AN EXAMINATION OF THE PETROGRAPHIC TYPES OF THE ELY GREENSTONE OCCURRING IN THE AREA OF TWIN LAKES, MINNESOTA

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ABSTRACT

AN EXAMINATION OF THE PETROGRAPHIC TYPES OF THE ELY GREENSTONE OCCURRING IN THE AREA OF TWIN LAKES, MINNESOTA

by LeRoy W. Smith

The Ely greenstone is an eight to fifteen mile wide strip of Early Precambrian rocks located in north central Minnesota just south of the Minnesota-Ontario boundary. This study is an attempt to evaluate the petrographic types of the Ely greenstone found in the area of Twin Lakes, Minnesota.

In the field the greenstone was subdivided into extrusive, metadiabasic, foliated, and massive greenstone. Felsic porphyry, diabase, and iron formation were found associated with the greenstone. On the basis of field relations and thin section study the felsic porphyry was called a dacite.

Spectrochemical analyses of seventy-eight samples of greenstone were performed to determine their chromium, vanadium, zirconium, nickel, and cobalt content. Elemental concentrations of samples grouped on the basis of petrographic field appearance, apparent trends in trace element concentrations, and enrichment in elemental concentration failed to produce any unequivocal information about the greenstone.

LeRoy W. Smith

Thin sections of thirty-six samples of greenstone were studied in an attempt to obtain more information about individual samples. Although all samples carried a high percentage of secondary minerals, eight distinctive thin sections of greenstone were found that had apparently originated as the following diverse rock types: diabase, porphyritic basalt, monzonite, and lamprophyre. This diversity of original rock type was not evident in the field. Trace element concentrations in these distinctive greenstones were not greatly different from published values of unaltered rocks.

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By

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INTRODUCTION

Problem

The most outstanding characteristics of the Ely greenstone are the amygdaloidal, spherulitic, and ellipsoidal structures that are recognizable in some rock exposures in the field. Other exposures of the greenstone differ in the absence of these structures, color, and texture. This study is an attempt to evaluate all of the petrographic types of the Ely greenstone found in the area of Twin Lakes, Minnesota. Field observations, thin section examination, and spectrochemical analyses were utilized in this study.

Geographic Setting

The Ely greenstone is an eight to fifteen mile wide strip of Keewatin (Early Precambrian) rocks that extends from the vicinity of the town of Tower, Minnesota on the west to the Minnesota-Ontario boundary on the east. Figure 1 shows the general location of the Ely greenstone, and the location of the area within the greenstone selected for this study.

The setting of this study is shown in greater detail in Figure 2. Centered around Twin Lakes, Minnesota, this

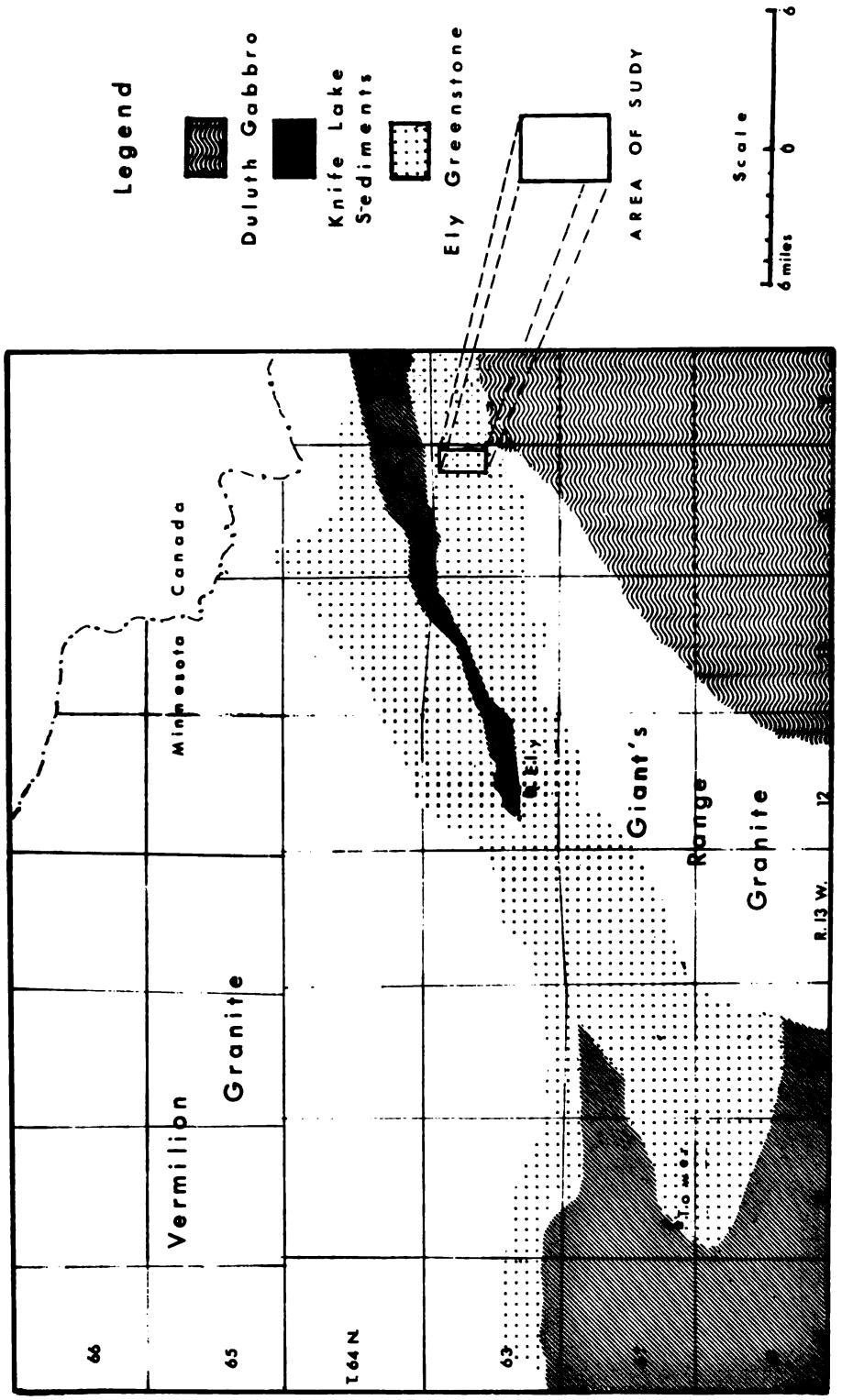
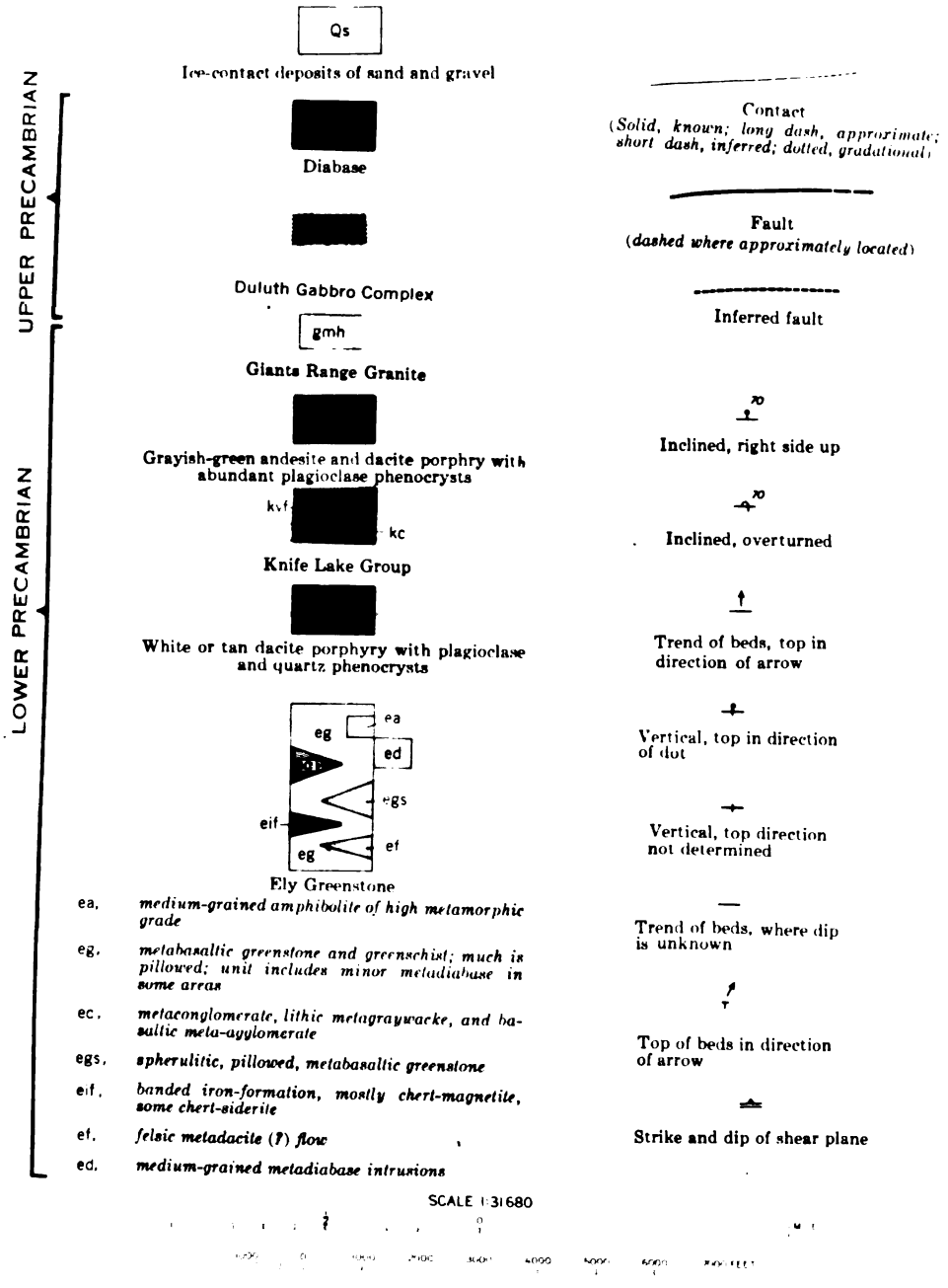


Figure 1. Location of Study Area.

EXPLANATION



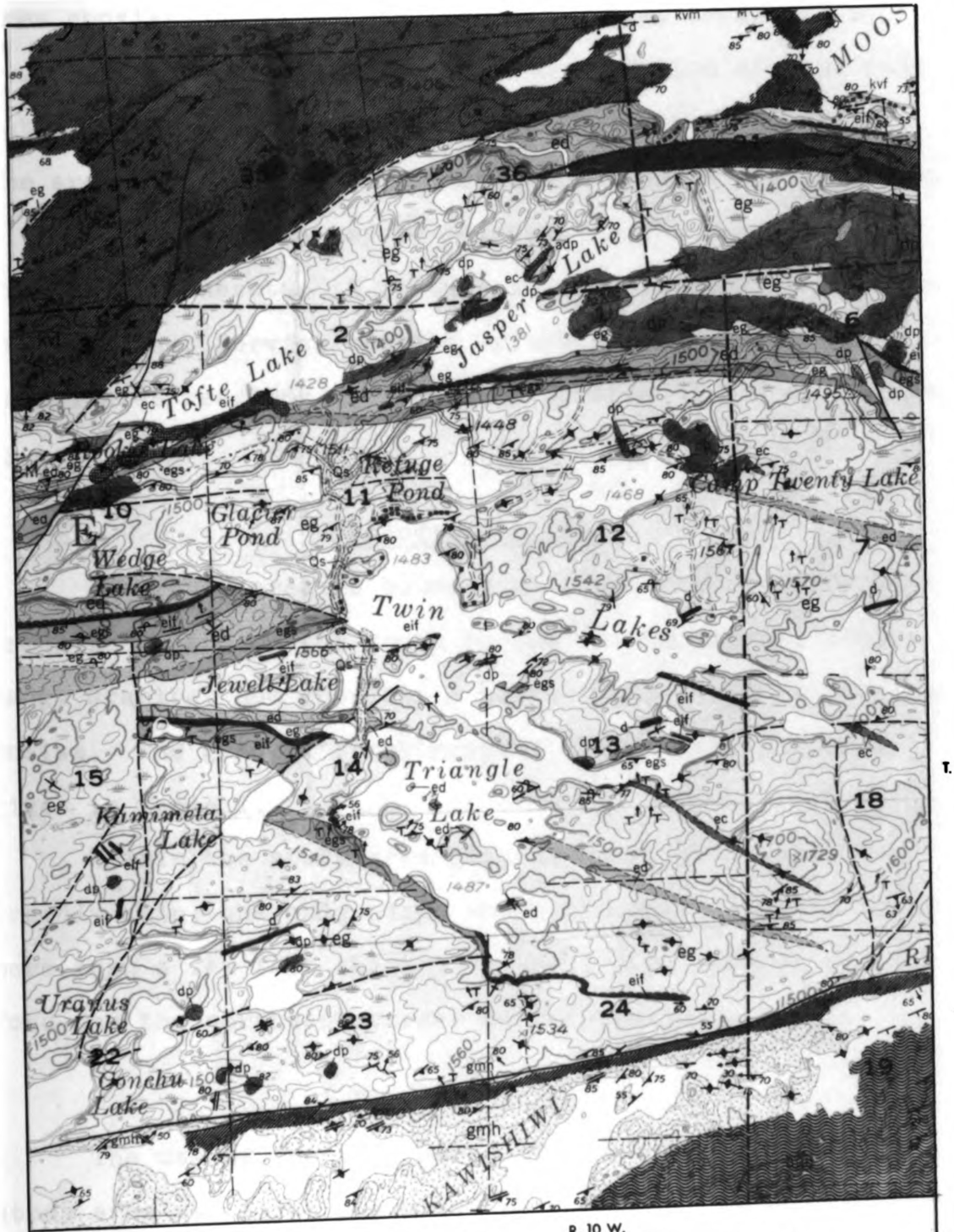


FIGURE 2. GEOLOGIC MAP OF TWIN LAKES, MINNESOTA (GREEN, 1966)

area consists of east-west trending ridges separated by swamps and lakes. Rapid changes in elevation are the rule rather than the exception although the overall relief of the area is only 319 feet. Rock outcroppings are abundant.

The study area may be reached via the Fernberg Road from Ely, Minnesota. A portage is maintained by the United States Forest Service between Triangle and Twin Lakes which facilitates reaching the southern portion of the study area by boat.

Geologic Setting

The study area is bounded on the north by Knife Lake Group rocks and on the south by the Duluth Gabbro, Giants Range Granite, and possibly a narrow band of Knife Lake age gneiss. The general stratigraphic column for this area is given in Table 1.

Within the study area glacial drift is usually extremely thin; the only place where the drift appears to be more than a few feet thick is a small area between Glacier Pond and the northwest corner of Twin Lakes.

Previous Work

The use of the term greenstone for the rocks in the study area was first suggested by Clements (1903).

> In the Vermillion district there is a great complex of igneous rocks whose members possess one general character in common. They are almost universally colored some shade of green; hence for want of a better one, the descriptive term "greenstone" is applied to the complex.

TABLE 1.--Stratigraphic succession and geochronology of the precambrian of Minnesota.[1]

Era (10^9 Years)	Period-System	Major Sequence	Formation	Orogeny	Intrusive Rocks
Paleozoic	Cambrian				
			.....Uncomformity.....		
(0.6 b.y.)			Hinckley sandstone		
			Fond du Lac sandstone		
			.....Unconformity.....		
(1.1 b.y.)					
Late Precambrian	Keweenawan	North Shore volcanic group	Undivided	Grenville	Duluth Complex
			Puckwunge		
			.....Unconformity.....		
			Sioux quartzite (?)		
			.....Unconformity.....	Penokean	
			Virginia argillite=Rove=Thomson		
		Animikie group	Biwabik iron-formation=Gunflint		
Middle Precambrian	Huronian		Pokegama quartzite		
			.....Unconformity.....	Algoman	Giants Range Granite Vermilion Granite
(2.5 b.y.)					
	Timiskamian	Knife Lake group	Undivided		
(? b.y.)			.....Unconformity.....	Laurentian	
			Soudan iron-formation		
Early Precambrian		Keewatin group			
	Ontarian		Ely greenstone		
		Coutchiching (?)	Undivided		
			Older rocks		

[1]Goldich (1961).

This series of green rocks, including the associated Soudan iron formation, had originally been named the Kawisiwin Series by Winchell (1899). Since Clements' (1903) work is the only comprehensive study of the greenstone ever completed and his nomenclature was that advocated by the United States Geological Survey, the terms Ely and Soudan have been generally adopted.

Clements (1903) gave particular emphasis to three macroscopic structures found within the Ely greenstone. He felt that the amygdaloidal, spherulitic, and ellipsoidal structures indicated strongly that the Ely greenstone originated as surface or submarine flows. He also recognized the presence of intrusives but considered that most of these were the result of magma that penetrated contemporaneous flows as dikes.

Clements (1903) found the ophitic texture to be most common in the coarse-grained greenstone. Ophitic, microphitic, intersertal, pilotaxitic, flowage, and spherulitic textures were noted in the fine-grained rocks.

The original textures of many thin sections of the Ely greenstone were found completely altered to a confused aggregate by Schwartz (1924). He observed that nineteen out of fifty thin sections he examined showed remnants of diabasic texture. Schwartz noted that porphyritic texture with feldspar as phenocrysts is common and felt that these rocks were a later contact intrusive phase of the greenstone.

Gruner (1941) made a study of the structure of the area around Knife Lake, Minnesota which extends to a point three miles east of the present study area. On the basis of structures within the Knife Lake sediments, Gruner delineated major longitudinal faults dividing the district as a whole into long segments or belts. Each one of these belts was thought to be distinct in itself but impossible to connect stratigraphically with any others.

Gruner (1941) observed a whitish-weathering acidic rock in the greenstone most of which consisted of a felsic groundmass and small quartz or feldspar phenocrysts. He set the age of these felsic porphyries as Laurentian since they were not found in the Knife Lake sediments.

Gruner (1941) felt that the greenstone found in the Knife Lake area was not in tight, isoclinal folds characteristic of the Knife Lake rocks. He believed that instead they may have been flexed, sheared, and tipped on edge in response to the same forces that folded the Knife Lake sediments. He cited as proof for this belief the vertical and straight attitudes of the felsic prophyry dikes. His rationale was that if the greenstones had been folded they would have shown defects of deformation due to folding.

Klinger (1956) found large amounts of clastic, tuffaceous, and sedimentary materials within the Ely greenstone in the vicinity of Tower, Minnesota. In one outcrop within the greenstone Klinger found sediments showing

graded bedding indicating the presence of a sedimentary sequence below the Ely greenstone.

In his comprehensive work on the geochronology of northern Minnesota, Goldich (1961) stated that the presence of a sedimentary formation below the Ely greenstone is difficult to demonstrate. Goldich's stratigraphic column for the Precambrian of the study area is reproduced as Table 1.

Post metamorphic hydrothermal solutions were responsible for the iron ore deposit within the Ely greenstone according to Machammer (1964). In his study of the Zenith Mine located at Ely, Minnesota he found mineralogical zoning within the ore body grading outward from the ore body through kaolinite, muscovite, and chlorite zones into unaltered greenstones. The localization of iron deposition within jasperlite was thought to be due to its brecciated condition.

Two recent maps of the area covered by this study are available. An aeromagnetic map by Meuschke and others (1963) recorded two long, narrow, high anomalies, one on the north end and one on the south end of the present study area. An egg-shaped high anomolous area appeared in the center of the present study area. Iron formation was located in the area of all three of these anomalies.

J. C. Green (1966) prepared the portion of the geologic map of the Gabbro Lake quadrangle that covers the

present study area. He differentiated the rocks within the map area into seven rock units. His structural interpretation followed closely that of Gruner (1941). A portion of Green's map was used for Figure 2.

Method of Attack

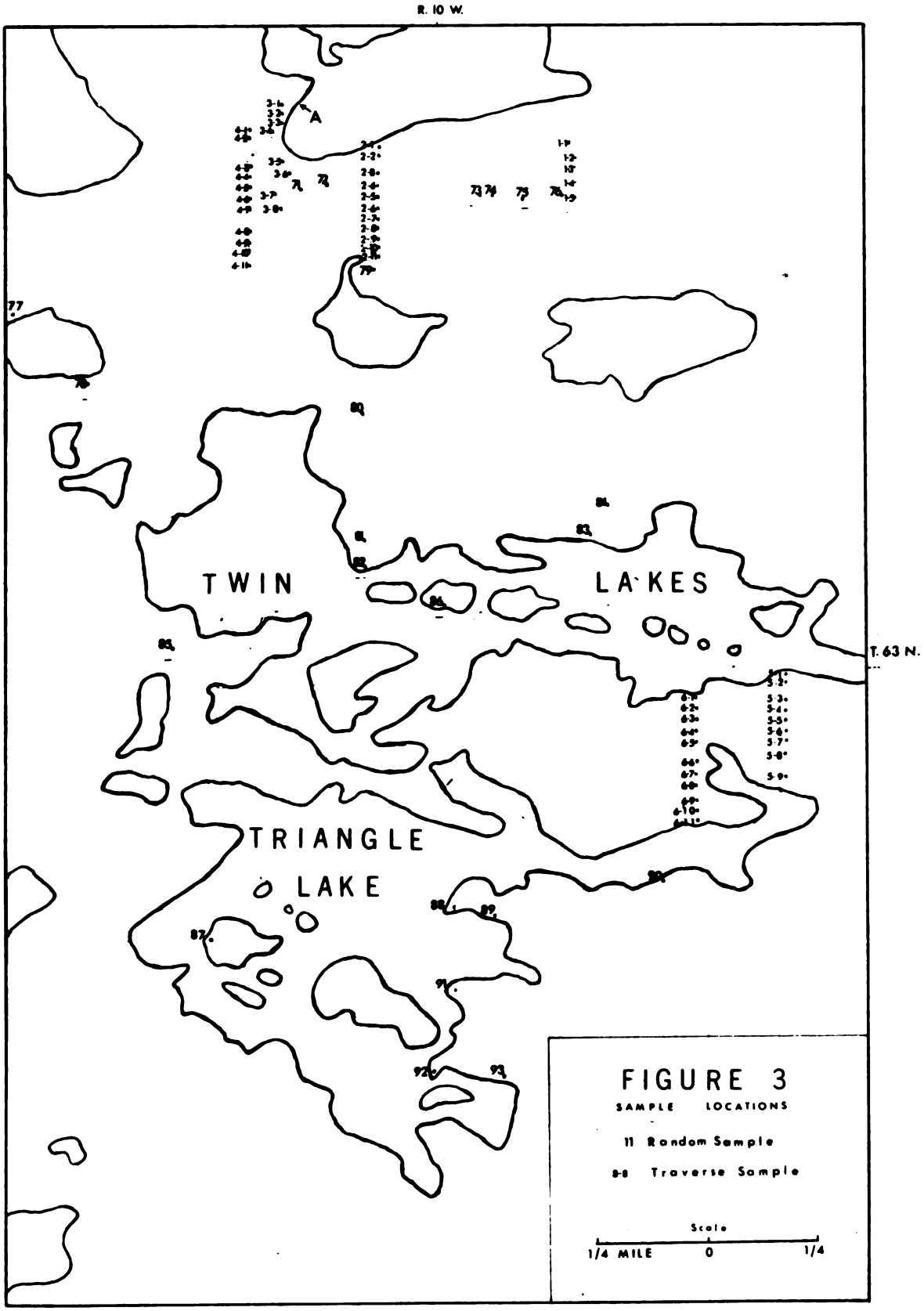
Field work was conducted with two objectives: (1) obtaining a representative sample of individual petrographic types for subsequent laboratory examination, and (2) establishment and examination of contacts between petrographic varieties within the greenstone.

The first objective was attempted during the 1966 field season by randomly picking points within the study area on aerial photos and then visiting these points to collect samples. These sample locations are numbered from 71 to 93 on Figure 3.

The second objective was accomplished during the 1967 field season by sampling along six traverse lines. These traverses were run perpendicular to the regional strike of the area and were laid out in the field by pacing with a solar compass using aerial photos for control. The locations of these samples are noted by the dashed numbers in Figure 3.

Petrographic Methods

Thin sections from throughout the area of the Ely greenstone, loaned by United States Steel, were examined.


R. 10 W.
A
TWIN
LAKES
T. 63 N.
TRIANGLE
LAKE
FIGURE 3
SAMPLE LOCATIONS
11 Random Sample
8-8 Traverse Sample
Scale
1/4 MILE
0
1/4

These together with a review of Schwartz's (1924) paper allowed the writer to obtain a preliminary idea of some of the rock types occurring in the Ely greenstone.

Thin sections of rocks from the area were studied, some commercially ground and some prepared by the writer. Sawed sections were compared with thin sections. Comments on individual samples will be presented later. In general, thin section examination had to be confined to the identification of major minerals and textures present because of the highly altered character of the rock.

Spectroscopic Analyses

Representative 15 gram samples were ground to coarse sand size between two rocks obtained from the same sample locations. Final grinding was then done in a Spex Mixer Mill fitted with a high-alumina ceramic vial and ball. This grinding procedure produced a powder, the bulk of which was less than 200 mesh.

Graphite powder (National Carbon Co., Grade Sp-2) was mixed with the sample to assure a smoother, more complete burn on the spectrograph. Spectrographically pure palladium was also added to the sample to act as an internal standard as recommended by Ahrens (1960). The proportions of the various constituents were as follows: Sample--91 parts, graphite--183.1 parts, and palladium--:01 parts.

Analytical conditions were as follows:

Excitation:	Interrupted arc, 30 ohms, 40 mfd, 360 mh, 15 sec burn, sample positive.
Slit:	20 microns wide, 3 mm long.
Transmittance:	60%
Electrodes:	.242-inch graphite electrodes.
Plates:	Eastman Kodak Spectrum Analysis No. 3.
Processing:	Developer D-19 3½ min., Stop 3% acetic acid 30 sec., fixer Kodak fixer 10 min.
Photometry:	Jarrel-Ash Microphotometer.
Calculations:	Seidal calculating board, calibration curve from iron spectrum by two step filter method.
Analysis Lines:	CR 2843.2 V 3185.34 Zr 3391.8 Ni 3414 Pd 3421 Co 3453.5

External standards were established as recommended by Dolwell (1967). Standard rock samples, granite G-1 and diabase W-1, were used to obtain a working curve over a limited range and this curve was extended for a wider range of concentrations utilizing the slope obtained from synthetic mixtures.

All values are based on duplicate analyses. Sample 2-7 was analyzed 29 times to obtain an estimate of the reproducibility of the data. The standard deviations for these 29 determinations were as follows:

Ni ± 8.8%

Cr ± 14.6%

Zr ± 16.7%

Co ± 17.5%

V ± 22.8%

The precision of the vanadium value was considered poor. It was also later observed that the vanadium values obtained for all samples were consistently about twice the expected values. Although the vanadium line read was that recommended by Ahrens (1960) and numerous other sources, a search was made of the literature to determine if any mention had ever been made of the unreliability of the 3185.34 angstrom line of vanadium.

This search of the literature revealed that Shaw (1958) had observed that this vanadium line is coincident with an unlisted calcium line. Shaw maintained that V 3185 angstrom could be used only if the sample contained less than 2% CaO. Since the lowest published analysis of CaO in the Ely greenstone is 4.46% (Schwartz, 1924), the values for vanadium determined in this study were undoubtedly high. No other suitable vanadium lines were present.

STRATIGRAPHY OF THE ELY GREENSTONE

Study of Green's (1966) geologic map and Meuschke's (1963) aeromagnetic map of the area revealed that the iron formation occurrences tend to strike roughly east-west to north 70° west. Green frequently shows dacite units and extrusive greenstone units roughly conformable with the iron formation. From this information it was decided that traverses run perpendicular to iron formation would be most likely to maximize the number of petrographic types encountered. The following rock types were recognizable in the field.

Extrusive Greenstone

The most distinctive rock type found within the greenstone is the spherulitic, ellipsoidal, and amygdaloidal greenstones. Rock outcroppings showing one or more of these extrusive characteristics were designated extrusive.

The most outstanding feature of this rock type in the field is its irregularly weathered surface. Figure 4 shows the broken nature of an outcrop of extrusive greenstone. Close inspection of this rock type often reveals a surface with many gash-like indentations as illustrated in Figure 5.

FIGURE 4.--Extrusive greenstone outcrop showing irregular weathered surface. Sledge hammer is 32 inches in length. Location is 600 feet east of sample location 6-2 in the NE 1/4 of section 13.

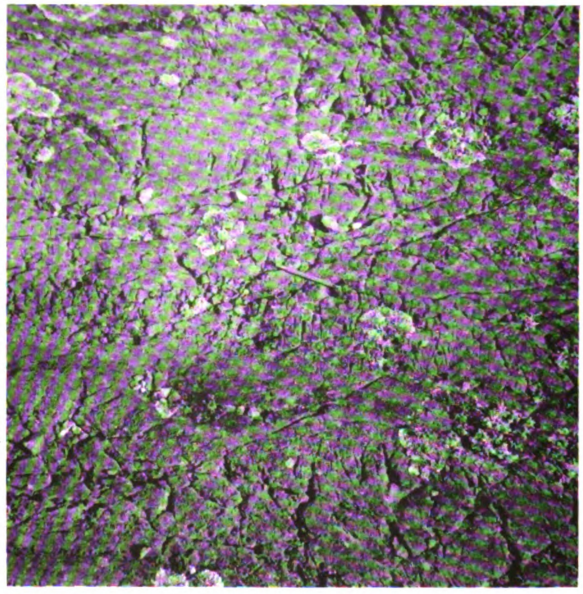


FIGURE 5.--Close-up of gash-like weathering of extrusive greenstone. Pencil is 5 inches in length. Location is 100 feet east of sample location 4-7 in the SE 1/4 of section 2.

Thin section examination of this rock type revealed an almost opaque mass of green. However, the radiating texture seen frequently suggests that zeolites were originally present. In one thin section dull brown, tangled fibers were observed. These probably represent chalcedony or zeolites.

Metadiabasic Greenstone

Almost always occurring within or adjacent to greenstone showing extrusive features is an extremely fine-grained light green rock type. This rock characteristically contains many small calcite veinlets. Its specific gravity is frequently slightly less than 2.9.

In several places where the contact of this rock with extrusive greenstone could be observed it appeared to have originated as a sill. Figure 7 shows this relationship.

Iron Formation

The iron formation occurring in the area is really three different rock types. A gray-black massive chert was found at the north end of traverse four. Banded chert-magnetite was found in traverses two, five, and six. Lastly, a well-banded chert and siderite rock was round in the roadcut 300 feet to the east of station 4-5 in traverse four.

FIGURE 6.--An extrusive greenstone-metadiabasic greenstone contact occurs between the two sample bags. Amygdules can be seen in the extrusive greenstone on the left. The sample bags are eight inches in length. Location is 200 feet east of sample location 3-8 in the SE 1/4 of section 2.

FIGURE 7.--Diabase dike contact with massive greenstone. Location is in the NE 1/4 of section 13.

It has been previously noted that the iron formation tends to occur adjacent to the extrusive greenstone and dacite.

Another distinctive feature of contacts of the iron formation with the greenstone was the tendency of the greenstone to become lighter in color and more mottled in appearance within one hundred feet of the greenstone-iron formation contact. This was observed in traverses three, five, and six.

Foliated Greenstone

Occurring just to the south of extrusive greenstone in traverse four was a 200-foot wide belt of crudely foliated rocks. Megascopic examination of these rocks seemed to indicate that their foliation was due to parallelism of green hornblende and/or chlorite flakes.

Field examination of this rock type failed to reveal any definite criteria to establish whether its texture was due to a sedimentary origin or to subsequent shearing. Although the occurrence cited was adjacent to extrusive greenstone, other occurrences were observed that did not appear to be associated with extrusive greenstone.

Thin section examination failed to produce any helpful information on this rock type.

Diabase

A relatively fresh diabase dike was observed in the NE¼ of section 13. This dike was shown on Green's (1966) map. Directly across the small bay from the location shown by Green the chilled contact of the dike shown in Figure 7 was observed. This was considered noteworthy because the other rock units observed in the field failed to show recognizable chill zones.

Massive Greenstone

This rock type represents what remains after the greenstones showing more distinct field characteristics have been described. Its weathered surface is smooth; it is medium to dark green in color; and its grain size is usually that of a basalt. Sawed sections of this rock usually reveal two or three shades of green that give it a mottled appearance.

Sawed sections revealed a curious variety of textures which indicated that this rock type actually contained several distinct types. Thin sections were obtained of several of these types and trace element analyses were determined for comparison with the extrusive greenstone and the foliated greenstone.

Dacite

Frequently occurring adjacent to iron formation or extrusive greenstone was a light feldspathic rock with

quartz or feldspar phenocrysts. Green (1966) designated this rock a dacite, and that designation will be used here.

Unfortunately this rock type is extremely limited in exposure, being frequently found on the edge of swamps or lakes or on islands in the swamps and lakes.

In megascopic appearance and the location of field occurrences, this rock type appeared to match the felsite porphyry described by Gruner (1941) as Laurentian dikes. Proof that the dacite was intrusive into the greenstone was extremely difficult to find in the study area due to the limited exposure of the dacite.

One contact of the dacite that was observed at the north end of traverse three was so interesting and problematic that it deserved detailed description. On the north side of the mouth of the small bay labeled A in Figure 2 is found the breccia pictures in Figure 8. It is composed of angular greenstone fragments in a carbonate matrix. The long axes of these fragments are roughly parallel. This breccia contacts the dacite a few feet from the water's edge. This contact can be seen in Figure 9.

Is this breccia eruptive, flow, or contact? The calcite matrix would tend to indicate that it was not a flow or eruptive breccia since these are usually cemented with fine basaltic or a felsic matrix. However, the aligned fragments are not what would be expected

FIGURE 8.--Breccia composed of greenstone fragments set in a carbonate matrix. Location is on the east shore of Jasper Lake in the NE 1/4 of section 2. Exact location is marked with an A in Figure 2.

FIGURE 9.--Breccia-dacite contact located four feet north of Figure 8.

from a contact breccia formed by the shattering of wall rock.

Thin section examination of this breccia revealed that the greenstone fragments do not have sharp contacts with the calcite. This seemed to suggest that the calcite has replaced a basaltic matrix that had corroded the fragments. Therefore, it would seem probable that this breccia was originally a flow breccia and likely that the dacite overlying it was not intrusive.

Thin section examination of the dacite reveals extremely large phenocrysts (up to 4 mm. in diameter) set in a fine-grained quartz, feldspar, and calcite matrix. The following outstanding features were noted in the dacite: (1) an extreme excess of calcite occurs in the ground mass over that expected in a dacite, (2) quartz grains present occur in a great variety of sizes, (3) some abnormally large crystals of both quartz and feldspar are present, (4) although most quartz was clear, some contained inclusions that appeared identical to the ground mass of the rock, and (5) embayment that is present suggests encroachment.

All these features of the dacite would indicate that the "phenocrysts" in the dacite are in part phyroblasts. These criteria are those suggested by Grout (1941) and for the development of igneous looking rocks by metasomatism.

One outstanding refutation of this view would be an explanation of the previously mentioned breccia adjacent to this dacite as a contact breccia. This was earlier considered unlikely. The development of this "dacite" is then believed to be due largely to metasomatic replacement. It is suggested that the original rock originally contained ferromagnesium minerals which have been replaced and whose volume is now occupied by quartz, feldspar, and calcite.

TRACE ELEMENT GEOCHEMISTRY

The behavior of many trace elements in a solidifying silicate melt is fairly well understood. Goldschmidt (1937, 1944) felt that an element's ionic structure, atomic structure, and ionization potential determined the affinity of each element between the various possible mineral structures. Work since Goldschmidt's has revealed the importance of other factors especially for non-ionic bonds. This recent work has been summarized by Taylor (1965). If the concentrations of these elements were due only to one or more solidifying silicate melts, the following factors would govern their distributions in minerals.

Vanadium

In magmas vanadium is probably present as Va^{3+}. Vanadium occurs in magnetite, pyroxenes, amphiboles, and biotite. Ringwood (1955) has linked the appearance of V in residual melts to the fact that its high ionic potential is sufficient to cause a complex to form in volatile-rich magmas.

Nockolds and Mitchell (1948) gave the vanadium distribution as follows in a diorite:

	ppm
Plagioclase	20
Hypersthene	100
Augite	200
Biotite	400

Zirconium

The high charge and large radius of zirconium make it difficult for zirconium to enter any of the common rock forming silicates. It has been found to enter early Skaergaard pyroxenes and late apatites but was not found in plagioclase or olivine. The majority of zirconium in igneous rocks is found in the mineral zircon.

Chromium

Chromium is present in magma as the Cr^{3+}; its radius is very close to that of Fe^{3+}. However, the smaller electronegativity of Cr^{3+} as compared with Fe^{3+} leads to chromium's preferential removal at an early stage of fractional crystallization of a basic magma. Chromium is found principally in the mineral chromite. It is also found in pyroxenes. Wager and Mitchell (1948, 1951) explained chromium's limited entry into Skaergaard olivines and ilmenites by its inability to occupy Fe^{2+} positions due to the charge difference.

The occurrence of chromium in a diorite is given by Nockolds and Mitchell (1948) as follows:

	ppm
Plagioclase	---
Hypersthene	200
Augite	1500
Biotite	800

Nickel

The radius of nickel is nearly identical to that of magnesium. In early basic rocks nickel occurs concentrated and apparently is substituting for magnesium. In later formed rocks the ratio Ni:Mg decreases indicating that perhaps the bonding character of Ni causes its preferential concentration in early crystallates. In igneous rocks nickel is found in silicates, sulfides, oxides, and occasionally as iron-nickel alloys. In silicates nickel is usually found concentrated in early formed olivine. The pyroxenes and to a smaller degree the amphioboles also contain some nickel.

Nickel was found in augite, hypersthene, and biotite in a norite by Nockolds and Mitchell (1948) as follows:

	ppm
Plagioclase	---
Hypersthene	300
Augite	200
Biotite	150

Cobalt

In basic rocks, Ni and Co enter the olivine structure because of their similar size and charge. The slightly larger size of Co^{2+} does restrict the acceptance of cobalt into magnesium positions to a greater degree than for nickel. The relationship between the depletion of Ni and Co has been shown by Taylor (1965). Because of the faster depletion of nickel, the Ni:Co ratio falls during fractionation.

Nockolds and Mitchell (1948) found cobalt distributed in the following manner in a diorite:

	ppm
Plagioclase	15
Hypersthene	100
Augite	70
Biotite	50

Trace Element Concentrations in Rocks

Since trace elements are preferentially accepted in specific minerals, rocks with a given mineral assemblage usually have similar trace element concentrations. Trace element analyses of basic igneous rocks usually show high concentrations of nickel, cobalt, vanadium, and chromium due largely to their high percentage of ferromagnesian minerals. Zirconium in contrast tends to be concentrated in acidic igneous rocks due to its selective

occurrence in the mineral zircon. Table 2 lists the trace element concentrations of several suites of igneous rocks.

Argillaceous sediments show less characteristic trace element concentration due to their more variable mineralogy. In general, the Cr, Co, and Ni concentrations in these rocks tend to be lower than in basic igneous rocks. A comparison of some published trace element values for basalts and argillaceous sediments is presented in Table 3.

In the field, the only evidence available suggests that the Ely greenstone, with the exception of the dacite, was all originally a basic igneous rock. It would then seem a reasonable hypothesis to test whether the trace element composition of the Ely greenstone is close to that of a basic igneous rock. Consistent trends in trace element concentrations could perhaps indicate differentiation in the original basic rock.

Since pelites derived from argillaceous rocks could easily be mistaken for metamorphosed basic igneous rocks, their trace element concentrations must also be considered.

This approach to trace element data assumes that no chemical migration or enrichment has occurred in the rock since it was formed. Unfortunately the analysis of the trace element concentrations is complicated by the possibility of chemical mobility after the rock was formed.

TABLE 2.--Trace element concentrations in rocks.

	Skaergaard Intrusive Rocks[1]				Tertiary Lavas of NE Ireland[2]				Hawaiian Lavas[3]				
	Gabbro-pierite	Olivine Gabbro	Ferro Gabbro	Grano-Phyre	Olivine Basalt	Tholeite Basalt	Quartz Trachyte	Rhyolite	Picrite Basalt	Basalt	Andesine Andesite	Oligodase Andesite	Trachyte
Ni	1000	120	62	9	900	50	65	13	950	85	7	13	15
Co	90	48	20	5	140	110	8	2	75	35	14	6	2
V	120	220	4	9	630	750	55	2	250	280	70	19	<5
Zr	30	33	20	1200	180	700	3000	2000	75	100	350	1250	1500
Cr	1500	230	<1	11	1600	150	50	<1	1750	470	<1	<1	20

[1]Skaergaard Rocks: L. R. Wager and R. Mitchell, "Distribution of Trace Elements During Strong Fractionation of a Basic Magma," Geochim. et Cosmochim. Acta, vol. 1, 1951, p. 199, Table F.

[2]Irish Lavas: M. E. Patterson, "A Petrochemical Study of the Tertiary Lavas of Northeast Ireland," Geochim. et Cosmochim Acta, vol. 2, 1952, p. 291.

[3]Hawaiian Lavas: L. R. Wager and R. L. Mitchell, "Trace Elements in a Suite of Hawaiian Lavas," Geochim. et Cosmochim. Acta, vol. 3, 1953, p. 218.

TABLE 3.--Trace element concentrations in shales and basalts.

	Shales		Basalts	
	Shaw (1954)	Leutwein (1951)	Patterson (1952)	Wager & Mitchell (1953)
Cr	110	40	150	470
Ni	64	70	50	85
Co	18	11	110	35

One of the most obvious indications that elemental concentrations might have taken place are the pillow structures, amygdules, and volcanic breccias of the extrusive greenstone. They bear particular relevance to the topic under discussion since they all indicate an area of active volcanic vents. Investigation around recent volcanic areas quite frequently reveals encustations containing nickel, cobalt, and other constituents (Barth, 1952). Therefore, volcanic gases must be considered as a potential source of elemental concentrations within the Ely greenstone.

A further complication within the Ely greenstone is the fact that it has been subjected to low grade regional metamorphism. The extent to which elements are transported in a metamorphic environment remains problematic. Shaw (1954) found the distribution of trace elements was little changed by the metamorphism of pelitic rocks of the Devonian Littleton Formation, New Hampshire.

Devore (1955) maintained that there were distinct changes in trace element concentrations in minerals from metamorphic rocks. He proceded one step beyond his results and stated that a change in metamorphic facies could result in the release of vast amounts of various elements. He further stated:

> The presence of a fault, fold fracture, or tensional shear zone could localize a physically different environment which might be either the site of subsequent mineral formation or the means by which different physical and chemical environments are brought into chemical communication. Therefore, during metamorphic transformations there are commonly present the conditions to localize and concentrate efficiently and effectively certain dispersestate materials in the area and cause others to migrate.

The last mechanism to consider as a possible cause of chemical redistribution is metasomatism. As defined by Grout (1932)

> Metasomatism or replacement is a practically simultaneous solution and deposition through small openings, usually submicroscopic, and mainly by hypogene water solutions, by which a new mineral of partly or wholly differing composition may grow in the body of an old mineral or mineral aggregate.
> . . . . . .
> The common examples of metasomatism in metamorphism are those of contact action and those of hydrothermal attack on walls of veins. The prominent effects noted in contact action are the replacement of limestone by andradite and other heavy silicates, the replacement by iron ores, the formation of metacrysts in schists, and a general silification of both limestones and shales. Hydrothermal action typically propylitizes and sericitizes the igneous rock.

Local hydrothermal replacement within the Ely greenstone has been discussed by Machammer (1964), Schwartz

Reed (1955), and Klinger (1956). These instances were all in connection with commercial iron formation. Perhaps a more relevant consideration was Schwartz's (1924) labeling of the entire Ely greenstone as having been subjected to hydrothermal metamorphism. The implication was that considerable chemical transfer accompanied metamorphism throughout the greenstone.

SPECTROCHEMICAL ANALYSES OF THE ELY GREENSTONE

Seventy-eight samples of greenstone were spectrochemically analyzed for chromium, vanadium, zirconium, nickel, and cobalt. The results of these analyses are listed in Appendix A.

Answers to the following questions were sought from these analyses: (1) How do the concentrations of trace elements in the various petrographic field types compare with published analyses of shales and basalts? (2) Could trends in trace element concentrations be found that indicate differentiation in an original igneous rock? (3) What significance could be attached to significant enrichments in trace element concentrations?

Figure 10 shows a comparison of the range of concentrations for basalt and shale as compared to petrographic field types of greenstone located north of Twin Lakes. Examination of the Cr and Ni reveals that these values are low compared to the other field types and to concentrations usually found in basaltic rocks.

Because of the extreme variability of element concentrations in various petrographic field types,

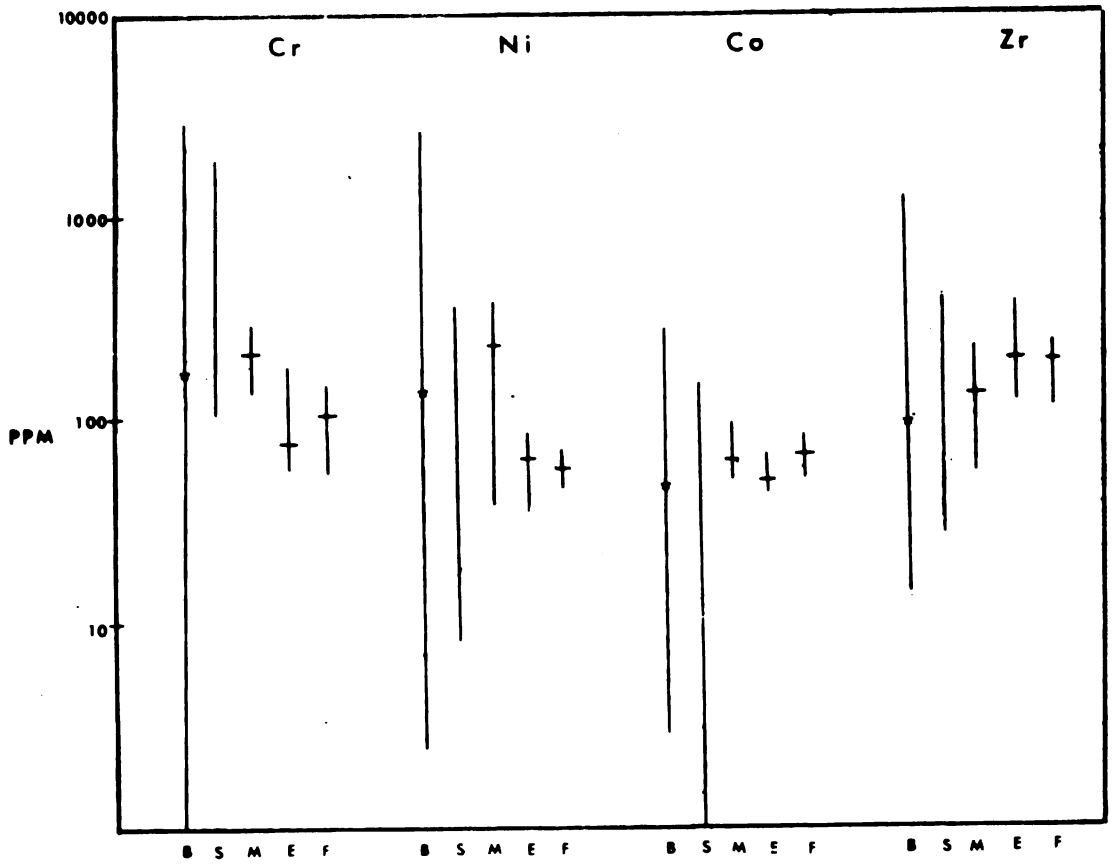


FIGURE 10.--The range in trace element concentrations in parts per million for basalt (B) and shale (S) as compared to petrographic field types of greenstone. Greenstone types are massive (M), extrusive (E), and foliated (F). The average basic igneous rock is indicated by a cross. The horizontal line on the greenstone range indicates the arithmetic mean.

Average basic rock values and the ranges are as summarized by Evans and Leake (1960). The average basic igneous rock is indicated by a cross. The values were obtained from Turekian (1956) for Cr and Ni, Degenhardt (1957) for Zr, and Green (1954) for Co. The abundance ranges for basalts were compiled from Amstutz (1953); Cornwall and Rose (1957); Degenhardt (1957); Fairbairn, Ahrens, and Gorfinkle (1953); Nockolds and Allen (1954-56); Patterson (1951); Patterson and Swaine (1955); Wager and Mitchell (1953); and Young (1957). The abundance ranges for shales were compiled from Krauskopf (1955); Macpherson (1958); Mohr (1959); Rankama and Sahama (1950); and Shaw (1954).

little other unequivocal information could be derived from Table 4. The low Cr and Ni concentrations of the foliated greenstone could indicate that this rock was originally a shale.

When the data was examined for trace element concentrations that showed trends over several traverse points, samples 4-1 through 4-4 and 6-11 through 6-7 were the only ones that could be cited for consistent trends over more then two sample points. These values are reproduced for convenience in Table 4.

TABLE 4.--Trends in trace element concentrations.

Sample	Cr*	V	Zr	Ni	Co
4-1	250	640	175	132	92
4-2	250	630	140	73	76
4-3	140	520	115	48	79
4-4	90	440	230	52	72
6-7	260	440	140	67	90
6-8	200	360	120	83	64
6-9	180	510	180	77	52
6-10	<72	460	320	<40	58
6-11	<72	trace	540	<40	<27

*All values in ppm.

Samples 4-1 through 4-4 shown in Table 4 show a continuous trend that could indicate that these rocks were originally part of a differentiating igneous body. Co, Cr, and Zr all decrease regularly from 4-1 to 4-4. This would put the top of this body to the north. This agrees with the pillow tops just north of this unit.

In opposition to this theory Ni does not wholly reflect this trend, and Zr values for these samples reflect almost the opposite of what might be expected. A more serious objection to a differentiation interpretation to this trend is the foliated appearance of samples 4-3 and 4-4. This trend could also be interpreted as gradational sedimentary variation.

Samples 6-11 through 6-7 also show somewhat consistent trends in element concentration. Although sample 6-11 could be described as a metamonzonite in thin section, microscopic examination of samples 6-10 and 6-7 did not reveal recognizable original textures. In general, unequivocal evidence of original igneous differention in these greenstones was impossible to find.

Using the values of massive greenstone for comparison, eight samples were selected from the analyses whose concentrations were more than two standard deviations greater for two or more elements. Thin section examination of two of these samples failed to reveal whether the high concentrations of these elements were due to the fact

that these rocks were originally ultrabasic igneous rocks or were caused by the introduction of these elements into the rock.

One outstanding feature these samples have in common is their proximity to iron formation. However, not every sample close to iron formation carried high concentrations of Cr, Ni, or Co. This indicated that the stratigraphic position close to the iron formation was the important factor rather than the iron formation itself.

In summary, the preceding was a discussion of spectrochemical analyses of rock samples grouped on the basis of petrographic field appearance, apparent trends in trace element concentrations, and enrichment in elemental concentration. Since no unequivocal information could be obtained with these groupings, individual samples were considered next.

MICROSCOPICALLY DISTINCTIVE SAMPLES OF GREENSTONE

Thin sections were obtained of thirty-six samples of greenstone to facilitate the study of individual samples. Although all samples carried a high percentage of secondary minerals, these thin sections appeared to have originated from an amazing array of original rock types. Eight of these thin sections were distinctive and will be discussed in detail.

Metadiabase

Metadiabase was previously discussed as a petrographic field type. Thin section examination of this rock type reveals laths of albite more or less completely saussuritized. The alignment of these laths in places suggests a fluidal arrangement. The matrix of this rock is light green and impossible to resolve into individual mineral constituents.

The trace element content of three of these rocks was as follows:

	Cr	V	Zr	Ni	Co
Sample 1-3	680	315	40	280	81
Sample 2-8	520	265	59	267	82
Sample 2-9	570	240	45	480	115
Irish olivine basalt*	900	630	180	900	140
Irish tholeiite basalt*	50	750	700	50	110
Hawaiian picrite basalt*	1750	250	75	950	75
Hawaiian basalt*	470	280	100	85	35

*Values reproduced from Table 2.

Porphyritic Basalt

Microscopic examination of samples 3-3 and 4-10 revealed a relic ophitic structure with large patches of serpentine and calcite that appear to be pseudomorphic after olivine or pyroxene. In the field this rock was classified as massive greenstone.

The trace element content of these rocks was as follows:

	Cr	V	Zr	Ni	Co
Sample 3-3	500	360	50	175	74
Sample 4-10	82	330	60	170	66
Irish olivine basalt*	1600	630	180	900	140
Hawaiian basalt*	470	280	100	85	35

*Values reproduced from Table 2.

Although only pseudomorphs of original minerals are present in this rock, the trace element composition is what would be expected of a basalt.

Acidic Greenstone

Samples 5-7 and 6-11 were found to contain 12 per cent quartz and 30 per cent feldspar. The feldspar present consisted of approximately equal parts of albite and orthoclase with frequent grains of perthite. In sample 6-11 magnetite composed 9 per cent of the rock. Although highly serpentinized, the mineralogy and texture of this rock suggest that it was originally at least as acid as a monzonite.

The following trace element contents were found:

	Cr	V	Zr	Ni	Co
Sample 5-7	<72	165	trace	<40	42
Sample 6-11	<72	trace	540	<40	25
Irish Rhyolite*	1	2	2000	13	2
Hawaiian Trachyte*	20	<5	1500	13	2

*Values reproduced from Table 2.

Lamprophyre

Classified in the field as massive greenstone, sample 90 was round to consist of orthoclase and green hornblende with perhaps a minor amount of plagioclase. The plagioclase is all anhedral.

The trace element content of this rock was as follows:

	Cr	V	Zr	Ni	Co
Sample 90	1800	260	80	650	48

Undifferentiated Greenstone

The remainder of the thin sections examined had been so completely altered that little could be determined

about their original character. The most abundant minerals present were chlorite, calcite, quartz, hornblende, plagioclase, and magnetite.

The quartz provided the only clue to the history of these rocks. In most thin sections the quartz occurred in extremely small grains and it was impossible to determine if it was primary or secondary. However, in two sections examined, 4-8 and 4-9, the quartz occurred in larger grains and showed unmistakable signs of secondary enlargement. Therefore, in these samples both the material and the volume for secondary growth were available.

CONCLUSIONS

1. The felsic prophyry found associated with the Ely greenstone originated as a dacite. This conclusion was based on the occurrence of the dacite immediately overlying a flow breccia and the interpretation of the present fabric of the dacite's being due largely to secondary metasomatic growth of minerals.
2. The lack of comprehensive knowledge of original rock types made the establishment of the reason for element trends and concentrations impossible to determine uniquely.
3. Trace element analyses of rocks whose original character could be established showed no major change in concentration from the concentrations reported for unaltered samples of that rock type. The secondary growth of quartz indicated that the rock was permeable to some extent but evidently this permeability did not allow for substantial mobility of vanadium, chromium, zirconium, nickel, or cobalt.

4. The outstanding feature of thin section study of the Ely greenstone was the diversity of original rock types that could be identified. This diversity was not recognizable in the field.

RECOMMENDATIONS FOR FURTHER WORK

1. The outstanding feature of this greenstone is not the green color that all rocks so named possess. The possibility of diverse parentage for the rocks masked by a common development of green minerals should be recognized as a first consideration in the evaluation of any detailed petrographic, geochemical, or geophysical study conducted in the Ely greenstone.
2. Since alteration renders many thin sections unusable for diagnosing the original rock types, several times the number of thin sections studied for a normal petrographic study should be perused in work in the Ely greenstone. For example, thirty-six thin sections were examined in this study only eight of which were strictly usable. Ideally 162 thin sections should have been perused, thirty-six of which might have been useful in diagnosing the original rock type.

3. The dacite described in this study should be subjected to a thorough study throughout the area of the Ely greenstone with the aim of establishing its relationship to the greenstone.

APPENDIX A

Sample	Petrographic Field Type	Cr ppm	V ppm	Zr ppm	Ni ppm	Co ppm
1-1	Massive	280	590	160	107	76
1-3	Metadiabasic	680	315	40	280	81
1-5	Extrusive	100	450	140	47	58
1-6	Extrusive	110	520	200	62	70
1-7	Massive	500	480	110	270	84
2-1	Massive	130	300	80	160	74
2-2	Massive	145	250	80	130	74
2-4	Massive	205	420	96	59	74
2-5	Massive	105	260	70	40	49
2-7	Massive	200	420	78	130	76
2-8	Metadiabasic	520	265	59	267	82
2-9	Metadiabasic	660	225	160	360	90
2-10	Massive	400	375	68	120	110
2-12	Extrusive	62	330	150	41	52
2-14	Massive	210	230	56	292	83
2-15	Massive	190	200	44	110	51
3-1	Massive	420	440	170	81	39
3-2	Other	84	110	230	31	
3-3	Massive	500	360	50	175	74
3-4	Massive	1280	46	48	202	67
3-5	Massive	480	520	96	400	115
3-6	Foliated	115	600	245	64	57
3-7	Massive	115	580	230	71	51

Sample	Petrographic Field Type	Cr ppm	V ppm	Zr ppm	Ni ppm	Co ppm
3-8	Extrusive	105	520	220	81	68
3-9	Massive	160	560	230	63	70
4-1	Massive	250	640	175	132	92
4-2	Massive	250	630	140	73	76
4-3	Foliated	140	520	115	48	74
4-4	Foliated	90	440	230	52	72
4-5	Extrusive	105	440	200	54	64
4-6	Extrusive	60	420	130	38	34
4-7	Extrusive	94	540	190	52	44
4-8	Massive	90	590	130	46	52
4-9	Massive	84	730	115	42	74
4-10	Massive	82	330	60	170	66
4-11	Massive	50	550	105	69	65
5-1	Massive	2000	320	57	285	64
5-2	Massive	730	440	64	321	84
5-3	Extrusive	115	490	140	52	48
5-4	Massive	94	500	200	48	65
5-5	Massive		105			36
5-6	Massive	100	480	180	63	46
5-7	Massive		165			42
5-8	Massive	100	430	160	54	58
5-9	Massive	730	470	68	305	68

Sample	Petrographic Field Type	Cr ppm	V ppm	Zr ppm	Ni ppm	Co ppm
6-1	Massive	96	560	260	52	64
6-2	Massive	84	510	200	35	30
6-3	Extrusive	140	580	260	51	54
6-4	Diabase	115	360	190	255	68
6-5	Massive	56	520	200	120	68
6-6	Massive	190	380	200	70	56
6-7	Massive	260	440	140	67	90
6-8	Massive	200	360	120	83	64
6-9	Massive	180	510	180	77	52
6-10	Massive		460	320		58
6-11	Massive			540		25
83	Massive	500	390	68	245	78
78	Massive	430	640	120	145	92
90	Massive	1800	260	80	650	48
82	Massive	600	48	84	270	78
86	Massive	1200	420	70	185	64
91	Massive	540	370	70	320	84
87	Massive	2000	360	140	750	130
92	Massive	3000	430	120	820	110
72	Foliated	84	610	330	48	66
80	Massive	100	1000	260	115	145
88	Massive	166	520	90	345	86
76	Massive	156	400	66	360	95

Sample	Petrographic Field Type	Cr ppm	V ppm	Zr ppm	Ni ppm	Co ppm
73	Extrusive	80	610	390	44	56
77	Massive	160	610	190	136	86
81	Massive	370	500	80	275	92
84	Foliated	27	350	300	20	42
93	Foliated	2500	290	110	800	110
89	Massive	500	400	90	420	92
74	Extrusive	84	480	230	47	58
75	Extrusive	71	520	300	44	54
79	Foliated	56	380	120	70	82
71	Massive	260	460	90	175	80

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