Lake.

the two is quite difficult. The contact between the two is impossible to determine and may be grussic in nature. On fresh surfaces the rock is light green with abundant pyrite. Clast recognition on fresh surfaces is difficult in most instances. Grain size ranges from coarse-sand (0.6 mm in diameter) up to boulders (up to 0.5 m in diameter). Clasts are mostly subrounded to rounded and rarely angular. Bedding thicknesses range from a few centimeters, where bedding attitudes are easily recognized, to massive with no ascertainable attitudes. Graded bedding and other sedimentary features are infrequent.

A total of 17 thin sections of the dacite porphyry conglomerate was petrographically studied, with 15 of the slides being point counted. A summary of the modal analyses is shown in Table 2. Microscopically, the dacite porphyry conglomerate is moderately to poorly sorted, with no grading evident. Clasts are mostly subrounded to rounded and consist dominantly of dacite porphyry or plagioclase and quartz derived therefrom. Quartz clasts are mostly volcanic quartz and rarely common quartz. Plagioclase is commonly tabular to lathy, polysynthetically twinned, occasionally zoned and partially or completely altered to sericite. Sericitic pseudomorphs may be locally abundant. Matrix is composed of fine-grained quartz, plagioclase, carbonate, sericite, epidote and opaques. Opaques are cubic to amorphous and are mostly pyrite.

Table 2--Dacite Porphyry Conglomerate Modes from Spoon Lake Segment

	1	2	3	4	5	6	7
Volcanic Quartz	2.2	6.8	1	7.7	4.3	11.6	10.7
Common Quartz	1.2	1.8	.2	3.7	.3	3.7	2.2
Plagioclase	6	8.7	.3	51.3	30.9	45.7	43.0
Rock Fragments							
Dacite Porphyry	74.3	48.5	31.7	17.1	48	13.8	28
Andesite	3						2.7
Carbonate			2.5	.3	.8		2.8
Sericite	4.2	5.7	16.3	7.7	6.3	11.5	2.2
Vein Quartz	.83	1.5		.16			.5
Opaques	.3	1.2	.5	.2	.3	.5	
Matrix	6.8	21.7	39.5	8.8	8.2	10.3	5.8
Others		*4.2		+.2			*.3

*Zeolite found in veins and veinlets
+ Clastic dike
@ Zircon

Table 2--Dacite Porphyry Conglomerate Modes from Spoon Lake Segment (cont.)

	8	9	10	11	12	13	14
Volcanic Quartz	3.3	6.6	7.7	7.8	.6	1.2	2
Common Quartz	4.8	.8	.3	5	7	12.3	.7
Plagioclase	34.1	42.5	40.8	22.5	9.2		25.8
Rock Fragments							
Dacite Porphyry	28.2	26.7	46	34.2	58.3		62.7
Andesite							
Carbonate	1.5			.2	.8		.3
Sericite	9	12	1.8	3	3.8		1.2
Vein Quartz							
Opaques	.3	.3	.3	.7	.5	2.3	.5
Matrix	12	11	3	12	10.2	84	6.3
Others				+12.3		@.3	

*Zeolite found in veins and veinlets
+ Clastic dike
@ Zircon

Anomalous occurrences noted within the dacite porphyry conglomerate include aphanitic volcanic rock fragments found in 2 thin sections from the northwest corner of the segment, and a fine-grained, dark, highly epidotized and silicified clastic dike approximately 3 cm wide, from the central part of the segment.

Feldspathic Graywackes and Argillites

A minor part of the sedimentary strata found within the Spoon Lake segment consists of graywackes and well-banded argillites. These lithologies are found interbedded with and gradational into the dacite porphyry conglomerate. Many sedimentary structures, useful for structural interpretation and provenance determination, are found within this unit, including graded bedding, flame structures and "Bouma sequences" (Figure 9).

Megascopically, the graywackes are fine-to medium-grained with bedding thicknesses that range from approximately 1 cm to 10 cm, and average about 3 cm. Many of the beds are continuous and consistent over considerable distances across outcrop. One such bed extended for a minimum of 20 m. Many of the graywacke beds are graded, with grading usually from medium-to fine-grained. The graywackes are light gray to dark gray on weathered surfaces, often with an orangish-brown limonite coating caused by the alteration of ferruginous minerals, notably pyrite. They are dark gray to black on fresh surfaces.

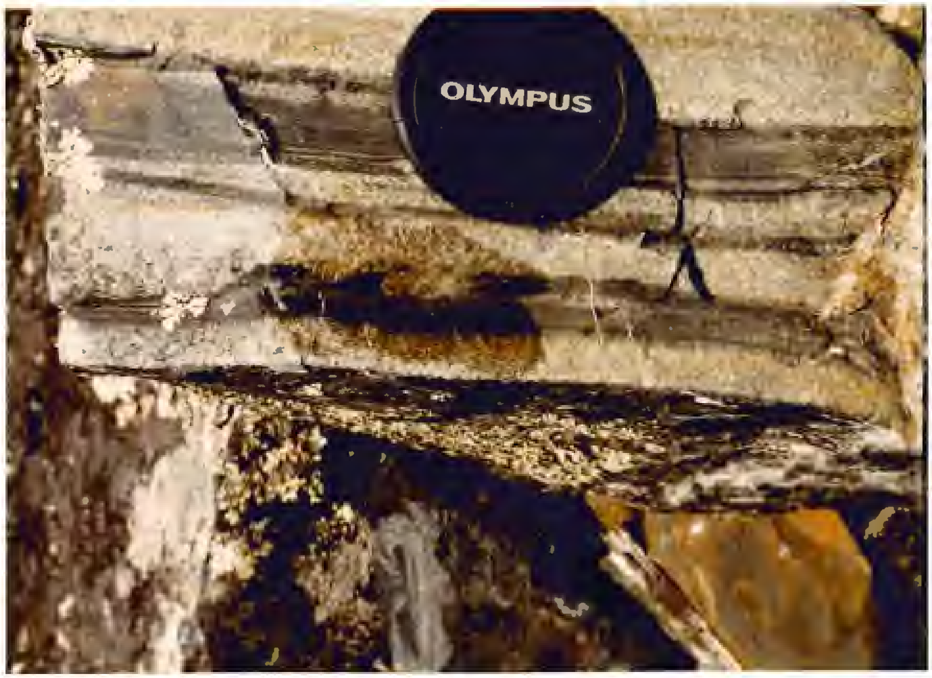


Figure 9: Flame structure in graywacke-argillite sequence from the narrows in the South Arm of Knife Lake.

Argillites are interbedded with the graywackes, have a very fine grain size, and do not exhibit slaty cleavage. On weathered surfaces the argillites are light gray to white, with orangish-brown ferruginous beds being common and locally abundant. Fresh surfaces are commonly black. These argillites are interbedded with the graywackes and have bedding thicknesses that range from 1 cm to 3 cm, with an average thickness of 1.5 cm.

A total of 8 thin sections of graywackes and argillites was examined, with 6 of the slides being point counted to obtain modal analyses (Table 3). When choosing samples of graywackes and argillites for microscopic study, the author selectively chose coarser grained samples, both in the field and in the lab, reasoning that coarse-grained material would yield a greater quantity of useful information.

In thin section, the graywackes consist of subrounded to subangular grains of plagioclase, dacite porphyry and SRF's in an aphanitic matrix of plagioclase, quartz, chlorite, epidote and sericite. Feldspar in an abundance of matrix indicates that most of the graywackes should correctly be called feldspathic graywackes, although lithic graywackes were noted. Grain size ranges from 0.5 mm to 1.0 mm, and many of the beds are beautifully graded. Plagioclase, the dominant grain, is tabular to lathy, polysynthetically twinned and moderately altered to sericite. This plagioclase is similar to the plagioclase found in

Table 3--Modal Analyses of Feldspathic and Lithic Graywackes From the Spoon Lake Segment

	1	2	3	4	5	6
Volcanic Quartz	6.8	5.5	6.8	3.0	8.6	13.7
Common Quartz	1.7	3.0	1.8	.7	.6	.7
Plagioclase	6.5	7.8	11.8	15.8	32.8	24
Rock Fragments						
Dacite	6.7	6.3	3.3	47.2	5.4	10.5
SRF	.2	1	6		7	18.3
Rock Fragment Totals	6.9	7.3	9.3	47.2	12.4	28.8
Epidote	.5	7.2	1.7	4.8	3.4	.5
Carbonate	1.5		2	1.8	1.2	.5
Sericite	1.5	1.8	1.2	1.8	1.2	.5
Vein Quartz		.8	1	1	.4	.2
Opaques	1	.3	2.7	1	2.6	1.3
Matrix	73.3	64.9	60.6	22.5	26.8	28.5
Chlorite	.5	.6	.83	.3	.6	.2
Others		*.83			#6.4	

*Actinolite
#MVRF

the dacite porphyry, and is probably derived therefrom. Dacite porphyry clasts are common, fine-grained and unaltered. Quartz is minor, mostly volcanic, rarely common. The matrix consists of a fine-grained mesh (<0.2 mm) of quartz, plagioclase, dacite porphyry rock fragments, epidote, sericite, and carbonate. Vein quartz is minor. Opaques are minor and mostly anhedral.

Microscopically, the argillites are fine-grained (<0.2 mm) with few identifiable grains. Sorting is good.

Greenstone

Two narrow belts of greenstone, one of which is pillowed, are located in the study area. Clements (1903) originally mapped these outcrops as Keweenawan diabase, while Gruner (1941) described them as greenstone. In this paper, the unit is considered to be metabasalt or meta-andesite. No plagioclase determination could be made due to the highly altered nature of the plagioclase, hence the distinction between basalt and andesite could not be made. The contact between the greenstone and the dacite porphyry conglomerate is obscured by the vegetation, but the sheared nature of both rock types, the close proximity to a major longitudinal fault, and the absence of other greenstones in the segment suggest a fault contact, perhaps a small peripheral fault related to the major longitudinal fault. The greenstone may be a fault slice.

Megascopically, the greenstone contains ellipsoidal pillows (as much as 0.5 m in diameter), is dark brown to orangish-brown on weathered surfaces and dark green on fresh surfaces. The grain size is fine, although coarse trachytic plagioclase laths (as large as 1 cm) are locally abundant. Slickensides and polished fracture surfaces are common in the central portion of the outcrop, and ubiquitous along its margins.

Three thin sections were studied, but due to the highly sheared nature of the rocks, none were point counted to obtain modal analyses. Microscopically, the greenstone is hypidiomorphic and fine-to medium-grained (1 mm to 5 mm) with occasional very coarse-grained (up to 1 cm) plagioclase laths in a felty groundmass. The rock is highly sheared and highly altered, and only a remnant ophitic texture remains. The trachytic texture displayed by the coarser grained plagioclase laths in hand sample is not seen in thin section. Epidote, saussurite and chlorite are the major mineral components (up to 60%) and are associated with the severe alteration suffered by the pyroxenes, amphiboles and plagioclase. Plagioclase is highly altered, and makes up 20% of the rock. Pyroxene and amphibole are highly altered, not easily distinguished, and relatively minor. Groundmass consists of fine-grained epidote, saussurite, chlorite, opaques, carbonate and plagioclase, and makes up 15% of the rock. The remaining 5% of the rock consists of quartz veins, the result of later solutions, bladed actinolite found associated with the alteration of pyroxene, and volcanic rock fragments which resemble chert and are probably xenoliths.

Keweenawan Diabase Dikes

Several diabasic dikes believed to be Keweenawan in age (personal communication, J. C. Green, 1980) cut the dacite porphyry conglomerate and the graywacke-argillites within the present study area (Figure 10). The dikes range from a minimum of 3 m thick to a maximum of 10 m, with unknown lengths due to obscuring vegetation. The rocks are dark brown on weathered surfaces and almost black on broken surfaces. The grain size is medium to fine, and no texture is visible.

Four thin sections were examined, with 3 of these being point counted. Table 4 is a summary of their modal analyses.

In thin section, the dikes are holocrystalline, hypidiomorphic and ophitic with a felty groundmass (Figure 11). The grain size is fine (0.75 mm to 2 mm) and the rock is relatively fresh. Lathy plagioclase is the dominant mineral and is slightly altered and mostly anhedral. The groundmass consists of fine-grained plagioclase, augite, epidote, sericite, chlorite, carbonate and opaques. Two thin sections studied contained bladed actinolite, found in rounded pockets associated with chlorite and carbonate. These rounded pockets may be vesicles, and indicate a shallow emplacement for the dikes. One small dike contained numerous xenoliths of dacite porphyry and graywacke.

Figure 10: Photograph of contact between Keweenawan diabasic dike and dacite porphyry conglomerate from South Arm of Knife Lake.

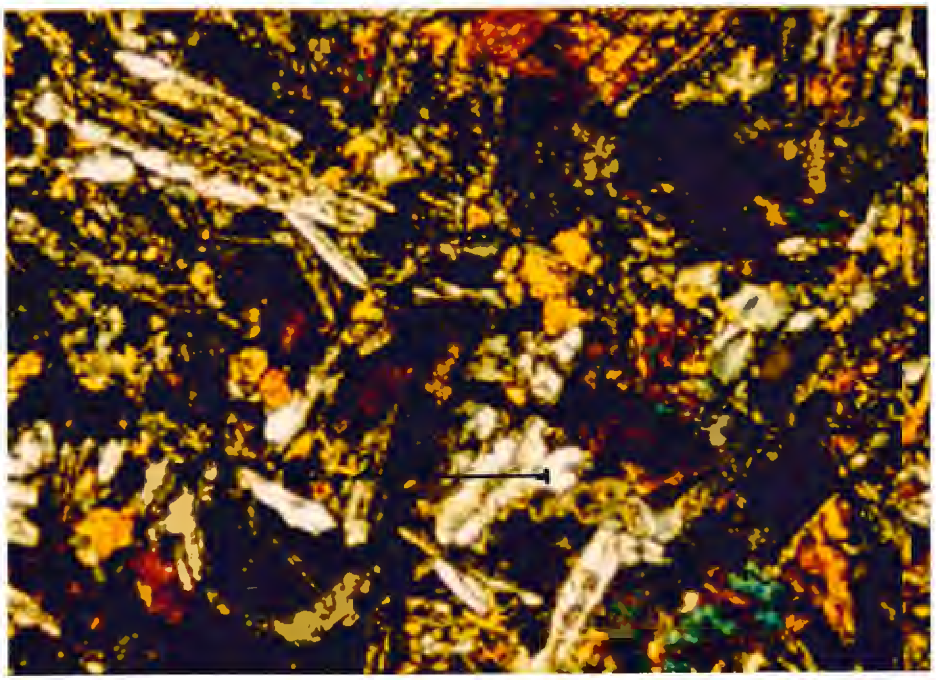


Figure 11: Photomicrograph of Keweenawan diabasic dike (crossed polars) from South Arm of Knife Lake.

Table 4--Modal Analyses of Keweenawan Diabasic Dikes From Spoon Lake Segment

	1	2	3
Plagioclase	46.8	48.3	48.7
Augite	35.8	34.5	.5
Hornblende		.5	
Chlorite	6.3	3.8	.7
Epidote	.3	.2	
Carbonate	1	2.8	.3
Sericite	1.3	.5	.3
Saussurite	.7		
Opaques	6.0	8.3	7.7
Groundmass	1.6	1	41.8

Knife Lake Greenstone Segment

The Knife Lake Greenstone segment consists of a narrow belt of greenstone and sedimentary rocks, and comprises approximately 5 square kilometers in the eastern and central parts of the study area (Figure 2). This segment is separated from the Spoon Lake segment on the south by a major northeast-trending longitudinal fault, and from the Knife Lake Synclinorium segment to the north by another northeast-trending longitudinal fault (Gruner, 1941).

Greenstone is the dominant lithology of this segment, and Gruner (1941) mapped this area as Ely Greenstone. Texturally and compositionally the Ely Greenstone and the greenstones of this segment may be similar, but no direct correlation with the Ely Greenstone type section in Ely, Minnesota, is possible. Overlying the greenstone and containing abundant clasts of greenstone, is a greenstone pebble conglomerate. This is a small unit and grades laterally into graywackes. A total of 28 thin sections from the Knife Lake Greenstone segment was studied.

Description of Rock Types

Greenstone

Greenstone is the oldest and the dominant unit found within this segment. Gruner (1941) implies from his mapping that these greenstones are also the oldest rocks located within the present area of study. Megascopically, the rocks are brownish-orange on weathered surfaces, dark green on fresh surfaces, are occasionally pillowed and infrequently contain spherulites (Figure 12). Weathered surfaces are commonly rough and pitted, resulting from the differential weathering of mafic minerals. Overall, the rocks are more resistant to weathering than surrounding sedimentary rocks, and often form prominent ridges. The grain size is fine, rarely medium and megascopic identification of individual crystals is impossible, with the exception of rare, coarse-grained plagioclase laths. Greenstone breccias and conglomerates are found infrequently and may be the result of shearing or explosion-implosion of ellipsoidal pillows.

Twenty-one thin sections from the greenstone unit were examined, and all were found to be mostly fine-grained, and subject to varying degrees of shearing, alteration and metamorphism (Figures 13 and 14). Point counting to obtain modal analyses was considered hopeless. Additionally, exact compositional determination is impossible because no plagioclase compositions could be obtained; therefore, the greenstone may be either andesitic or basaltic in composition.

In thin section, the greenstones are fine-grained (average crystal size 1 mm), occasionally medium-grained (average crystal size 1-5 mm), and rarely coarse-grained, with the notable exception of one sample in which broken augite phenocrysts 9-11 mm long were observed. Original textures have been mostly obliterated, but remnant ophitic textures were observed in several slides, and

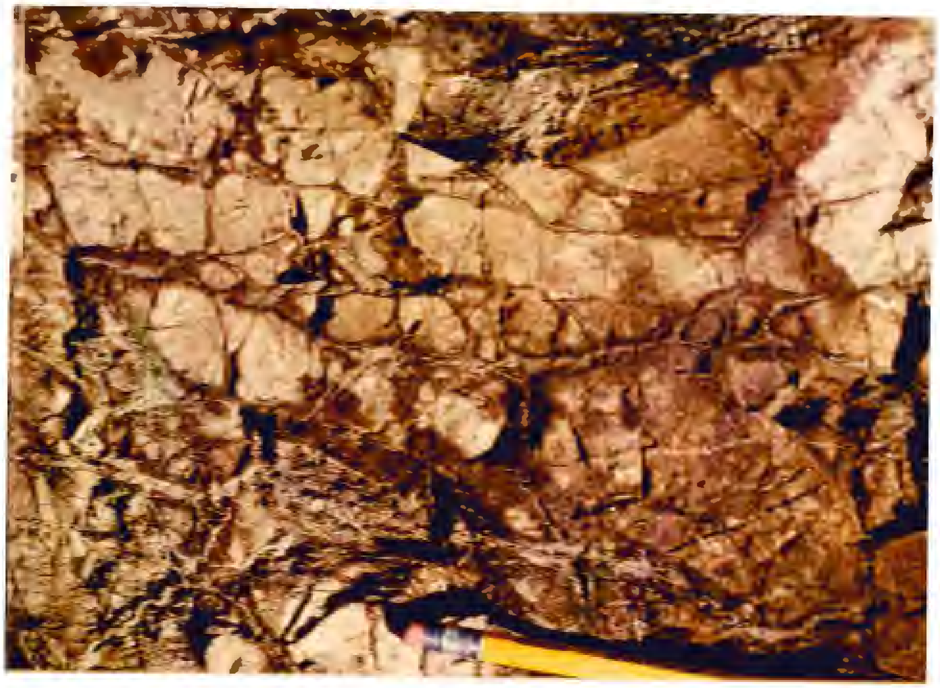


Figure 12: Sheared greenstone showing pillowed ellipsoids with rinds located west of the portage between the South Arm of Knife Lake and Hanson Lake.

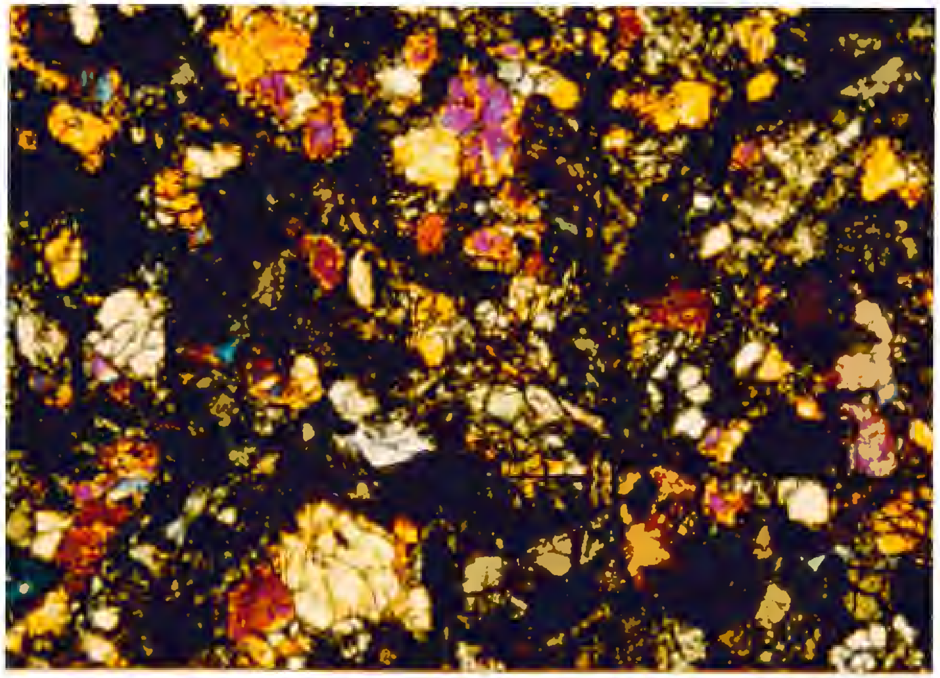


Figure 13: Photomicrograph of greenstone (crossed polars) located west of the portage between the South Arm of Knife Lake and Hanson Lake.

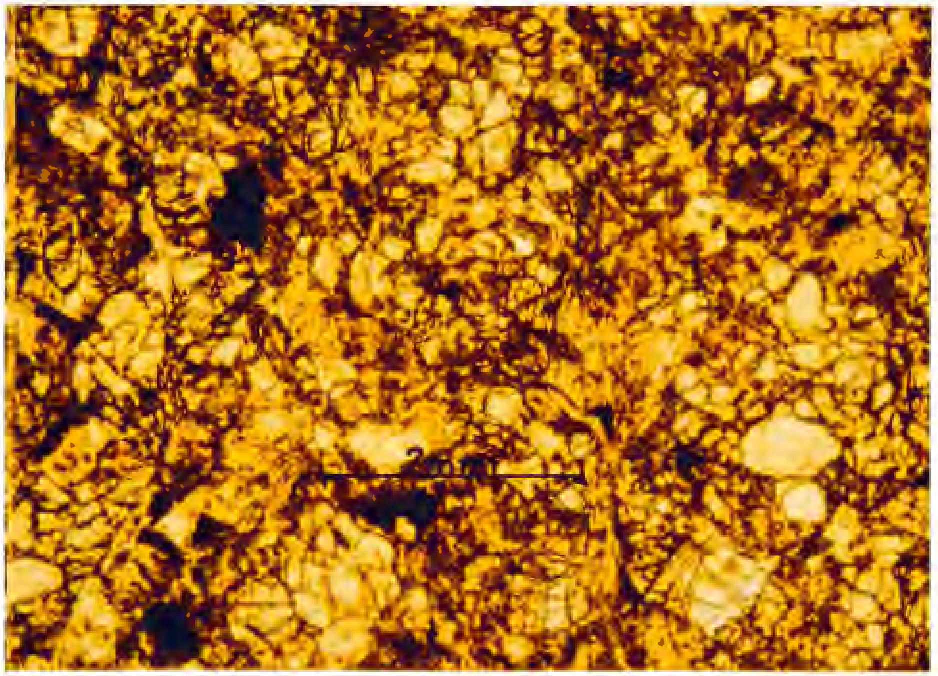


Figure 14: Photomicrograph of greenstone (one polar) located west of the portage between the South Arm of Knife Lake and Hanson Lake.

a trachytic texture was observed in one. Surviving grains are commonly allotrimorphic and rarely hypidiomorphic. The groundmass is fine-grained (<1 mm) and amorphous, occasionally felty in fresher samples. Augite is the dominant phenocryst, averaging 5-8% by visual estimation, up to 15-17% by visual estimation in one slide. The augite is commonly medium-grained, anhedral, and highly altered to epidote and opaques, and rarely hornblende. Plagioclase is common, averaging 3-5% in thin section, rarely exceeding 10%, is lathy to tabular, and highly altered to saussurite, sericite and carbonate. Hornblende is minor, does not average more than 2% in any thin section, and is mostly formed from the alteration of augite. Olivine is a rare phenocryst found in three thin sections, and quartz, as an even rarer phenocryst or inclusion, is found in two of the thin sections. The fine groundmass averages 60-70%, and in one sample, 99%. Epidote is the main component of the groundmass, and often imparts a dark, nearly opaque, appearance. Chlorite, saussurite and calcite are common in the groundmass, with fine-grained augite, hornblende and plagioclase being minor. Veins and veinlets are common within the greenstones, averaging 5-10% but are as abundant as 45-50% in some thin sections. Epidote, calcite and polycrystalline quartz are the most common vein minerals, but chlorite and serpentine have been noted. The presence of serpentine suggests some hydrothermal fluids may have acted upon the greenstones. Opaques are common in small amounts, averaging 1%, are anhedral to cubic and are mostly magnetite formed by primary differentiation from the melt, and the alteration of augite. Some of the opaques may be ilmenite or pyrite.

Interesting occurrences within the greenstones include fine- to medium-grained rounded vesicles, filled with actinolite, chlorite and carbonate, spherulites up to 10 mm, and greenstone breccia fragments capable of being fitted back together to form rounded fragments.

Greenstone Pebble Conglomerate

A small lens of greenstone pebble conglomerate occurs north of the greenstones and immediately east of Hanson Lake within the present study area. Gruner (1941) originally mapped this unit as a granite pebble conglomerate. The author was unable to determine any potassium feldspar in hand sample, thin section or by staining and concluded that granite pebbles do not occur within this unit.

Clasts within the conglomerate are well-rounded, moderately sorted, and pebble to cobble sized (Figure 15). Bedding is massive, but preferred orientations of elongate clasts are compatible with bedding attitudes taken from the graywackes within the segment. Six clast types were recognized in hand sample, including chert, mudchips (SRF), amygdaloidal basalt, basalt, and dacite. The conglomerate is interbedded with gray-

Figure 15: Greenstone pebble conglomerate located east of Hanson Lake.

wackes and grades laterally into them. Pyrite is common and upon weathering imparts an orange coating of limonite on the unit. The contact between the greenstone and the conglomerate was not seen in the field; however, this conglomerate contains a dominance of greenstone clasts, is in close proximity to the greenstone, and appears to grade laterally into graywackes, suggesting the possibility that this is a basal conglomerate which overlies the greenstone.

A total of 3 thin sections was used for the petrographic study of the conglomerates. Modal analyses are summarized in Table 5. Modal analyses of the greenstone pebble conglomerate, however, should not be regarded as being quantitatively representative of the unit, as the average clast size ranges from 65 mm up to 30 cm, allowing for considerable bias in any one thin section. Reliable quantitative representation would require many additional modal analyses.

In thin section, the conglomerate is composed dominantly of well rounded greenstone and dacite clasts in a fine-grained matrix. Grain size is very coarse, up to 3 cm, and no grading or sorting is evident. The greenstone clasts are petrographically very similar to the previously described greenstones, are in close proximity and probably derived therefrom. Clasts of medium to coarse-grained greenstones were denoted as diabasic in the modal analyses to reflect textural differences, while greenstone

Table 5--Modal Analyses of Greenstone Pebble Conglomerate From Knife Lake Greenstone Segment

	1	2	3
Volcanic Quartz			2
Common Quartz	4.1		2
Rock Fragments			
Greenstone	75.2	25.3	63.2
Dacite	5.2	23.7	13.9
SRF	.5	.7	
MVRF	1.2	11.5	
Diabase	6	19.5	13.8
Rock Fragment Totals	88.1	80.7	90.9
Epidote		2.2	.3
Carbonate		.5	.8
Sericite		.3	
Opaques	.5	.2	
Matrix	7.3	16	4
Others		*.2	

*Hornblende

clasts comprised dominantly of epidote were denoted as highly altered mafic rock fragments. Clasts of dacite rock fragments are common within this unit, and are composed of medium-grained, polysynthetically twinned, zoned, unaltered plagioclase, medium-grained, volcanic quartz, and minor fine-grained euhedral hornblende, all in a fine-grained quartz-feldspar groundmass. SRF are minor and consist of fine-grained mudchips. Brecciated mafic rock fragments occur in one thin section only, and consist of highly altered angular fragments in a fine-grained groundmass. The matrix is very fine-grained, and consists of epidote, carbonate, sericite, opaques and rock fragments.

Feldspathic Graywackes and Argillites

Graywackes and fine-grained interbedded argillites, are prominent lithologies in the northern part of the Knife Lake Greenstone segment. Megascopically, the graywackes are light gray to dark gray on weathered surface, and dark gray on broken surfaces. The grain size is fine to medium, and bedding thickness ranges from approximately 0.5 cm to 8 cm, with the average thickness being about 3 cm. Graywacke beds are commonly graded, and indicate a topping direction to the east. Other sedimentary structures are absent. Argillites are interbedded with the graywackes, have a very fine grain size, and do not exhibit any cleavage. The argillites are commonly light gray on weathered surfaces and dark gray on fresh surfaces. Bedding thicknesses range from approximately 1 cm to 4 cm, averaging 1.5 cm.

Microscopically, 4 thin sections were examined, and 3 were point counted to obtain modal analyses. Modal analyses are summarized in Table 6. Modal analyses indicate the graywackes are feldspathic graywackes.

In thin section, the graywackes are fine-to medium-grained (average clast size 0.05 mm to 1.0 mm), subrounded and poorly sorted. Lathy to tabular plagioclase grains, moderately to severely altered, are the dominant clasts found within the graywackes. Hornblende andesite rock fragments, dacite rock fragments and quartz are common and account for most of the remaining clasts. Hornblende is mostly euhedral with slight chlorite alteration. Hornblende andesite rock fragments, the probable source of the hornblende grains, are mostly fine-grained and moderately altered. Dacite rock fragments are fine-grained, and the quartz is mostly subrounded common quartz. The matrix is composed of minute plagioclase, quartz, and hornblende clasts, with minor chlorite, epidote and carbonate. Chlorite, epidote, and carbonate are common in veins, infrequently the result of alteration of plagioclase and hornblende. Opaques are commonly euhedral cubes of pyrite.

Microscopically, the argillites are very fine-grained (<0.2 mm). Sorting is excellent and graded bedding is common. Interesting features include several thin beds (2 mm to 5 mm)

Table 6--Modal Analyses of Feldspathic Graywackes From Knife Lake Greenstone Segment

	1	2	3
Common Quartz	1.8	1.7	2.7
Plagioclase	30.8	55.8	70.3
Rock Fragments			
Hornblende Andesite		2.8	
Dacite	3	4.7	1.7
Rock Fragment Totals	3	7.5	1.7
Hornblende		7	
Chlorite		4.8	3.5
Epidote	.3	3.8	1.8
Carbonate	.2	3.5	2.2
Sericite		.7	
Opaques	7	.5	5.2
Matrix	56.3	14.5	12.5
Others	*.5	+.2	¢.2

*SRF
+MVRF
¢Biotite

composed of sericite and carbonate, which formed from the alteration of plagioclase-rich beds.

Keweenawan Diabase Dike

One diabase dike was found within the Knife Lake Greenstone segment, located on the portage from Hanson Lake to Link Lake. This dike intrudes graywackes and argillites, and is very similar to the diabasic dikes found within the Spoon Lake segment in the South Arm of the Knife Lake area. The dike is a minimum of 5 m wide, is dark reddish brown on weathered surfaces and almost black on fresh surfaces. The rock is very broken and sheared, and quartz fracture fillings are common. Grain size is fine and only occasional coarse-grained plagioclase laths are identifiable. Secondary pyrite is common. Unfortunately, no sample was examined petrographically.

Knife Lake Synclinorium Segment

The Knife Lake Synclinorium segment comprises approximately 15 square kilometers of area in the central and northern section of the study area (Figure 2). This segment is separated from the Knife Lake Greenstone segment to the south by a major longitudinal fault, from Todd Duex's thesis area on the east by an arbitrary north-south line extending from Cypress Lake through the portage between Topaz and Cherry Lakes, and in the north from the Canadian greenstones by a major longitudinal fault, which also marks the international boundary.

Structurally and petrographically, the Knife Lake Synclinorium segment is the most interesting of the segments studied. Rocks within this segment strike predominantly northeast and dip steeply to the northwest. Topping and dip directions are frequently reversed and indicate an overturning of the beds. Other structural measurements, which include fold axes, cleavage and lineation attitudes, suggest the rocks are part of a large overturned syncline. A tuff-mafic conglomerate-mixed conglomerate unit and a younger graywacke unit account for most of the rocks within the area. These two units are interbedded, and gradational into one another. The contact between the two is arbitrary, reliable to within 100 meters and drawn to reflect the gross structure within the area (Plate 1). One diabase dike, similar to the Keweenawan diabasic dikes, was found in the segment. A total of 58 thin sections from the Knife Lake Synclinorium segment was studied.

Description of Rock Types

Volcanic Tuffs, Mafic Conglomerates and Mixed Conglomerates

Delineation and definition of this unit proved quite difficult, because the transition between these lithologies and overlying graywackes is commonly gradual, and the units are frequently interbedded with the other.

Megascopically, the tuffs are dark green on weathered surfaces, light green on fresh surfaces, and in places weather to a "beautiful light-green sandy material, consisting chiefly of hornblende" (Gruner, 1941, p. 1607). Field differentiation between some tuffs and graywackes was very difficult; tuffs were usually distinguished on the basis of their green color, whereas the graywackes are black or gray. The grain size is fine, and bedding thicknesses range from 1 cm up to 1 m. Graded beds are infrequent.

The mafic conglomerates are gray-green on weathered surfaces and dark green on fresh surfaces. The grain size is much coarser than the tuffs, with an average clast diameter of approximately 0.5 cm, but up to 0.5 m. Clasts within the mafic conglomerate are subrounded to rounded, and consist of coarse-grained hornblende and augite in an aphanitic groundmass. The groundmass of the clasts and the matrix of the mafic conglomerate are often very similar in appearance (Figure 16). A distinctive weathering, characterized by hollows and a rough pitted appearance, is locally common along shorelines, and may be the result of differential weathering of the augite and hornblende (Figure 17). Some of the mafic conglomerates may in fact be agglomerates or lahars.

The mixed conglomerates are commonly light gray on weathered surfaces, and dark gray on fresh surfaces (Figure 19). The grain size ranges from 2 mm up to 25 cm, with pebble size (4 mm to 64 mm) being the most common. Bedding thicknesses range from 0.5 m

Figure 16: Mafic conglomerate showing the field resemblance to an agglomerate. Located on the southeast shore of Glen Lake.

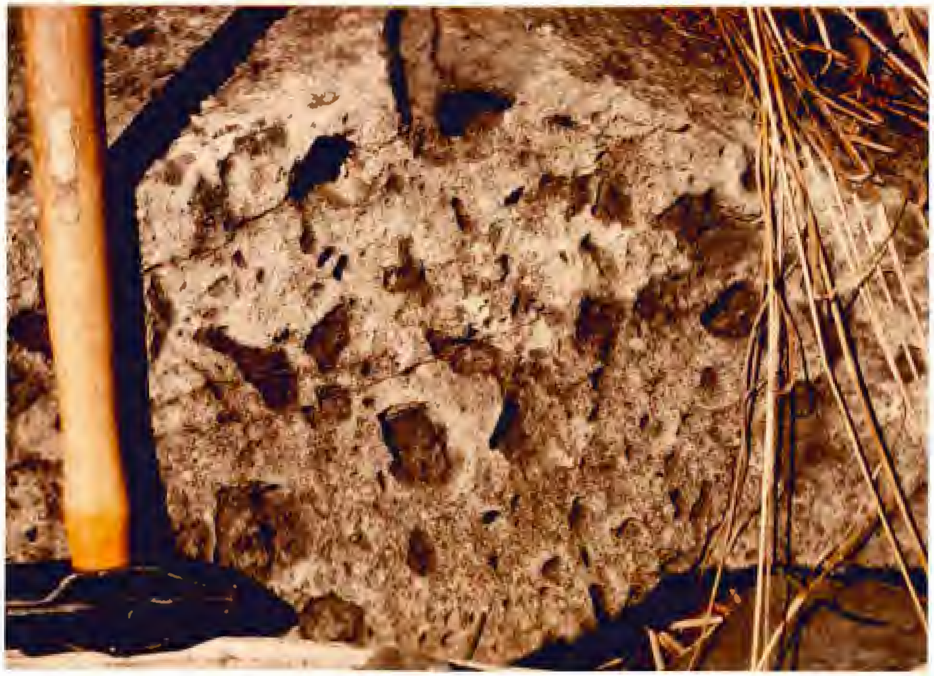


Figure 17: Mafic conglomerate showing hollowed and pitted appearance, the result of differential weathering of mafic components. Located on small island northeast of large island on Cedar Lake.

up to 5 m. Clasts are commonly subrounded to rounded, but a few are angular. Clast types recognized in the field include dacite porphyry, hornblende andesite, MVRF, SRF and rarely banded iron-formation. The matrix of the conglomerate is dark gray to black and aphanitic. Pyrite is common. Some outcrops of the mixed conglomerate, and rarely the mafic conglomerate, appear to be diamictic (matrix-supported), and may be debris flows or lahars respectively.

Microscopically, 3 thin sections of the tuff were examined, and 2 were point counted and modal analyses obtained. Table 7 is a summary of the modal analyses. One tuff sample was taken from a large rounded tuff clast located in the mafic conglomerate unit.

In thin section, the tuffs are fine-to coarse-grained, with the average grain size being 0.5 mm to 3 mm. Sorting and grading is absent in one slide and excellent in the other, suggesting subaerial and subaqueous deposition respectively. Augite is the dominant clast within the tuffs, is subhedral, occasionally twinned and rarely zoned. Hornblende is common, mostly as subhedral laths, but rarely as an amorphous alteration product after augite. Quartz is minor and mostly volcanic in origin. Plagioclase is minor, is highly altered, and euhedral laths are rare. The matrix is composed of fine-grained chlorite, epidote, hornblende, plagioclase, augite and quartz, with ghosts of shards

Table 7--Modal Analyses of Tuffs From Knife Lake Synclinorium Segment

	1	2
Volcanic Quartz	3	
Plagioclase	2.8	
Hornblende	4.5	2.5
Augite	12.1	29.5
Chlorite		2.8
Epidote		1.2
Opaque	.8	4.8
Matrix	76.7	59.2

being rare. The tuffs were probably originally deposited with crystal, lithic and vitric components, but remnant vitric textures are obscured by devitrification and metamorphism.

Microscopically, 13 thin sections of mafic conglomerates were examined, 12 were point counted, and their modal analyses are summarized in Table 8. A problem encountered in the petrographic study of the mafic conglomerates is similar to the one encountered with the mixed conglomerates. Clast size is large enough to encompass a whole thin section, and on occasion a slide will be composed of a single clast, and a representative modal analysis is not achieved. Two thin sections made from random samples are composed completely of augite andesite fragments, and another, as previously mentioned, is composed completely of tuff. Modal analyses for these were noted as individual rock types.

In thin section, the mafic conglomerate is composed of subrounded to rounded rock fragments and euhedral to subhedral phenocrysts in an aphanitic groundmass (Figure 18). Common clasts include hornblende andesite, augite andesite, MVRF, and tuff, while infrequent clasts include hornblendite, dacite, lamprophyre and SRF. Hornblende andesite fragments are composed of euhedral to subhedral, medium-grained hornblende phenocrysts and fine-grained plagioclase laths in an aphanitic groundmass composed of hornblende, plagioclase, chlorite, epidote, and quartz. Alteration is minor, and hornblende phenocrysts occa-

Table 8--Modal Analyses of Mafic Conglomerate From Knife Lake Synclinorium Segment

	1	2	3	4	5	6
Volcanic Quartz		.5	.3	2.3	.6	
Plagioclase	51.7	46	19	13	31.7	9.5
Rock Fragments						
Hornblende Andesite			11.7	7.3	5.2	8
Augite Andesite				23.2	2	20.8
Dacite			.6	21.8		
SRF				3.8		
MVRF			.5	3.5		.3
Rock Fragment Totals			12.8	55.8	7.2	29.1
Hornblende			19.8	.5	9.8	.5
Augite	13.8	29.7	7.5	5.2	13.8	2.7
Chlorite		.2	2.5	2	2	15.5
Epidote	2.8	1.2	1.3	1.2	9.8	1.2
Carbonate		.5	.5	1.3	.3	1
Vein Quartz			.3		.3	4.8
Opaques		.3	1	1.3	.6	1.3
Matrix	31.7	21.8	30	6.7	21.9	12
Other			*4.6	@6.8	#2	*22.3

$Thin section composed completely of one clast of augite andesite
*Tuff rock fragment
@Lamprophere rock fragment
#Actinolite
+Hornblendite rock fragment

Table 8--Modal Analyses of Mafic Conglomerate From Knife Lake Synclinorium Segment (cont.)

	7	8	9	10	11
Volcanic Quartz		.3			
Plagioclase	46	16.8	2	4.2	
Rock Fragments					
Hornblende Andesite		26.2	3.8	18.8	13.8
Augite Andesite	29.7	3.3	16.1	14.5	29.8
Dacite		1.2			
SRF					
MVRF		11.3	9.8	7	
Rock Fragment Totals	29.7	42	29.7	40.3	43.6
Hornblende		10.5		2	
Augite			1.5	1	
Chlorite	.2	13.3	5.5	4	
Epidote	1.2	4.8	17.3	2.8	
Carbonate	.5		3	6	
Vein Quartz	.3	2.8		1.5	
Opaques	.3	.6	2.3	.83	.3
Matrix	21.8	5	38.5	35.8	2.8
Other		+3.7		+2	*53.2

$Thin section composed completely of one clast of augite andesite
*Tuff rock fragment
@Lamprophere rock fragment
#Actinolite
+Hornblendite rock fragment

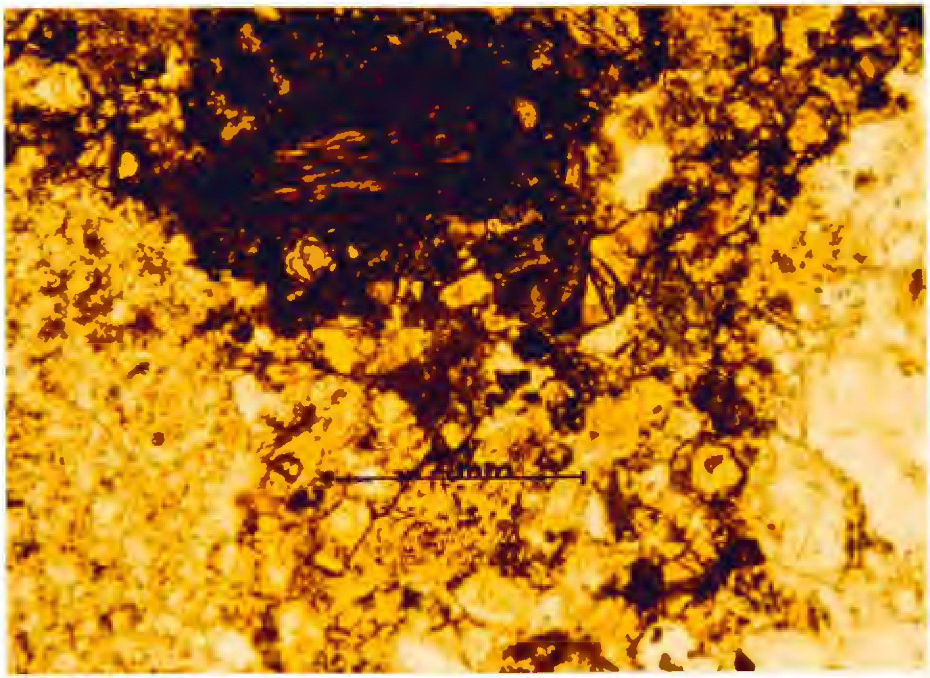


Figure 18: Photomicrograph of mafic conglomerate from Glen Lake (one polar). Hornblende andesite rock fragment on left containing hornblende with oxidized rim.

sionally have oxidized rims. Augite andesite fragments are composed of unaltered, medium-grained augite phenocrysts and fine-grained plagioclase laths in an aphanitic groundmass. MVRF are dominantly metabasalts (greenstone), but include MVRF which are diabasic in nature. Tuff rock fragments are previously described. Common crystals include hornblende, augite, and plagioclase, while opaques and alteration minerals are minor. Augite is the dominant crystal, occurs as euhedral crystals ranging in size from 0.5 mm up to 8 mm, and is unaltered; twinning is common, and zoning is infrequent. Hornblende is a common crystal, is subhedral and ranges in diameter from 0.5 mm up to 6 mm, and is moderately altered to chlorite. Plagioclase crystals are lathy to tabular, range in size from 0.5 mm to 8 mm and are highly altered to saussurite. The matrix is aphanitic, $<$ 0.5 mm, and consists of fine-grained rock fragments, augite, hornblende, plagioclase, epidote, chlorite, carbonate and rare ghosts of shards.

Anomalous occurrences were noted within the mafic conglomerate. One clast of lamprophyre was found and consists dominantly of a kelly-green amphibole, with minor potassium-feldspar and plagioclase. The source of the lamprophyre is unknown. Hornblendite rock fragments, composed of 85% fine-grained pleochroic-green hornblende, are found in mafic conglomerates, mixed conglomerates and graywackes. Hornblendite is relatively rare, and of unknown origin. Actinolite is rare, and found as bladed aggregates associated with the alteration of augite.

Sixteen samples of mixed conglomerate were examined microscopically, and 14 were point counted. Table 9 is a summary of the modal analyses. The mixed conglomerates found within this segment are gradational with the mafic conglomerates, and are distinguished from them chiefly on the basis of matrix type and the percentage of SRF and dacite rock fragments. The mixed conglomerates have a higher percentage of SRF and dacite rock fragments, and a lower percentage of epidote and chlorite in the matrix.

Spatial relations between the mafic conglomerate and the mixed conglomerate appear random in the field, but gradational contacts between the two suggest that as the mafic conglomerate was weathered and transported, the augite and hornblende constituents were differentially removed, resulting in the transformation to mixed conglomerate.

In thin section, the conglomerate consists of rounded hornblende andesite, dacite and SRF clasts in an aphanitic matrix (Figure 20). Hornblende andesite rock fragments consist of moderately altered medium-grained hornblende and plagioclase phenocrysts in a fine-grained groundmass. Dacite rock fragments consist of highly altered medium-grained plagioclase and occasionally quartz in a fine-grained groundmass. SRF are fine-

Table 9--Modal Analyses of Mixed Conglomerate From Knife Lake Synclinorium Segment

	1	2	3	4	5	6	7
Volcanic Quartz	.5	.3	1.2	1.3	1.2	.2	.8
Common Quartz	.8	4.7	1.7	7.8	3.7	6.8	6.7
Plagioclase	36.8	13	29.2	28.2	32.5	24.2	61.8
Rock Fragments							
Hornblende Andesite	20.3	24.8	32	12		1.2	.2
Dacite	3.8	15.2	3	10.5	5	46.3	17
MVRF	4.2	7	.2	16.3			
SRF			.3	1.8	39.8	1.2	
Augite Andesite Tuff		4		6.8			
Rock Fragment Totals	66.1	50.8	35.5	47.4	44.8	48.7	17.2
Hornblende	23.3	10.5	21	6.2		.5	.2
Augite		.7		.5			
Chlorite	1.5	.5	.8	.5		1	.8
Epidote		1	2.3	.3	4.8	1.3	1.6
Carbonate			1	.5		.83	.8
Sericite			.2				.7
Opaques	.83	1.2	.2	.3	2.7	.7	1.3
Matrix	7.7	16.7	7	6.8	10.3	15.8	8
Others		*.5					

*Actinolite
@Hornblendite rock fragments

Table 9--Modal Analyses of Mixed Conglomerate From Knife Lake Synclinorium Segment (cont.)

	8	9	10	11	12	13	14
Volcanic Quartz	.9			.3	3.1		1.5
Common Quartz	5			2	4.3	.3	5.8
Plagioclase	21.7	18.3	38	20.3	53.8	4.7	25.5
Rock Fragments							
Hornblende Andesite	9.9	15.2	8.5	14.5		57.8	13.8
Dacite	16	.3		7.3	5.3		16
MVRF	.5			3.8	2.5	5.3	12.3
SRF	2.2			17.2	17.2	12.7	4
Augite Andesite		5.5	1.5	.3			
Tuff	25.3					.8	3.8
Rock Fragment Totals	53.9	21.0	10	43.1	25.0	76.6	49.9
Hornblende	2	5	2.8	8.7	.3	9.5	7
Augite	5.3	21.3	12	1.5		2	1.2
Chlorite	.8	4	8.5	.7		2	1
Epidote	1.8	16.2	3.5	1.2			
Carbonate	.5		.3	.5	.7	.2	
Sericite				.2	.3		.2
Opaques	1.5	1.8	2.2	1.3	1.2	.5	.5
Matrix	5.7	10.7	22	20	11.2	2	7.3
Others		@1.7	@.7			*2.2	

*Actinolite
@Hornblendite rock fragments

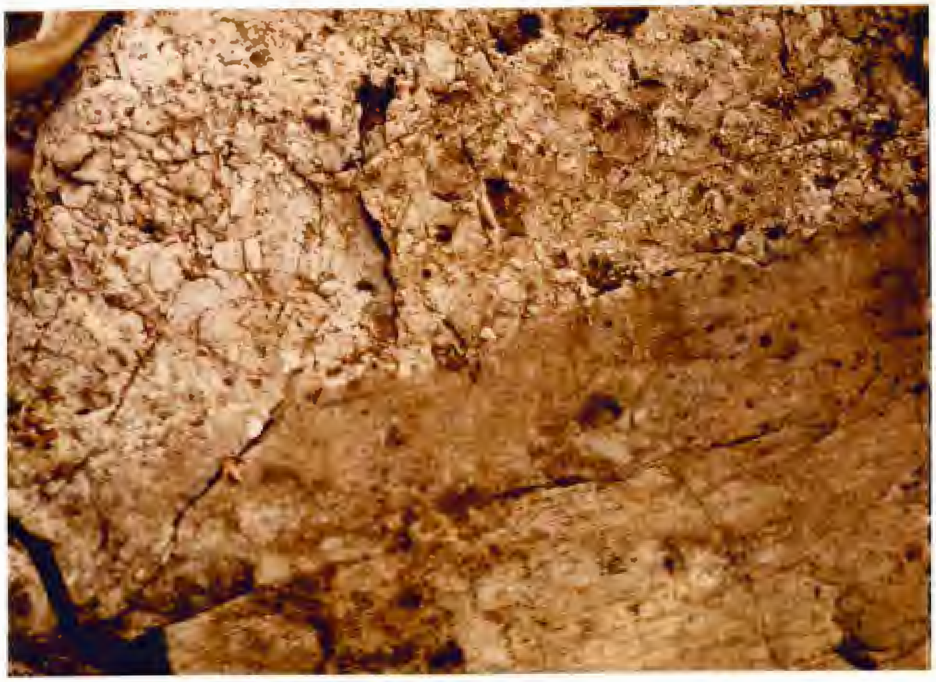


Figure 19: Mixed conglomerate interbedded with graywacke from northeast end of Rabbit Lake.

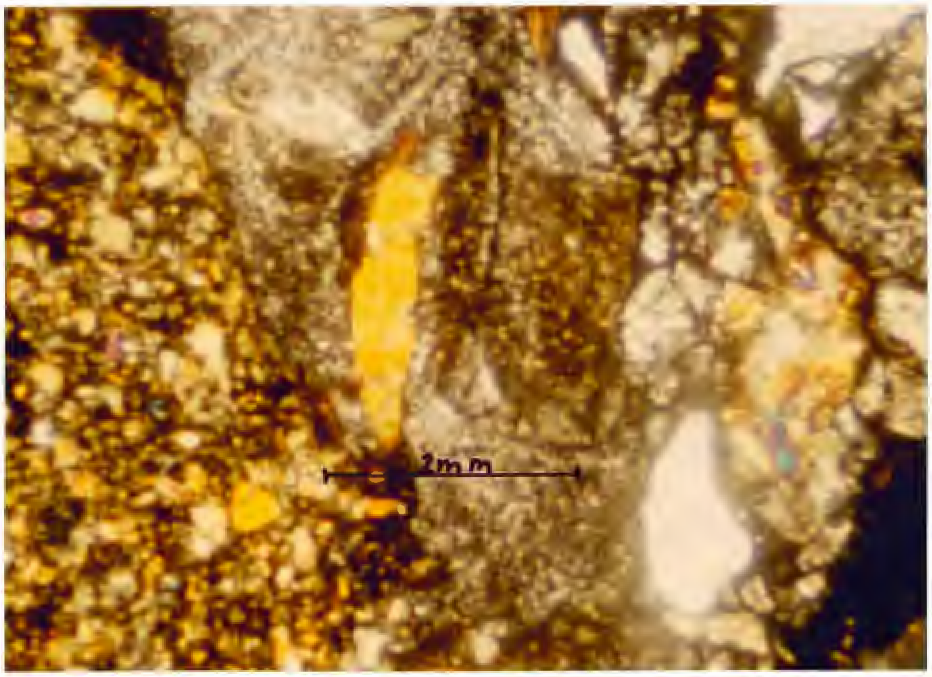


Figure 20: Photomicrograph of mixed conglomerate (crossed polars) from northeast end of Rabbit Lake. Note MVRF on the left, dacite rock fragment center, and angular quartz grains bottom center and top right.

grained mudchips probably picked up by channel scouring during deposition. Augite andesite rock fragments and MVRF are subrounded to rounded and minor. Plagioclase is the dominant mineral, and is ubiquitous to all samples studied. Plagioclase crystals are commonly lathy, polysynthetically twinned, rarely zoned and highly altered to sericite and saussurite. Hornblende is common, euhedral and moderately altered to chlorite. Common quartz and augite are abundant, while vitric hornblende tuff, hornblendite, actinolite and volcanic quartz are minor. The matrix is composed of previously described rock fragments and phenocrysts, along with epidote, chlorite, sericite, carbonate, and opaques.

Feldspathic Graywackes and Argillites

A significant part of the Knife Lake Synclinorium segment consists of a monotonous sequence of fine-grained graywackes interbedded with finer-grained argillites. This unit is gradational into and interbedded with the tuffs, mafic conglomerates, and mixed conglomerates, particularly in the western part of the study area. The beds commonly strike northeast and dip steeply to the northwest and less frequently to the southeast. Sedimentary features include graded beds, flame structures, cross beds, sole marks, and "Bouma sequences," and in conjunction with the structural measurements suggest that many of the beds are overturned and are part of a major overturned syncline.

Megascopically, the graywackes are light gray to dark gray on weathered surfaces and dark gray to black on fresh surfaces. Bedding thickness ranges from 1 cm to 10 cm, with the average thickness being about 2 cm. Many of the beds are consistent and continuous over several meters. Interbedded with the graywackes are very fine-grained argillites which are light gray on weathered surfaces, dark gray to black on broken surfaces and do not exhibit slaty cleavage. Bedding thickness ranges from 0.5 cm up to 5 cm, with an average thickness of approximately 1 cm. No sedimentary structures were observed within the argillites.

Twenty-four thin sections of the graywackes and argillites were examined microscopically, and 16 were point counted. Modal analyses are summarized in Table 10.

In thin section, the graywackes consist of subangular clasts in a fine-grained matrix (Figure 21). The grain size ranges from fine to medium (average clast size 0.05 mm to 1 mm). Sorting is moderate and grading is common. Tabular to lathy, severely altered plagioclase grains are the dominant clasts found within the graywackes. Hornblende andesite rock fragments, dacite rock fragments and common quartz clasts account for most of the remaining clasts. The matrix is very fine-grained (<0.05 mm) and consists of previously mentioned clasts plus fine-grained chlorite, epidote, carbonate and opaques. Little petrographic data was obtained from eight thin sections of argillite.

Table 10--Modal Analyses of Feldspathic and Lithic Graywackes From Knife Lake [illegible] Segment

	1	2	3	4	5	6	7	8
Volcanic Quartz	.7	2.2		.5	1.2			
Common Quartz	3.6	1.3	.2	1.6		1.6		2.2
Plagioclase	62	27.8	19.3	31	37.2	71.7	58.7	8.5
Rock Fragments								
Hornblende Andesite		2	23.8	13.5	20.5		3.7	1.3
Dacite	10.5	3.8	1.3	2.8	2.5	4.7	2.8	4.3
MVRF	1.2	1	1.5	1.8	.5	.3		1.2
SRF	.3	1.5						
Tuff	.5	1			3.7	3.7	.5	3.9
Rock Fragment Totals	12.5	9.3	26.6	18.1	27.2	5.7	6.5	10.7
Hornblende	2.2	12.3	10.2	18.5	18.3		21.8	2.8
Chlorite		1.5	1.7	3.8	2.2			.8
Epidote	.5	.5	9.2	9.3	.7	2.3		.2
Carbonate	2.2		10	1.7		2		.3
Opaques	.5	1	.3	.7		1.5		2.3
Matrix	15.6	42.8	13.2	10.2	11.5	11.8	6	71.2
Other		*.8		¢2.8	#1.3			

*Augite
¢Actinolite
#Saussurite
@Sericite

Table 10--Modal Analyses of Feldspathic and Lithic Graywackes from Knife Lake Syn
Segment (cont.)

	9	10	11	12	13	14	15
Volcanic Quartz							
Common Quartz		1.7	.7	1.3	2.8		3
Plagioclase	24.5	45.2	31.5	10.7	32	34.2	57
Rock Fragments							
Hornblende Andesite	2.2		6.3			13.7	
Dacite		12.7	37.2				27.2
MVRF							.3
SRF					2	5.5	.7
Tuff	2.2	5.5			7		
Rock Fragment Totals	4.4	18.2	42.5		9	19.2	28.2
Hornblende	15.7		5.2	3.2		22.2	
Chlorite	2.2	.2			1.3	8.8	
Epidote	1.5	5.5	4	2	2.7	7	
Carbonate		1.7	1.5		2.2	1	1
Opaques	1.5	1.2	3.5	1	2.8	1.2	.3
Matrix	43.2	26.2	9.8	80.8	46	4.7	9.5
Other	*7.2						@.5

*Augite
¢Actinolite
#Saussurite
@Sericite

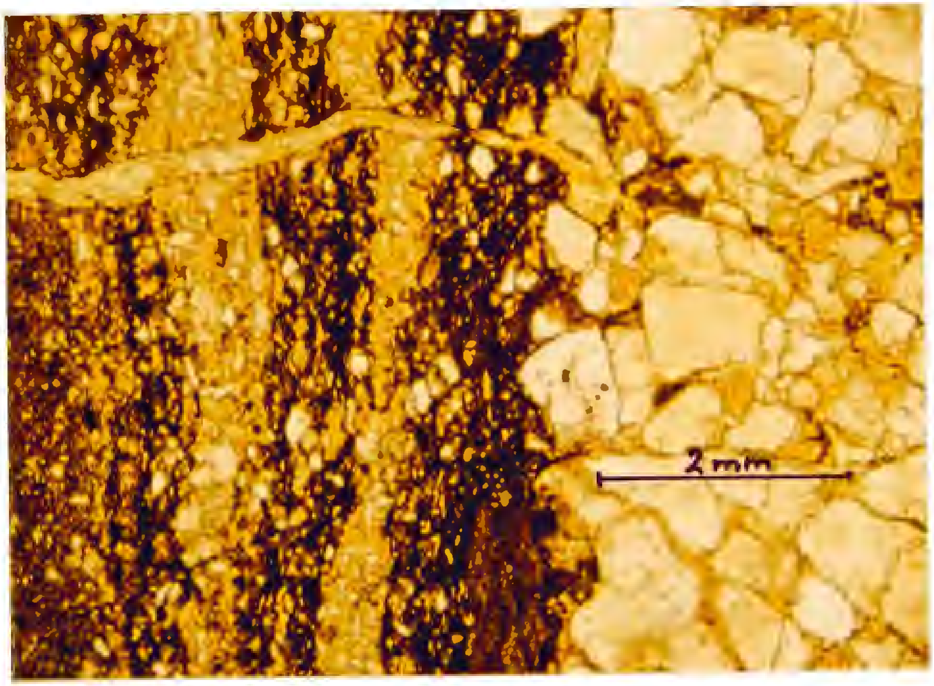


Figure 21: Photomicrograph of graywacke-argillite interbed (one polar) from southwest shoreline of Cherry Lake. Note subangular quartz grains in the graywacke bed.

Canadian Greenstones

Greenstone

A cursory examination was given greenstones lying just to the north of the International Boundary along Cypress Lake in Canada (Figure 2). The greenstones are separated from the Knife Lake Synclinorium segment to the south by a major longitudinal fault (Gruner, 1941) which is topographically marked by Cypress Lake.

Megascopically, the greenstones are fine-grained, brownish-orange on weathered surfaces, and dark green on fresh surfaces. Pillows up to several meters in diameter are common (Figure 22), vesicles and amygdules are found occasionally, and megacrysts of feldspar up to 3 cm are rare. Weathered surfaces are rough and pitted, and very indurated, attested to by a broken rock hammer and scarred knuckles. Pillow tops are infrequent, and generally indicate a north topping direction (personal communication, R. W. Ojakangas).

Microscopically, two of the greenstones were studied, but due to the highly altered nature of the rock, neither was point counted. The greenstones are highly altered to epidote with little primary texture remaining. One sample contains fine-grained, highly altered plagioclase laths and medium-grained augite in a dark epidote groundmass. These greenstones are similar to the greenstones of the Knife Lake Greenstone segment, but no direct correlation between the two is possible.

Figure 22: Large pillow in the Canadian greenstones located on bluffs along Cypress Lake.

Banded Iron-Formation

One outcrop of banded iron-formation is located on a small, low island in Cypress Lake, NW¼, of Sec. 30, T. 66N., R. 6W., between graywackes of the Knife Lake Synclinorium segment and Canadian greenstones. Megascopically, the rock consists of highly folded bands of jasper, hematite and magnetite, and is very similar to two outcroppings of banded iron-formation associated with the Canadian greenstones approximately 2 km to the northwest, outside of the study area. No banded iron-formation was seen within the Knife Lake Synclinorium segment. Proximity and association suggest that this little island of banded iron-formation is itself related to the Canadian greenstones.

One thin section was examined, but was not point counted. Microscopically, the thin section contains amorphous bands of opaque material, mostly magnetite with some hematite, a dominant amount of fine-grained chert, and fine acicular pleochroic green to colorless grunerite blades associated with the chert.

PROVENANCE AND SEDIMENTATION

Provenance

Sedimentary rocks within the Hanson, Cypress and South Arm of Knife Lake Area include conglomerates and graywackes which are almost exclusively volcanogenic in origin. A contemporaneous plutonic source area may have existed (Ojakangas, 1972a, 1972b; McLimans, 1971, 1972; Severson, 1978; Vinje, 1978; and Duex, (pending) but did not contribute any framework material to the present study area.

Anhaeusser and others (1969) suggests that a mixed provenance of volcanic and plutonic rocks is typical of continental orogenic belts or island arc systems, and Goodwin (1968) suggests that all the known greenstone belts of the Canadian Shield belong to the basalt-andesite-rhyolite association also typical of continental orogenic belts or island arc systems.

A total of 14 conglomerate samples and six graywacke samples from the Spoon Lake segment was used for petrographic study. Framework material within the conglomerate consists of approximately 40 percent dacite rock fragments, and 28 percent plagioclase which is very similar to that in the dacite and probably derived from the dacite. Volcanic quartz averages approximately 3 percent. Framework material within the graywacke consists of 14 percent dacite rock fragments, 8 percent plagioclase grains, 5 percent sedimentary rock fragments and 1.5 percent volcanic quartz.

The conglomerates and graywackes of the Spoon Lake segment are comprised dominantly of dacite porphyry fragments and plagioclase and quartz derived from the dacite porphyry. Sedimentary rock fragments found in the graywackes comprise a minor portion of all the rock fragments studied, and presumably formed by the gouging of previously deposited fine-grained sediments by depositing currents. The source area for the sediments is monolithic, and is dacite porphyry. Sediment derived from the dacite porphyry accumulated in piles along the margin of the dacite porphyry, forming the conglomerates, while finer-grained unstable material which formed along the margin was jarred loose and transported downslope and deposited via turbidity currents as indicated by graded graywacke beds.

A total of 3 conglomerate samples and 3 graywacke samples from the Knife Lake Greenstone segment was used for petrographic study. Framework material within the conglomerate consists of approximately 60 percent greenstone rock fragments and 15 percent dacite rock fragments. Framework material within the graywackes consists of approximately 55 percent plagioclase, 3 percent volcanic quartz and 2 percent hornblende.

The greenstone conglomerates and the feldspathic graywackes of the Knife Lake Greenstone segment contain a minimum of two different clast types, implying a mixing of the source area. The different clasts found within the conglomerate and graywacke in order of decreasing abundance are greenstone, dacite, and andesite, all of which are volcanic in origin. The greenstone conglomerate grades into a plagioclase-rich graywacke. Framework plagioclase grains in both units compare favorably with those observed in the greenstones and dacites, and were probably derived therefrom.

A total of 40 thin sections from the Knife Lake Synclinorium segment, representing four different lithologies, was used for petrographic study. Two tuff samples were studied petrographically and framework material consists of approximately 20 percent augite crystals and 3 percent hornblende crystals. Nine mafic conglomerate samples were studied petrographically and framework material consists of 31 percent volcanic rock fragments, mostly augite andesite, hornblende andesite and mafic rock fragments, 16 percent plagioclase, 5 percent hornblende and 4 percent augite. A total of 14 thin sections of the mixed conglomerate was used for petrographic study. Framework material within the mixed conglomerate consists of 42 percent rock fragments, mostly hornblende andesite, dacite and sedimentary rock fragments, 29 percent plagioclase, 7 percent hornblende and 2 percent augite. Fifteen thin sections of graywacke were used for petrographic study. Twelve of the graywackes were determined to be feldspathic graywackes and 3 were determined to be lithic graywackes. Plagioclase averages 37 percent of the graywackes framework material, volcanic rock fragments comprise 16 percent and hornblende averages 9 percent.

The volcanic clasts within the Knife Lake Synclinorium segment in order of decreasing abundance are hornblende andesite, dacite, augite andesite, SRF and MVRF. The diversity of volcanic rock fragments indicates a varied source area. Framework grains of hornblende, plagioclase, augite and volcanic quartz grains resemble phenocrysts seen within the volcanic rock fragments, and were probably derived therefrom. Clast type and the rounded nature of the clasts found within the conglomerate suggest erosion of pyroclastics, hypabyssal intrusives and subaerial flows. No plutonic rock fragments were noted and no potassium feldspar grains were found. Minor potassium staining was noted in the matrix of a few of the mafic conglomerates and mixed conglomerates found within this segment and is probably related to sericite.

Plutonic rock fragments, dominantly quartz and potassium feldspar derived from the Saganaga Tonalite, have been noted in graywacke samples from the eastern Vermilion district by Ojakangas (1972a, 1972b), Severson (1978), and Duex (pending). Vinje (1978) found quartz-plagioclase aggregates lacking in potassium feldspar which resemble the Saganaga Tonalite, and presumed derivation therefrom. Plutonic rock fragments other than the Saganaga type were not recognized in the studies by

Ojakangas, Severson, and Vinje. Gruner (1941) suggested on the basis of field observation that a granite-pebble conglomerate existed within the Knife Lake Greenstone segment. Samples collected from the granite-pebble conglomerate do not take a stain for potassium, and petrographic study indicates that the granite-pebbles are in fact dacite. No plutonic rock fragments, Saganaga Tonalite or otherwise, have been recognized within any of the structural segments studied.

The graywackes from all three structural segments are similar, but the graywackes from the Knife Lake Synclinorium segment can be distinguished from the graywackes of the Spoon Lake segment and the Knife Lake Greenstone segment by a greater diversity of volcanic rock fragments. Framework feldspar grains within all of the studied graywackes constitute a considerable percentage, averaging approximately 31 percent. All of the feldspar grains studied are plagioclase. No potassium feldspar grains were found either microscopically or by staining with sodium-cobaltinitrate. Staining of both the conglomerate and the graywackes indicates that potassium feldspar occurs, for the most part, as a microcrystalline groundmass, and only then in a few samples from the Knife Lake Synclinorium segment. Walker and Pettijohn (1971) feel that the absence of potassium feldspar in Archean graywackes could be explained as a secondary phenomenon or a deficiency in the source area. No rock fragments within the present area of study have a composition more felsic than dacite, suggesting that the absence of potassium feldspar is due to a deficiency in the source rock, and not related to a secondary process.

The rock fragments observed within the present area of study are exclusively volcanic in origin. No plutonic rock fragments were observed, and potassium feldspar is restricted to groundmass in a few samples from one segment. The volcanic rock fragments range in composition from basalt to dacite, and were eroded from hypabyssal intrusives, porphyritic flows and pyroclastic deposits. This would typify the erosion of the lower part of an Archean volcanic pile as modeled by Goodwin (1968).

Sedimentation

The sedimentary rocks within the Cypress, Hanson and South Arm of Knife Lake area consist of conglomerates and rhythmic sequences of graywacke-argillite. The conglomerate and the graywacke-argillite sequences are occasionally interbedded, and in the Knife Lake Synclinorium segment, both are interbedded with some tuffs. These rocks comprise thick sedimentary sequences, up to 1,200-1,500 meters in the Knife Lake Synclinorium segment (Gruner, 1941), and were derived from subaqueous to subaerial porphyritic flows, hypabyssal intrusives and pyroclastic rocks typical of Archean volcanic piles (Goodwin, 1968).

In outcrop, the conglomerate beds are poorly defined, range from a few centimeters to massive, and generally, with the exception of some graded beds, lack sedimentary features. Graywacke (and argillite) beds are well defined, regularly bedded and where exposed show good lateral continuity. Bedding thickness ranges from less than 1 cm in some argillite beds to 15 cm in some graywacke beds. Graded bedding is common in the graywackes and is generally from medium (0.5 mm to 1.0 mm) to fine-grained (0.5 mm). Graded beds, convolutions, flame structures, mudchip zones and Bouma sequences are characteristic of turbidite sequences and are herein interpreted to be the result of deposition by turbidity currents. Graywackes throughout the eastern Vermilion district have been interpreted by Ojakangas (1972a, 1972b) as being dominantly the result of turbidity currents.

Shallow agitated water indicators, such as ripple marks or medium to large scale cross-beds, were not observed in any of the graywackes or argillite outcrops, suggesting deposition in a moderate to deep water basin. Severson (1978) and Vinje (1978) reached the same conclusion on the basis of similar observations. The eastern slope of the basin was relatively steep since Saganaga tonalite clasts, up to 15 cm in diameter, have been transported some 40 kilometers from the source area to Ensign Lake (McLimans, 1971, 1972). The presence of gray-

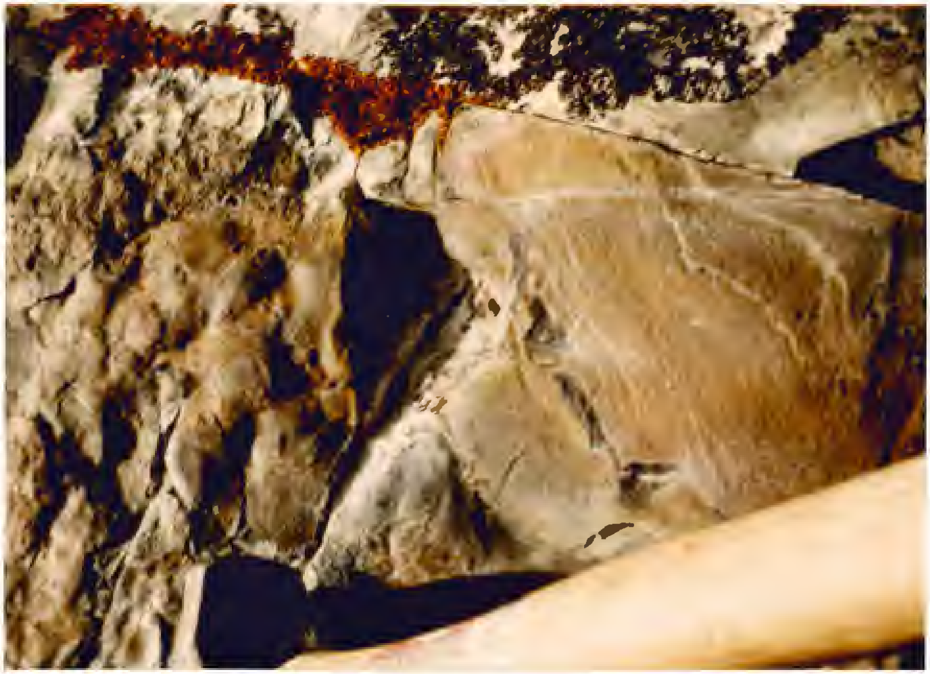


Figure 23: Sole marks from the Knife Lake Synclinorium segment located along the northwest shoreline of Cherry Lake.

Figure 24: Graywacke-argillite sequence showing convoluted bedding and flame structures from the Knife Lake Synclinorium segment along the southwest shoreline of Cherry Lake.

wacke-argillite sequences interbedded with conglomerates, the well rounded nature of the clasts in the conglomerates, and the angular nature of the quartz framework grains and the fine-grained lithic fragments, suggest transportation to the unstable basin slope may have been by high-velocity streams.

The conglomerates and graywackes probably originated as temporary accumulations on the slopes of volcanic piles. These accumulations were periodically jarred loose by explosive volcanism or earthquakes, which caused submarine landslides which deposited the conglomerate, or as they became fluid enough, developed into turbidity currents which deposited the graywackes (Ojakangas 1972a, 1972b). The currents flowed into a deep subsiding basin (Gruner, 1941) and deposited sediments with various sedimentary structures and textures depending on the initial velocity and sediment load. Some argillite interbeds may represent the slower-settling, fine-grained parts of turbidity currents which accumulated in a few days, while others could represent hundreds or thousands of years of slow accumulation (Ojakangas, 1978; 1972a; 1972b). Argillite represents the background deposition of the basin, but was repeatedly interrupted by the arrival of short lived turbidity currents. Sedimentation proceeded in this manner throughout Knife Lake time as evidenced by the lack of unconformities between members (Gruner, 1941).

Bouma (1962) has described a "complete" turbidite bed composed of five internal units (Figure 25). Within the present area of study the majority of graywacke sequences consist of top-truncated A or A-B units. "Complete" sequences are not found, but sequences with A-B-C, B or D, and C are found. Bouma units B or D cannot be segregated except where found in sequence, and Bouma unit C is recognized by the presence of convolutions or small scale cross-beds. Composite beds composed of two to five thin (1-2 cm) graded units without intervening argillite layers are present in both of the measured sections studied (Table 11). No bed-by-bed descriptions were obtained from either the Spoon Lake or Knife Lake Greenstone segments, but detailed Bouma bed descriptions were done on two relatively clean, unweathered outcrops within the Knife Lake Synclinorium segment.

A combination of erosion at the head of a turbidity current and deposition from the body and tail of the current can account for most turbidite features (Middleton and Hampton, 1973). Composite A units and Bouma sequences where the top units are missing can be explained either by erosion of preceding turbidite beds, or a lack of deposition within the turbidity current, such that the coarser material was deposited closer to the source and the rest of the turbidity current deposited the upper units farther from the source. "Complete" sequences or

Measured Section Cherry Lake Area (82 beds)	Graded	32.8%	37.9%	1.7%	8.6%	8.6%
	Not Graded	10.3%				
Measured Section Cedar Lake Area (63 beds)	Graded	33.3%	31.1%		8.9%	2.2%
	Not Graded	24.4%				

Figure 25: Summary of Bouma sequences found in graywacke beds of the present study. Thicknesses of sections in Table 11.

Table 11--Two Measured Sections of Graywacke-Argillite Sequences from the Knife Lake Synclinorium Segment

	1	2
Thickness of Section	1.99 m	1.55 m
Number of beds in Section	82	63
Graywacke beds		
Percent of total thickness	78.7	69.8
Average bed thickness	2.7 cm	2.4 cm
Range of bed thickness	.4-5.6 cm	.7-3.8 cm
Number and percent of total	58-70.7	45-71
Number and percent graded	40-48.8	19-46
Percent with convolutions	7.3	1.5
Percent composite beds	26.8	22.2
Argillites		
Percent total thickness	21.3	30.2
Average bed thickness	1.8	2.6
Range of bed thickness	.3-3.2	.2-6.1
Number and percent of total	24-29.3	18-29

Measured Section I-Station BW-221, Cherry Lake, NE¼, NW¼, Sec. 9, T65N R6W.

Measured Section II-Station BW-268, Cedar Lake, SW¼, SW¼, Sec. 33, T66N, R6W.

sequences with missing lower units, would be deposited from the body and tail of the current as a function of flow regime. The units of the sequence represent from bottom to top, successively lower flow regimes (Walker, 1967, 1976). Major factors in determining flow regime would be the distance traveled and the initial velocity and sediment load of the current.

Walker (1967, 1976) suggested that turbidites can be classified as either "proximal" or "distal" depending on the order of Bouma units. A Bouma A-A-A sequence would be proximal, whereas sequences beginning with units B or C would be distal. Indicators of distal deposition, as opposed to proximal deposition would include: thinner beds, finer-grained beds; parallel-sided regular beds; well developed argillite layers between graywacke beds; well-graded beds; beds with sharp bases (a marked contrast in grain size compared to underlying fine-grained beds) and tops which grade into fine sediment; and a lack of scours, channels, and composite beds. The combined characteristics of a large number of beds however would be necessary before any environmental predictions could be made (Walker, 1967, 1976).

Walker (1976) has also described several turbidite facie and facies associations which allow generalizations to be made as to where a particular turbidite sequence may occur in a turbidite basin. Turbidite sequences and associated conglomerate occur in both the Spoon Lake segment and the Knife Lake

Greenstone segment. Detailed measurement of graywacke beds was not possible in either segment, but generalizations may be inferred from conglomerate-graywacke relationships. The turbidites of the Spoon Lake segment and the Knife Lake Greenstone segment correspond to facies within the submarine fan of a slope-fan-basin floor system of a turbidite basin. The graywackes are contained in the depositional lobe of the inner to middle portion of the submarine fan, where they would be associated with channel conglomerates. Vinje (1978) suggested that the graywacke beds contained within the Spoon Lake segment, which are in close proximity to the present area of study, generally have the attributes of deposition in a proximal environment and the middle portion of the submarine fan. Vinje was also unable to obtain any related information from the Knife Lake Greenstone segment.

Two sections of graywacke beds (Table 11) from the Knife Lake Synclinorium segment were measured, and generally have the attributes of deposition in a proximal environment. The graywackes from the Cherry Lake Area consist of dominantly medium- to coarse-grained A and A-B sequences. In addition, intervening argillite layers are not well developed, beds are not well-graded, composite beds are common, conglomerate beds are present and channel scours (sole marks, Figure 23) were noted. The graywackes at this locale are however, very thinly bedded, which is the only suggestion of distal deposition. The graywackes from the Cedar Lake Area compare favorably to those of the Cherry Lake Area including: dominance of A and A-B beds; common occurrence of composite beds; presence of interbedded conglomerate beds; and poor development of argillite layers. Features of the graywackes at this locale that may be suggestive of more distal deposition include fine-grain size, thin beds, and a lack of channel scours. The term distal, as defined by Walker (1967, 1976), would not be feasible for either of the measured sections, but the graywackes in the Cedar Lake Area could be classified as more distal than those of the Cherry Lake Area. The turbidite sequences of the Knife Lake Synclinorium segment correspond to facies within the inner fan of the slope-fan-basin model proposed by Walker (1976). The conglomerates would be mainly restricted to channels, while the diamictic conglomerates would be representative of the feeder channel on the foot of the slope.

Vinje (1978) and Severson (1978) concluded from their study of "distal" and "proximal" relationships of turbidite sequences within the Kekekabic Lake segment that sediment transport was from the northeast to the southwest. This coincides with a southward decrease in the size and abundance of Saganaga tonalite clasts in the conglomerate of Ogishkemuncie Lake (McLimans, 1971, 1972). No reliable transport direction however, could be determined for the Knife Lake Synclinorium segment based on turbidite sequences, due to the limited amount of turbidite data and the highly faulted nature of the segment.

Miscellaneous sedimentary features such as flame structures, sole marks and mudchips were noted in outcrop. Flame structures are indicative of soft sediment deformation, primarily due to compaction, sole marks (Figure 23) are the result of currents or unequal loading, while mudchips apparently result from the gouging of previously deposited beds by later turbidity currents.

A total of eight paleocurent measurements, all that were observed, were taken at only three locations within the Knife Lake Synclinorium segment. These occur as small-scale cross-beds located within the finer-grained parts of the graywacke-argillite sequences. Measurements were rotated to the horizontal, with the plunge (determined by cleavage-bedding intersections) removed (Ramsey, 1961). Four paleocurrent measurements taken at the portage between Lake-of-the-Clouds and Lunar Lake suggest sedimentation occured along a northeast-southwest trend; however, the direction of current flow could not be determined due to the extremely low-angle of the cross-beds, (less than 5 degrees). One paleocurrent measurement was taken on Cherry Lake and indicated a current direction towards S 50°E. The reliability of this measurement is questioned, however because the angle of the cross-bed at this locale when rotated back to horizontal, is 76° degrees, clearly beyond the angle of repose. Three paleocurrent measurements were taken on Canoe Lake and indicated a current direction with an average trend towards S 23°E.

Evidence within the rocks, including a cross-bed which when deposited would have exceeded the angle of repose and a strained pebble conglomerate bed, (Figure 26), indicates that the rocks have undergone internal strain, and a much more detailed strain analysis (beyond the scope of this investigation) would be necessary to determine accurate paleocurrent directions (Ramsey, 1961). In addition, many more paleocurrent measurements would be necessary to obtain an accurate paleocurrent direction, which would be statistically independent of localized conditions.

Figure 26: Interbedded mixed conglomerate and graywacke from the Knife Lake Greenstone segment showing strained pebbles. Located along northwest shore of Embla Lake.

STRUCTURE

General Statement

The present area of study is part of a narrow belt of metavolcanic and metasedimentary rocks known as the Vermilion district. The rocks within the district have been subjected to at least two generations of folding which were broadly contemporaneous with emplacement of the Vermilion granite-migmatite massif on the north, the Giants Range batholith to the south, and the Saganaga batholith on the east (Sims, 1972). Folding was followed by a major period of longitudinal faulting that was regional in scope (Sims, 1972).

The rocks within the Vermilion district trend eastward and northeastward, generally dip steeply and dominantly constitute a northward-facing stratigraphic succession. Gruner (1941) observed that within the eastern part of the Vermilion district the rocks are generally parts of isoclinal folds whose hinge surfaces strike east to northeast with near vertical dips and nearly horizontal fold axes. Additionally, cleavage is poorly developed, but wherever found generally strikes about N 60°E to N 90°E with steep dips to the southeast. Gruner (1941) also recognized major longitudinal faults which divide the metavolcanic and metasedimentary rocks into discrete structural segments. The Knife Lake area has been divided into seven structural segments (Figure 2) based on these faults. Parts of three of these segments, the Spoon Lake segment, Knife Lake Greenstone segment and the Knife Lake Synclinorium segment, comprise the present area of study. Structural data within the Spoon Lake segment and the Knife Lake Greenstone segment are scarce compared to the Knife Lake Synclinorium segment. This is due to a lack of observable structural features found within these segments and their smaller field areas.

Gruner (1941), while mapping a burned stretch between Ester Lake and Amoeba Lake, discovered the key element to the structure of the whole Knife Lake Synclinorium segment. Much of this key was based on "red jasper beds" that could be traced for distances up to half a mile. It should be noted that the area has since recovered its full growth of flora, and the author was unable to locate any "red jasper beds" after a day and a half of brush beating, including stooped traverses with a compass in the hopes of picking up magnetic deflection.

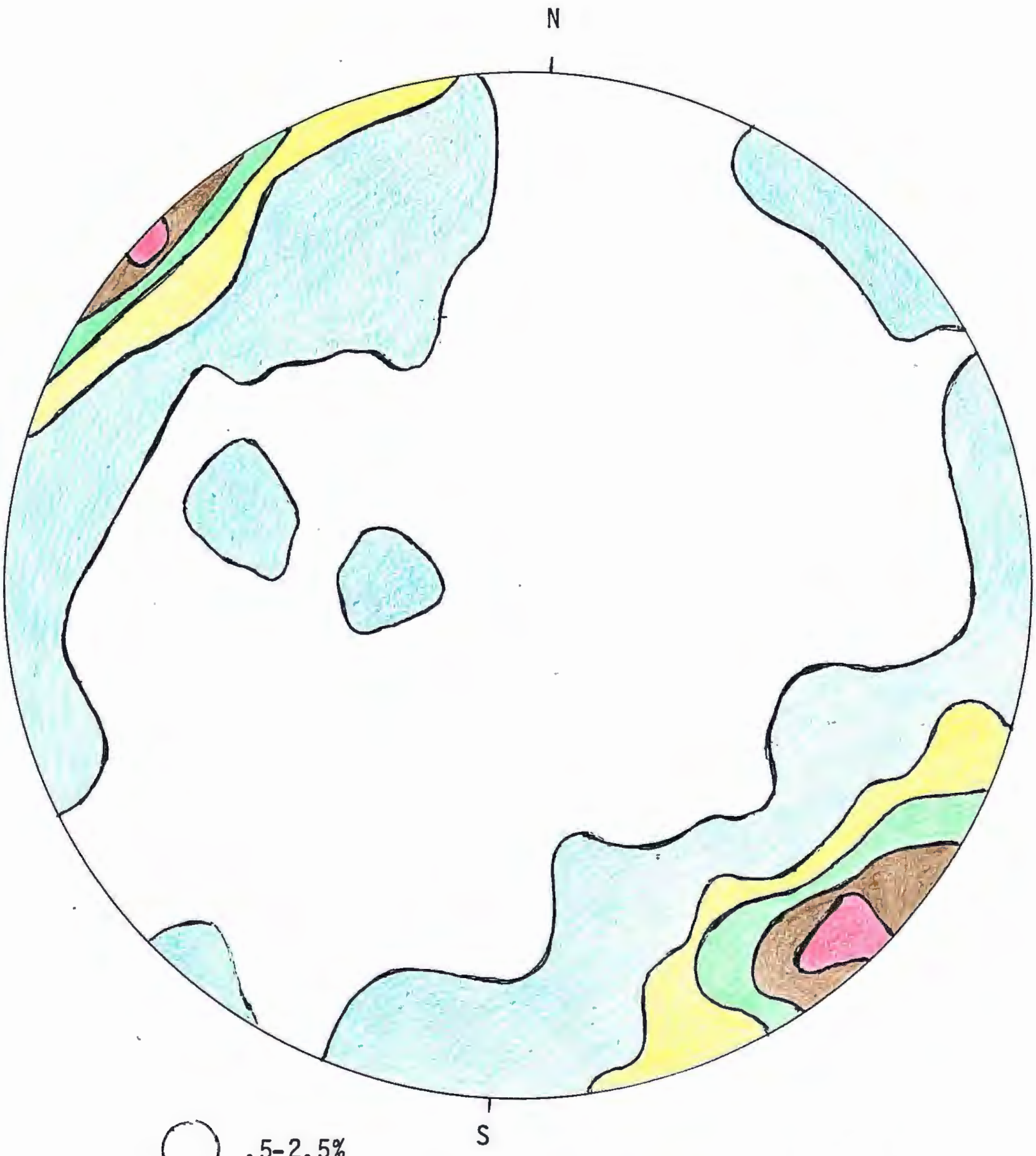
The rocks within the present area of study were deformed and metamorphosed during the Algoman orogeny 2.7 billion years ago. Fortunately, deformation was not severe enough to obliterate graded graywacke beds, Bouma sequences and pillow top, which made interpretations of the structure possible.

Bedding Planes

Bedding planes are found nearly everywhere within the present area of study. Bedding of graywacke-argillite sequences is easily recognized by a sharp difference in grain size between the two. Bedding planes within the conglomerates are less easily recognized but are also determined primarily by grain size differences. Strikes and dips of bedding planes were generally measured along lakeshores, as exposures inland were obscured by vegetation, and not suitable for such measurements. Bedding planes within all three structural segments of the present study area strike dominantly N 40° to 50°E, with steep dips (65° to 90°) to the southeast and northwest, subparallel to the major longitudinal faults. Topping directions indicate that many of the beds are overturned. Bedding planes within all three segments are generally linear, but are locally warped around minor folds. Poles to bedding planes were plotted and contoured by computer (Figure 27).

Cleavage Planes

Cleavage planes were the predominant penetrative structures measured in the field. The cleavage planes occur as both slaty cleavage, restricted to the finer-grained argillite beds, and fracture cleavage which was found penetrating both argillite and graywacke beds. The distinction between slaty cleavage and fracture cleavage may be tenuous in places since the amount of micaceous minerals in the muddy beds is not known (Hobbs and others, 1976). Sims (1972) concluded that both slaty and



○ .5-2.5%

○ 3-5%

○ 5.5-7.5%

○ 8-10%

○ 10.5-12.5%

Figure 27: Poles to bedding for the Knife Lake Synclinorium segment, 198 points.

fracture cleavage are typical of low-grade metamorphic rocks, which includes the majority of the rocks in the eastern Vermilion district. As previously mentioned, Gruner (1941) found cleavage poorly developed within the eastern Vermilion district, and within the present area of study only 46 total cleavage measurements were obtained. Many more cleavage measurements would be needed before the results would be statistically significant. Poles to cleavage were plotted and contoured using a computer.

Two cleavage trends have developed within the present area of study. The dominant cleavage trend is N54° to 62°W, with steep dips to the northeast or southwest. The second cleavage trend is N 75° to 82°E with steep to moderate dips to the southeast. Additionally, there is a scattering of cleavage poles. The dominant northwest cleavage trend coincides with the S_3 cleavage of Severson's (1978) and with Gruner's (1941) older northwest generation of folding. The east to northwest cleavage compares favorably to the S_2 cleavage of Vinje (1978). Neither cleavage trend parallels the N 40° to 50°E strike of the fold axis of the Knife Lake Synclinorium segment, and therefore the cleavage planes of the present area of study are assumed to have been produced during a second period of deformation.

Spoon Lake Segment

A total of four cleavage measurements was taken in the

Spoon Lake structural block. The cleavages within this structural block strike approximately N 5°E and dip 60° to the southeast. Vinje (1978) took 29 cleavage measurements from the Spoon Lake segment and determined a dominant strike of N 70°E with a dip of 60° to the southeast. The present measurements differ substantially from Vinje's, and may be explained as the result of local variations.

Knife Lake Greenstone Segment

A total of eight cleavage measurements was taken in the Knife Lake Greenstone structural block. The cleavages within this structural block strike N 20°W to N 40°W and dip steeply to the northeast.

Knife Lake Synclinorium Segment

A total of 35 cleavage measurements was taken in the Knife Lake Synclinorium structural block (Figure 28). The cleavages within this structural block strike dominantly N 54° to 62°W and dip steeply to the northeast or southwest. A second set of cleavage planes strikes N 75° to 82°E and dips moderately to steeply to the southeast.

The poles of cleavage shown in Figure 28 reflect cleavages taken throughout the Knife Lake Synclinorium segment, mostly along lakeshores and a few portages. Inland areas within the Knife Lake Synclinorium segment yielded few cleavage measurements.

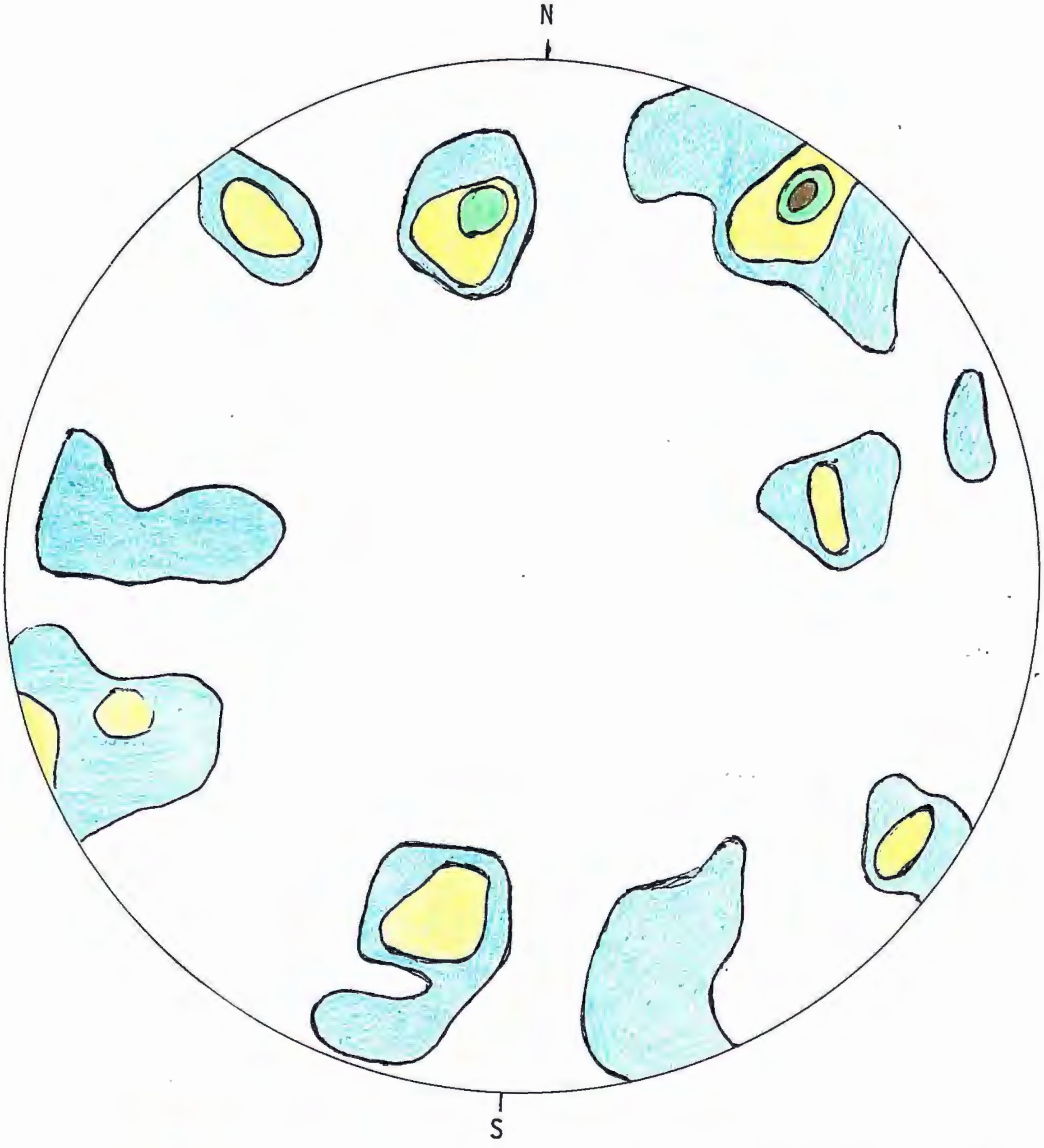


Figure 28: Poles to cleavage for the Knife Lake Synclinorium segment, 35 points.

Lineations

Cleavage-bedding intersections are the major linear features considered in this study. Several fold axis lineations are discussed later in the chapter pertinent to minor folds. A few cleavage-bedding intersections were measured in the field, but most were hand plotted and contoured using a stereonet. A total of only 33 intersections was obtained. Thirty intersections were obtained from the Knife Lake Synclinorium segment, three from the Knife Lake Greenstone segment, and none from the Spoon Lake segment.

Knife Lake Synclinorium Segment

A total of 30 cleavage-bedding intersections were plotted for the Knife Lake Synclinorium segment (Figure 29). The measurements vary in both orientation and plunge, the result of changes in trends of both bedding and cleavage, but general trends can be determined, particularly if the intersections are subdivided between the northern part of the segment (Plate 1) and the southern part of the segment (Plate 1).

The cleavage-bedding intersections within the northern part of the Knife Lake Synclinorium segment plunge 30° to N 42° to 52° E (Figure 30). This trend parallels the axis of the major fold within the segment, which plunges approximately 30° to N 40° to 50°E.

The cleavage-bedding intersections within the southern

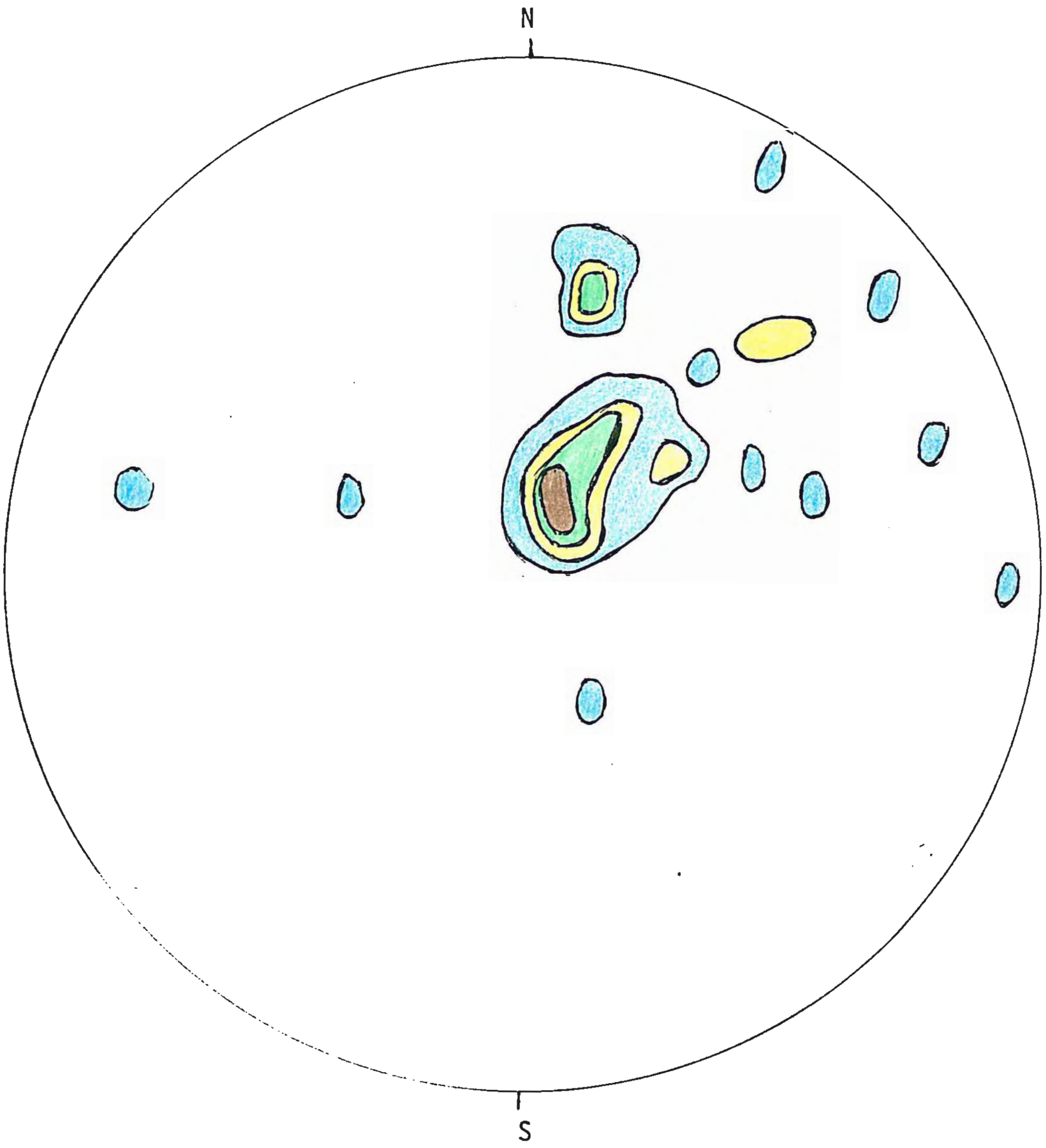


Figure 29: Cleavage-bedding intersections (lineations) for the Knife Lake Synclinorium segment, 30 points.

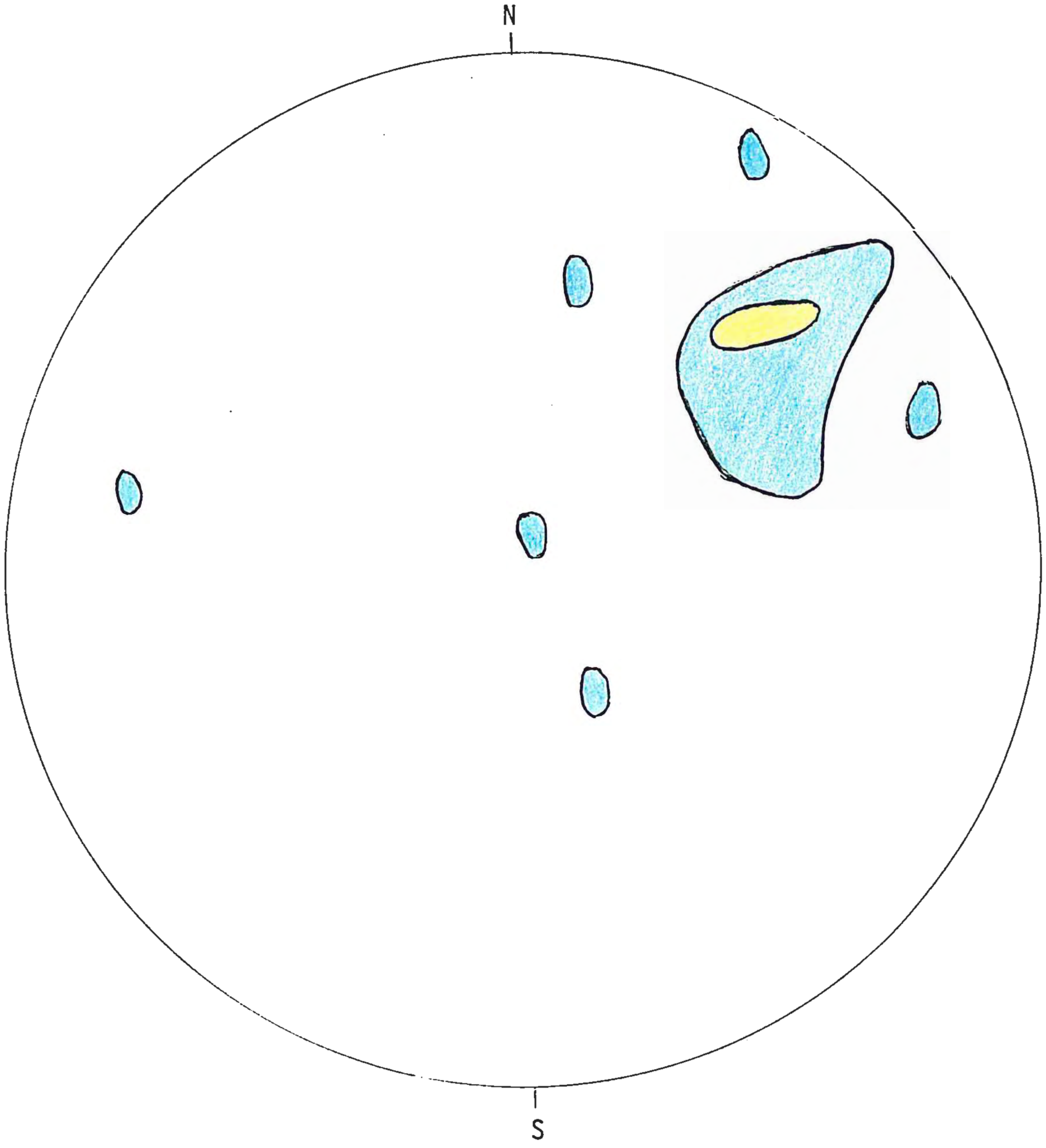


Figure 30: Cleavage-bedding intersections (lineations) for the northern part of the Knife Lake Synclinorium segment 14 points.

part of the Knife Lake Synclinorium segment plunge approximately 75° to the N 19° to 31°E (Figure 31). The intersections within this segment are closely bunched near the center of the stereonet and hence the trend is difficult to delineate, and may only represent an approximation. This lineation varies from the axis of the major fold by an average trend of 20° to the northeast and a dip of 45°. The aberration between the two sets of lineations may be explained most easily by a rotation of the southern part of the segment relative to the northern part of the segment related to the several minor longitudinal faults which subdivide the segment. Gruner (1941) believed that movement along these faults was not restricted to a single plane.

Knife Lake Greenstone Segment

A total of three lineations was obtained from the Knife Lake Greenstone segment. The lineations plunge 50° to 60° to N 10° to 20°E.

Major Folds

Only one major fold axis has been recognized within the present area of study. The axes of other major folds however, can be inferred from bedding and cleavage measurements taken on the flanks of the folds and cleavage-bedding intersections which were hand rotated on stereonets.

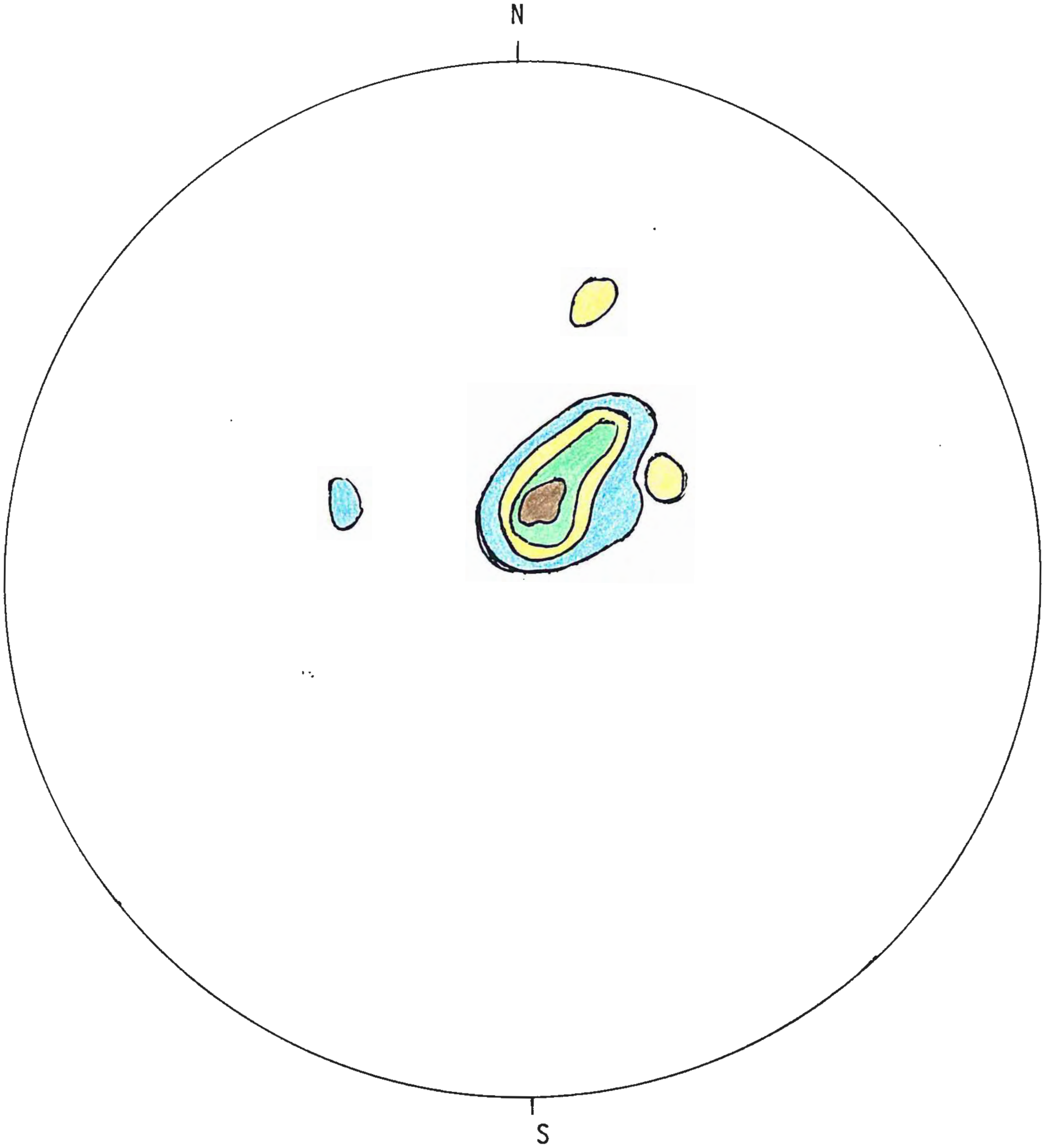


Figure 31: Cleavage-bedding intersections (lineations) for the southern part of the Knife Lake Synclinorium segment, 16 points.

Knife Lake Synclinorium Segment

Topping directions within graded graywacke beds, cleavage-bedding measurements (Figure 29), and vegetation expressions on air photos suggest a major syncline makes up the northern part of the Knife Lake Synclinorium segment. Gruner (1941) originally mapped this segment as a series of isoclinal and overturned synclines and anticlines. Lithologic contacts between the units were drawn to reflect the postulated gross structure within the segment. Detailed mapping using this premise resulted in many lithologic discrepancies with Gruner's interpretation. These lithologic discrepancies observed in the field can be accounted for by a series of minor longitudinal faults which divide the area into several smaller segments. Supporting evidence includes lineaments on air photos and the fact that lithologic discrepancies can be resolved in this manner.

The axis of the syncline which lies in the northern part of the segment is in the vicinity of Cedar Lake (SW¼, Sec. 33, T. 66N., R 6W.) and plunges 30° to N 45°E. Determinations are based on lineations (cleavage-bedding intersections) and air photo expression. The syncline has a strike length of at least 3.5 kilometers and a wavelength of at least 1.5 kilometers. Gruner (1941) suggested an amplitude of 5 to 6.5 kilometers within this segment. Cleavage-bedding intersections (Figure 31) indicate the southern part of the segment, including

Hanson, Cherry and Lunar Lakes, lies on the limb of a fold (or folds) whose axis plunges 75° to N 19° to 30°E. Longitudinal faulting has removed the axis of the fold (or folds) from this part of the segment.

Knife Lake Greenstone Segment

A total of 19 bedding plane measurements and 3 cleavage-bedding intersections was obtained from the Knife Lake Greenstone segment. Several reversals of top and dip directions occur which indicate the presence of several folds. The axis of the fold based on cleavage-bedding intersections plunges steeply to N 20° to 30°E. Vinje (1978) found no evidence of a fold in this structural block based on a minimal amount of bedding plane measurements.

Spoon Lake Segment

Bedding within the Spoon Lake segment strikes N 40° to 50°E and dips steeply to the northwest or southeast. Vinje (1978) suggested on the basis of topping indicators that a syncline, with a strike length of 4 kilometers and a wavelength of 1 kilometer, lies in the northern part of the Spoon Lake segment. The axis of the syncline plunges 35° to S 45°W. Reversals of top and dip directions were noted in this segment, but no determinations could be made.

Minor Folds

Minor folds within the metasediments of the present area of study were restricted to outcrops on Cedar Lake (SE¼, Sec. 33, T 66N, R 6W). No minor folds were found elsewhere in the Knife Lake Synclinorium segment, the Spoon Lake segment or the Knife Lake Greenstone segment. Minor folds related to soft sediment deformation were not recognized within the present area of study, excluding a small outcrop of banded iron-formation on the border of the area which was given only a cursory examination.

Eight minor folds were observed in the Cedar Lake area near the hinge of the major syncline of the Knife Lake Synclinorium segment. The fold axes commonly plunge 45° to N 60°E to N 73°E. Two abberant folds plunge 70° to N 24°W to N 30°W. The folds have wavelengths that range from 20 cm to 50 cm and unknown amplitudes. These folds are dominantly "S" folds (Figure 32).

Faults

The rocks of the Vermilion district were profoundly affected by the longitudinal and to a lesser extend, transverse faulting. The longitudinal faults are probably shear fractures, while the transverse faults may be secondary features that formed as a consequence of movement on the longitudinal faults (Sims, 1972). The development of these faults is considered a late phase of the Algoman orogeny and the pattern of the faults is

Figure 32: Small "S" fold in graywacke-argillite sequence from southeast end of large island on Cedar Lake, Knife Lake Synclinorium segment. Fold axis plunges 45° to N 73°E.

similar to that in much younger island arc-trench environments (Sims, 1972).

Gruner (1941) noted the presence of major longitudinal faults which divide the eastern Vermilion district into seven discrete structural blocks. Four of these major longitudinal faults transgress the present area of study and slice it into three distinct structural blocks; the Knife Lake Synclinorium segment, the Knife Lake Greenstone segment and the Spoon Lake segment (Figure 2). Additionally, transverse faults and smaller longitudinal faults occur in all of the structural blocks.

The longitudinal faults which transgress the present area of study are curvilinear to the northeast, have steep dips (Gruner, 1941) and are subparallel to bedding. Vertical or horizontal displacements are difficult to determine because bedding closely parallels these faults, but displacements are generally believed to be large. Gruner (1941), p. 1622-1623) discussed this problem:

> "The major longitudinal faults divide the district as a whole into segments or belts, each one distinct in itself, but very difficult, if not impossible, to connect stratigraphically with any of the others .... When a unit of structure is completely delineated by faults it is left to one's imagination how it ever reached its present position, possibly by great displacements measurable in miles horizontally and thousands of feet vertically."

Gruner also believed that the shear zones are so broad that displacement is not confined to a single plane. Recognition of the longitudinal faults, as well as transverse faults, is difficult in the field due to the amount of vegetation, lake and swamp cover. Actual faults contacts are rarely exposed and "... are found only after the realization that certain structures do not 'make any sense' when fitted together ..." (Gruner, 1941, pp. 1637). Faults are marked by depressions in the field and are expressed as lineaments on aerial photographs. Longitudinal faults and minor longitudinal faults were plotted on the geologic maps (Plate 1) according to Gruner's (1941) map and after air photo study. Gruner was quite accurate in the placement of the major longitudinal faults which divide the area into the distinct segments, but did not recognize the minor longitudinal faults. Recognition of the minor longitudinal faults was essential to unraveling the structure of the Knife Lake Synclinorium segment.

The Spoon Lake segment is separated from the Kekekabic Lake segment by a major longitudinal fault which is curvilinear to the northeast (Plate 1). The southern boundary of the present area of study is marked by this fault which extends from the South Arm of Knife Lake in the vicinity of Eddy Lake (NW¼, Sec. 20, T 65N., R 6W) to northeast of Link Lake (NW¼, Sec. 2, T 65N, R 6W) and beyond the limits of the mapped area. The fault was observed in the field in only one area, at approximately the intersection of Sections, 16, 15, 21, and 22 in T 65N., R 6W. The fault here is marked by a low, trench-like depression which forms an anomalous swampy area. The rocks within this area are highly sheared dacite porphyry conglomerate and greenstones. The relative displacement between the Spoon Lake segment and the Kekekabic Lake segment to the south is unknown (Gruner, 1941).

The Knife Lake Greenstone segment is separated from the Spoon Lake segment to the south by a major longitudinal fault which trends approximately N 60°E (Plate 1). In the present area of study, the fault extends from the South Arm of Knife Lake (SW¼, NW¼, Sec. 16, T 65N, R 6W) to the vicinity of Pitfall Lake (SE¼, Sec. 11, T 65N, R 6W) where it joins with the major fault which separates the Spoon Lake segment from the Kekekabic Lake segment. The fault is best observed in the eastern part of the study area on the South Arm of Knife Lake where a major gouge zone separates greenstones from graywacke. The gouge zone is marked by a linear trench peripheral to which the rocks are highly sheared. The Knife Lake Greenstone segment may have been raised relative to the Spoon Lake segment to the south by as much as 300 meters to 600 vertical meters (Gruner, 1941).

The Knife Lake Greenstone segment is separated from the Knife Lake Synclinorium segment to the north by a major longitudinal fault which trends approximately N 60°E, becoming curvilinear to the northeast. The fault extends from the South Arm of Knife Lake (SW¼, NW¼, Sec. 16, T 65N, R 6W) to the vicinity of Link Lake (NW¼, Sec. 2, T 65N, R 6W) and beyond the limits of the map area. The fault has not been observed in the field, but is marked by a lithologic break and a lineament on air photos. The displacement of the Knife Lake Greenstone segment relative to the Knife Lake Synclinorium segment to the north is unknown, but Gruner (1941) suggests the Knife Lake Greenstones are older than the conglomerates and graywackes of the Knife Lake Synclinorium segment, and may have been raised relative to them on the order of 3,000 vertical meters.

The Knife Lake Synclinorium segment is separated from the Canadian synclinal segment to the north by a major longitudinal fault which is curvilinear to the northeast. This fault is marked by Cypress Lake, which is also the international boundary between Canada and the United States. In the present area of study, the fault extends from Cypress Lake in the vicinity of Cedar Lake (NW¼, Sec. 33, T 66N, R 6W) to the vicinity of Ben Ambroses' cabin (N¼, Sec. 27, T 66N, R 6W) and northeastward beyond the limits of the mapped area. The faults can be recognized in the field by a sharp change in lithologies and prominent bluffs which border the fault. The Knife Lake Synclinorium segment was depressed vertically on the order of 300 to 600 meters, and the horizontal displacement may have been a "short distance or a mile" (Gruner, 1941, p. 1624).

Minor longitudinal faults within the present area of study are found dominantly within the Knife Lake Synclinorium segment. A probable minor longitudinal fault is located within the northern part of the Knife Lake Greenstone segment between Bullfrog Lake and the southeast tip of Hanson Lake. The probable fault was recognized as a lineament on an airphoto.

Gruner (1941) did not recognize any minor longitudinal faults within the Knife Lake Synclinorium segment, although he alluded that many more faults must exist. The structure of the segment was explained as a series of isoclinaly-folded anticlines and synclines. Field mapping on this premise did not give a coherent structural picture, and it wasn't until the minor longitudinal faults were recognized from air photos that lithologic inconsistancies were resolved. Four of these minor longitudinal faults (Plate 1) subdivide the Knife Lake Synclinorium segment into smaller segments. These faults are subparallel to the major longitudinal faults and displacements are of a much lower order. Transverse faults which transect the trend of the major longitudinal faults are included in the geologic map shown in Plate 1. These faults have much smaller vertical and horizontal displacements than the longitudinal faults and were recognized chiefly as gouge zones within the rocks.

Carbonate associated with shear zones was noted by Feirn (1977), Severson (1978) and Vinje (1978). Severson concluded the carbonate can be explained as the result of the influence of CO_2-rich fluids along faults. No carbonate was recognized within the present area of study.

Interpretation

The structure of the Knife Lake Synclinorium segment can be accounted for in terms of three tectonic deformations. The structural information obtained from the Knife Lake Greenstone segment and the Spoon Lake segment is minimal and no justifiable interpretation could be made with regards to the first or second periods of deformation. Additionally, soft sediment deformation is minor and is excluded from discussion here.

The first period of deformation produced isoclinal folds within the sedimentary rocks along northeast-trending axes. The folds have steep axial planes with subhorizontal folds axes which plunge to the northeast. The folds are defined by reversals in top directions inferred from graded beds. Minor folds which may reflect this deformation were observed near the hinge of the major fold in the Cedar Lake area.

A second tectonic deformation produced the dominant N 54° to 62°W cleavage observed in the Knife Lake Synclinorium segment. Evidence that this is a later deformation was not recognized within the present area of study, but Sims (1972) suggests on the basis of Gruner's (1941) map, that the northwest-trending fold generation is older than the northeast-trending folding. Vinje (1978) however, concluded that this was a later deformation, based on structural data compiled by Severson (1978) and Duex (pending). This deformation is herein considered a later deformation based on the results of Severson's and Duex's more recent work.

The third period of tectonic deformation occurred on a regional scale and produced the major longitudinal faults which divide the present area of study into discrete structural blocks. Sims (1972) assumed the longitudinal faulting to have been contemporaneous with emplacement of the granitic batholiths that surround the Vermilion district. The longitudinal faults within the present area of study are curvilinear to the northeast. Minor longitudinal faults which subparallel the major longitudinal faults are common within the Knife Lake Synclinorium segment. Transverse faults transect the trend of the longitudinal faults, are of smaller dimensions, and occur sporadically throughout the study area. The transverse faults may have formed as secondary fractures as a consequence of movement on the longitudinal faults (Sims, 1972).

SUMMARY AND CONCLUSIONS

Geologic History of the Cypress, Hanson and South Arm of Knife Lake Area

The metavolcanic and mestasedimentary rocks of the Cypress, Hanson and South Arm of Knife Lakes Area belong to a Lower Precambrian greenstone-granite complex known as the Vermilion district. The Vermilion district contains rock which belongs to a basalt-andesite-rhyolite association typical of continental orogenic belts or island arc systems (Goodwin, 1968).

Faulting has divided the rocks of the eastern Vermilion district into seven structural segments (Gruner, 1941). The present area of study is located in parts of three of these segments, the Spoon Lake segment, the Knife Lake Greenstone segment, and the Knife Lake Synclinorium segment (Figure 2). Gruner (1941) considered each of these segments structurally distinct in itself, and believed stratigraphic correlation between the blocks to be very difficult or impossible. For this reason, the depositional history of each structural segment will be given separate from the others, beginning with the Knife Lake Greenstone segment which Gruner (1941) inferred from his mapping was the oldest segment.

Development of rocks within the Knife Lake Greenstone segment began with the deposition of greenstones which Gruner (1941) believed to be analogous to the Ely Greenstone, the first recorded event in the Vermilion district. Deposition was subaqueous as many of the greenstones are pillowed. Subsequent to the formation of the greenstone, uplift and erosion produced a small lens of greenstone-pebble conglomerate peripheral to the greenstone. The conglomerate grades laterally into a plagioclase-rich feldspathic graywacke.

The first event recorded within the Spoon Lake segment was the formation of dacite porphyry as a shallow intrusion or subaerial flow. A massive dacite porphyry conglomerate was derived from the dacite porphyry and deposited adjacent to it. Feldspathic and lithic graywackes were deposited contemporaneously with the dacite porphyry conglomerate and are interbedded with the conglomerate. Their source was also a dacite pile.

The conglomerate and graywackes of both the Knife Lake Greenstone segment and the Spoon Lake segment presumably originated as temporary accumulations on the slopes of volcanic piles. These accumulations were periodically jarred loose by explosive volcanism and earthquakes, which caused submarine landslides which, as they became fluid enough, developed into turbidity currents (Ojakangas, 1972a, 1972b). Therefore, the conglomerates and graywackes are resedimented rocks.

The turbidites of the Knife Lake Greenstone segment and the Spoon Lake segment correspond to facies within a submarine fan of a slope-fan-basin floor system of a turbidite basin as modeled by Walker (1976). The graywackes are contained in the depositional lobe of the inner to middle portion of the submarine fan, where they would be associated with channel conglomerates. The turbidity currents flowed into a moderate to deep water basin since ripple marks and medium to large-scale cross-bedding, indicative of shallow agitated water, are absent. Argillites represent the background deposition of the basin which was repeatedly interrupted by the arrival of these short-lived turbidity currents.

Development of rocks within the Knife Lake Synclinorium segment began with the deposition of tuffs, mafic conglomerates and mixed conglomerates derived from the erosion of pyroclastics, hypabyssal intrusives and possibly subaerial flows. The diversity of volcanic rock fragments, including hornblende andesite, dacite, augite andesite, SRF and MVRF, indicate varied source areas. Deposition of feldspathic graywackes was contemporaneous with the later stages of deposition of the tuff-mafic conglomerate-mixed conglomerate unit, as the two units are interbedded. The turbidite sequences of the Knife Lake Synclinorium segment correspond to facies within the inner fan of the slope-fan-basin model proposed by Walker (1976).

Subsequent to the deposition of the rocks within the Knife Lake Greenstone segment, the Spoon Lake segment and the Knife Lake Synclinorium segment, folding on a regional scale produced isoclinal folds, the axes of which trend northeast. The folding presumably resulted from the diapiric rise of the Vermilion batholith to the north of the Vermilion district, and the Giants Range batholith to the south of the Vermilion district (Sims, 1972).

The rocks within the Knife Lake Greenstone segment and the Spoon Lake segment are steeply tilted an therefore folded.

Little other evidence of folding was noted for these two segments. Evidence for two periods of folding however, is found within the Knife Lake Synclinorium segment. The first period of folding produced isoclinal folds whose hinge surfaces strike east to northeast with near vertical dips and nearly horizontal fold axes (Gruner, 1941). The northern part of the Knife Lake Synclinorium segment contains a major syncline with a strike length of at least 3.5 kilometers and a wavelength of at least 1.5 kilometers, the axis of which plunges 30° to N 45°E. Minor folds are dominantly "S" folds. A second tectonic deformation produced the pervasive N 54° to 62°W cleavage observed in the Knife Lake Synclinorium segment. Relative ages bewteen the two generations of folding was determined by Vinje (1978).

Contemporaneous or subsequent to diapirism, but after folding, the rocks within the eastern Vermilion district were sliced into distinct segments by major longitudinal faults (Gruner, 1941). Four of these major faults divide the Cypress, Hanson and South Arm of Knife Lake area into three segments. The faults are curvilinear to the northeast. Gruner (1941) suggested the Spoon Lake segment may have been lowered relative to the Knife Lake Greenstone segment on the order of 300 to 600 vertical meters. The separation between the Knife Lake Greenstone segment and the Knife Lake Synclinorium segment may be on the order of 3,000 vertical meters. Minor longitudinal faults also cut the rocks within the present area of study, and presumably were responsible for emplacement of fault slices of pillowed greenstone into the Spoon Lake segment. Transverse faults of much smaller vertical and horizontal displacement transect the trend of the major longitudinal faults. The longitudinal faults are probably shear fractures, while the transverse faults are probably secondary features that formed as a consequence of movement on the longitudinal faults (Sims, 1972).

Rocks within all three of the studied segments were intruded during Keweenawan time by diabasic dikes. These dikes are markedly fresher than the older greenstones within the area.

Glacial drift is minor to absent in the eastern part of the Vermilion district. In the present area of study minor glacial debris is found; however, glacially polished and striated surfaces are common. Striations formed by ice sheets of the Rainy Lobe indicate the ice movement during Pleistocene time (15,000 years ago) was from the north-northeast.

Conclusions

Significant conclusions which can be drawn from this study include:

1) The granite-pebble conglomerate of the Knife Lake Greenstone unit mapped by Gruner (1941) is actually a greenstone-

pebble conglomerate. No granitic rock fragments or pebbles were noted in either thin section or hand sample respectively, and staining of heels with sodium-cobaltinitrate indicated no potassium feldspar was present. The dominant clasts in this unit are greenstone clasts derived from the nearby greenstones and dacite clasts which (albeit) resemble granite in hand sample.

2) Source areas for the metasediments of this study area exclusively volcanic in origin. No plutonic rock fragments were observed. The volcanic rock fragments range in composition from basalt to dacite, and were eroded from hypabyssal intrusives, porphyritic flows and pyroclastic deposits.

3) Framework feldspar grains within all of the studied graywackes constitute a considerable percentage, averaging approximately 31 percent. All of the feldspar grains studied are plagioclase. No potassium feldspar grains were found either microscopically or by staining with sodium-cobaltinitrate. No rock fragments within the present area of study have a composition more felsic than dacite, suggesting that the absence of potassium feldspar is due to a deficiency in the source rock, and not related to a secondary phenomenon.

4) Plutonic rock fragments, dominantly quartz and feldspar derived from the Saganaga batholith, have been noted in graywacke samples from the eastern Vermilion district by Ojakangas (1972a,

1972b), Severson (1978), and Duex (pending). Ojakangas (1972a, 1972b) on this basis postulated penecontemporaneous volcanism and unroofing of the Saganaga Tonalite. No plutonic rock fragments or volcanic rock fragments more felsic than dacite have been recognized in the study area. No Saganaga detritus was deposited within the sediments of the present study area and hence no supporting evidence for penecontemporaneous volcanism and unroofing of the Saganaga batholith was found.

5) Turbidite sequences within the Spoon Lake segment and the Knife Lake Greenstone segment are characteristic turbidites corresponding to the inner to middle lobe of a submarine fan. Turbidite sequences within the Knife Lake Synclinorium segment are characteristic of proximal turbidites, and correspond to facies associated with the inner fan of the slope-fan-basin system of a turbidite basin.

6) The structure of the Knife Lake Synclinorium segment can be accounted for in terms of three tectonic deformations. The first period of deformation produced isoclinal folds, which trend N 40° to 50°E and plunge 30° to the northeast. The second period of deformation produced a pervasive N 54° to 62°W cleavage throughout the segment. The third period of deformation occurred on a regional scale and produced major longitudinal faults which has divided the present area of study into distinct structural blocks. These blocks are petrographically distinct

in terms of gross lithologies (e.g., dacite porphyry conglomerate vs. greenstone-pebble conglomerate) and variations in lithologies (e.g., some types of rock fragments found in the graywackes of the Spoon Lake segment are not found in the graywackes of Knife Lake Synclinorium segment).

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