THE PETROLOGY OF A PORTION OF THE MELLEN GABBRO COMPLEX AND ITS RELATIONSHIP TO THE KEWEENAWAN BASALTS AND THE TYLER FORMATION

JOHN H. PUFFER

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BY

JOHN H. PUFFER

A THESIS

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ABSTRACT

Immediately northeast of the town of Mellen, Wisconsin there occurs a basic intrusive mass that separates the Tyler Formation from the Keweenawan Basalts. However, toward the east, the intrusion cuts into the Keweenawan Basalts. Field investigation combined with a petrographic analysis indicates that the intrusion has greatly affected the basalts through contact metamorphism whereas the effects on the Tyler Formation are less obvious. The intrusive itself is differentiated and becomes more acidic toward the north.

ACKNOWLEDGMENTS

I wish to express my sincere thanks to Dr. Justin Zinn, Dr. Harold Stonehouse, and Dr. James Trow for their assistance and encouragement in the development of this thesis.

My thanks are also offered to Mr. James Olmstead whose advice and counsel has proven to be very helpful.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

INTRODUCTION

It was stated as early as 1889 by R. V. Irving, that "For its variety of geological problems, structural, mineralogical, petrogenic, and metamorphic, there is probably no area comparable to the environs of Mellen. It would be an excellent location for a school of field geology". After studying the "environs of Mellen", I must wholeheartedly agree with Irving.

I have found the town of Mellen, Wisconsin to be very picturesque (see figure 1) and friendly. The greater part of Mellen is located in the upper half of section 6 (T. 44N. - R. 2W.) The town itself marks the extreme southwestern portion of the investigated area which includes sections 20-23, 26-30, 31 and 32 and the northern portion of section 33 and 34 of T. 45N. - R. 2W. in Ashland County, Wisconsin.

The area was chosen immediately after consulting the map published by Aldrich in 1929. Further limitations were made on the basis of a more recent map composed by the Bear Creek Company. Despite the fact that the area had been previously mapped, I felt that I would require a first hand observation of the field relationships, an accurate sampling of the rock types, and a relatively high degree of map detail in order to fulfill the purposes of my investigation.

PURPOSE OF INVESTIGATION

The chief purposes of my investigation consist of gathering factual information relative to three questions not adequately answered by

Figure 1 The town of Mellen Wisconsin

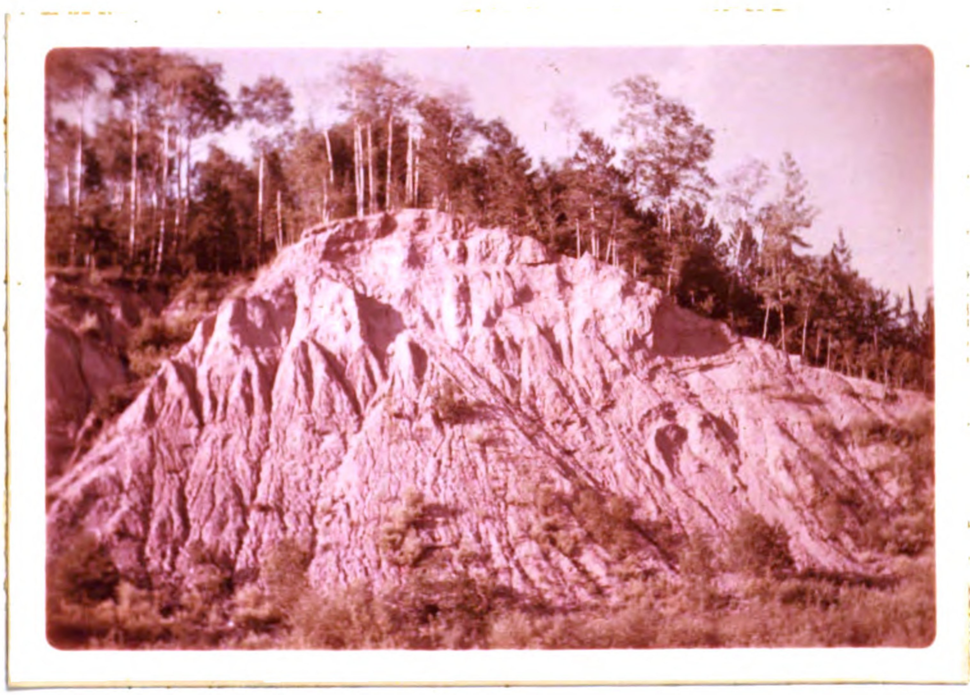


Figure 2 A glacial drift bank along the Bad River.

previous investigations:

(1) What are the effects of a basic intrusive on a (1) subgraywacke and (2) basalt?

(2) What lithologic variations or differentiations occur within the basic intrusive?

(3) What is the structural history of the area and the origin of the rock types that make up the area?

METHOD OF INVESTIGATION

Pace and compass mapping, using aerial photographs and 7.5 minute topographic maps, was conducted during the summer of 1964. A sample of each outcrop was taken and its location plotted on the field map. Structural information was observed and also plotted wherever possible. Thin sections of 82 representative samples were then made and analyzed. "Point counts" to determine mineral percentages were made on the majority of sections. The pyroxenes and olivine were then determined with the 5 axis universal stage on the basis of 2V measurements. The plagioclases were identified by using the Michel Levy method and extinction angles of combined carlsbad-albite twins. Samples which appeared to contain potash feldspar were stained so as to readily distinguish it from untwinned plagioclase, quartz and others. The stain that was quite successfully used was sodium cobaltinitrite using techniques developed by S. Rosenblum (1956), and F. Chayes (1952). Oil immersion techniques were employed to identify questionable mineral grains.

REVIEW OF THE LITERATURE

In 1892, Irving and Van Hise made one of the first studies of what was then known as the Penokie iron bearing series. A detailed description of the Huronian formations supported by thin section observation was carried out with emphasis on the iron formation. A large part of the Keweenawan was also mapped, but no attempt was made to define the contacts of the Mellen Gabbro. However, in 1911 Van Hise and Leith recognized the gabbro and correlated it with the Duluth gabbro which they observed was similar in every respect. Grout in 1918 suggested that the gabbro in Wisconsin may be an extension of the Duluth gabbro. Hotchkiss in 1919 described the Ironwood Iron Formation in detail and recognized the Pabst member at the base of the Tyler Formation suggesting that it represented a Middle - Upper Huronian unconformity. In 1923 he developed the theory that the Lake Superior Syncline was formed by subsidence during and immediately following the emptying of the basalt magma chamber which supplied the flows and intrusions. He also suggested that the gabbro intruded along a western extension of the Keweenawan thrust fault. In 1929, Aldrich redescribed in detail the Huronian sediments of the Gogebic district. He mapped the Huronian and Keweenawan formations and included a magnetic dip needle analysis and structural analysis of the area. In 1935, Leith, Lund, and Leith discussed the stratigraphic relationships of the Gogebic area with the entire

Lake Superior region. In 1954, M. W. Leighton described the petrogenesis of the westernmost exposure of the Mellen gabbro - granophyre complex using petrographic and chemical data. In 1956, the Bear Creek Mining Company remapped the area including the Keweenawan intrusives in the Gogebic Area. Aeromagnetic data was also obtained. At the present time (1964) extensive petrologic work is being conducted by James Olmsted on the portion of the Mellen gabbro complex located between the portion studied by Leighton and the granite mass that separates his area from the map area of this report. In addition, this same granite mass is being presently studied by M. Katsman.

GENERAL GEOLOGY

ARCHEOZOIC

The oldest formation found in the western Gogebic area is greenstone schist. The schist has been described by Irving and Van Hise (1892) as being quite finely laminated, dark colored and fine grained. The schist is composed chiefly of feldspar, hornblende, chlorite, and quartz, but the composition is quite variable. According to Irving and Van Hise, the greenstone is easily distinguished from the coarse grained granites and gneisses that occur west of the Bad River Valley. The granites and granite gneisses, also unconformably underlying the Huronian, are generally thought to be later than the greenschists. However, within the eastern Gogebic area, granite has been found intrusive into the Huronian. It may therefore be concluded that at least some of the granite in the Gogebic area may be post-Huronian. In addition, a large mass of granite north west of Mellen has been found to cut Keweenawan rock and has been classified by Leith - Lund and Leith (1936) as of Killarney age.

HURONIAN

After the orogeny that separated Archeozoic from Proterozoic time Lower Huronian deposition began with the deposition of Bad River dolomite in the western Gogebic area. The formation is very thin and is found only intermittently at the base of the Huronian series in Wisconsin. Aldrich (1929) has reported a thickness of 100 feet at the Penokee Gap where it grades from a lower cherty

dolomitic phase to an upper dolomitic cherty phase. The individual beds range from 1 to 2 inches in thickness.

Unconformably above the Bad River dolomite lies the Palms formation. The formation grades from a conglomerate at the base to quartz - feldspathic slate to a quartzite at the top. The conglomerate facies is 3-10 feet thick; the slate facies is about 390 feet thick; and the quartzite facies is about 50-60 feet thick.

Conformably overlying the Palms formation lies the Ironwood iron formation. Aldrich has reported that the formation is composed of roughly 65 percent quartz and 35 percent iron materials. The formation has been divided into zones of alternating ferruginous cherts, and cherty carbonates. The ferruginous chert beds are thick and wavy and have an oolitic texture. The cherty carbonate beds are thin and straight averaging an eighth of an inch in thickness. The thickness of the Ironwood in Wisconsin is about 650 feet.

Although there is considerable uncertainty, the Tyler Formation probably overlies the Ironwood unconformably. Although there is no divergence in dip or strike at the contact, a thin conglomerate which was named the Pabst member of the Tyler Formation by Hotchkiss in 1919 separates the two formations. According to Leith, Lund, and Leith (1936), the Pabst conglomerate is similar in every respect to the basal conglomerate of the Copps slate of the eastern Gogebic range. Since the Tyler formation is known to be equivalent to the

Copps formation which has a basal conglomerate that unconformably bevels the underlying iron formation, it may be concluded that the Pabst and the Copps conglomerate have the same unconformable relationship.

In the same article Leith, Lund, and Leith correlated the Tyler Formation with the Michigamme slate, the Copps slate, the Virginia slate, and the Rove slate of the Lake Superior area.

The Tyler Formation grades from a thin bedded, almost black graywacke at the base through a more typical graywacke phase to a subgraywacke and finally to a quartzite at the top of the formation. Its thickness is about 10,000 feet. The majority of the formation is poorly bedded. It is also a relatively soft formation and is poorly exposed.

KEWEENAWAN

A large time gap separates the Huronian Tyler Formation from the Keweenawan during which time a large amount of Tyler Formation was eroded away. The erosion however, was not uniform. Toward the east at Wakefield, Michigan, the overlying Keweenawan basalts bevel the Tyler Formation and are in contact with the Ironwood Formation. At the west end of the Tyler Formation, the entire Huronian is missing and is overlain by the Keweenawan igneous complex. One reason that the Tyler Formation was not uniformly eroded may be the presence of a resistent quartzite facies at the top of the portion of the formation which has escaped great erosion. In the map area of this report, where the formation is thickest, such a quartzite facies has been found to exist.

The first Keweenawan event to occur was the deposition of a thin quartz conglomerate and sandstone formation now existing as a pink quartzite. This lower Keweenawan deposition may correlate with the Puckwunge Formation of the Grand Portage area.

Following the deposition of the lower Keweenawan a thick series of flows were extruded. The great majority of the flows are basalt however, felsite flow layers are also included in the Keweenawan. The individual flows vary from a few feet to over 100 feet thick. According to Aldrich (1929), the lava pile probably exceeded 20,000 feet in total thickness. Following the extrusion of the flows, a series of Upper Keweenawan sediments starting with the Great Conglomerate was deposited. This conglomerate is composed largely of felsite pebbles. The deposition of the conglomerate was then followed by a continuation of extrusive activity known as the Lake Shore Traps. This final extrusion was followed by the deposition of about 800-1200 feet or more of conglomerate known as the Outer Conglomerate. Upper Keweenawan deposition continued with the formation of the Nonesuch Shale which is about 120-350 feet thick. The Nonesuch Shale is overlain by 12,000 feet of Freda Sandstone which is in turn overlain by 200 feet of Eileen Sandstone. Deposition finally ended with 5,000 feet of Amnicon shale and arkose and an upper group of about 7,000 feet of sandstone.

Before the close of the Keweenawan a large amount of intrusive activity had also taken place. The result of the intrusive activity was the implacement of the Mellen gabbro - granophyre complex, a portion of which occurs in the map area of this report.

PRE CAMBRIAN STRATIGRAPHY

OF

THE GOGEBIC DISTRICT

TABLE 1

Series		Gogebic
		(Unconformity)
Killarney		Granite Intrusives
		(Killarney Orogeny)
Keweenawan		Basic Intrusives Sandstone, Shale, and Conglomerate Basic flows Quartzite and Conglomerate
		(Unconformity)
Huronian	(upper)	Tyler Formation
		(Unconformity) ?
	(middle)	Ironwood Iron-Formation Palms Quartzite
		(Unconformity)
	(lower)	Bad River Dolomite Sunday Lake Quartzite*
		(Unconformity)
Laurentian		Granites and Gneisses
Kewatin		Greenstone

* occurs in eastern Gogebic District at Wakefield, Michigan but was not deposited in Wisconsin

THE TYLER FORMATION

The upper Tyler Formation ranges from a recrystalized subgraywacke to a quartzite. The central part consists of thick bedded recrystalized graywacke and subgraywacke with the lower portion a darker, thin bedded graywacke. From east to west there is also a variation. Westwardly, according to earlier literature, grain size, magnetite, hematite, biotite, and feldspar content increases with a corresponding decrease in chlorite and carbonate content.

The choice of the term "slate" in reference to the Tyler Formation is an unfortunate one and could cause confusion. Van Hise (1892), stated that "It is not meant to imply by the term 'slate' that any of the rocks have a slate cleavage". The cleavage when visible, rather than being at an angle to the bedding, is parallel to the bedding, unlike a slate. However, the term continues in the literature with the qualification that it is a graywacke slate.

The major part of the Tyler Formation is located in a valley bordered to the south by the range of hills formed by the Ironwood Iron Formation and to the north by the Keweenawan igneous mass. The upper Tyler formation is exposed quite well along the northern slopes of this valley just north of Montreal Creek.

MEGASCOPIC DESCRIPTION

The quartzite of the Tyler formation is usually completely massive in hand specimens and breaks with conchoidal fracture. In outcrops, however, a definite but sometimes poorly defined cleavage along the bedding planes occurs. All the samples examined were fine

grained and gray to light gray. The gray color in hand specimens is misleading to the extent that it tends to indicate a "dirtier" rock than is actually the case when examined in thin section. The majority of the samples are fresh, impermeable and completely structureless except for a faint bedding in some cases. The poorly defined bedding is quite variable in thickness. Definite cross-bedding was observed on three samples. Figure 3 illustrates an exposure with a wavy type of bedding often found in the upper Tyler Formation.

MICROSCOPIC DESCRIPTION

The mineralogy of the upper Tyler Formation is surprisingly simple in the sense that only a relatively few minerals occur in it. (See table 2).

QUARTZ: The average grain size of the quartz is .199mm. This places the size on the Wentworth scale as fine sand.

The extreme development of authigenic growth and recrystallization (figure 4) has in most cases obliterated original grain boundaries. However, in section 26-51 and 32-21, authigenic growth is less well developed allowing observation of original grain shape. In both cases it was observed that the grains were well rounded to spherical. (See figure 5).

In each quartzite thin section only fresh, inclusinn free quartz was observed, with minor exceptions. Strain shadows are also almost completely absent. The grains are almost all recrystallized with

interlocking sutured boundaries. In the sub-graywacke, most of the quartz is also fresh and free from inclusion. However, inclusions were quite abundant in some of the grains and many of the grains are fractured and strained.

BIOTITE: In most cases, the biotite occurs as unaltered flakes which are poorly or entirely unoriented. The flakes are large, fresh, and extremely pleochroic crystals with a few inclusions of zircon. In some cases there has been retrograde metamorphic alteration to chlorite. (See figure 6). In a few of the samples examined the biotite occurs as small faintly oriented grains.

PLAGIOCLASE: Albite was found in every Tyler Formation thin section examined. With few exceptions the crystals are fresh, unaltered, anhedral and twinned. (See figure 7). The grain size of the plagioclase roughly corresponds with the average quartz grain size . In some cases, the albite contains inner cores of a more calcic plagioclase, which may be explained as authigenic growth around a calcic nucleus. The occurence of unaltered plagioclase has been reported by Van Hise to exist throughout the entire Tyler Formation. Staining has indicated the absence of orthoclase feldspar.

OPAQUES: Hematite, titaniferous magnetite, limonite and pyrite are the chief opaque minerals in the Tyler Formation. The relative amount of each, however, was not determined, as all were grouped together in the point count analyses. The red rim around some of the thinner crystals was used as an easy identification for hematite.

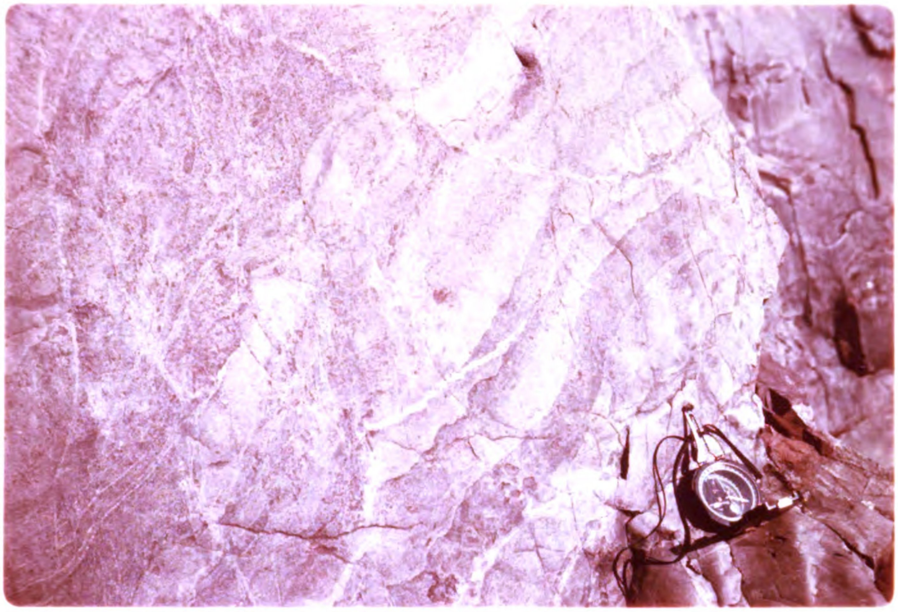


Figure 3 Tyler Formation displaying wavy bedding taken from section 6,outcrop #1.

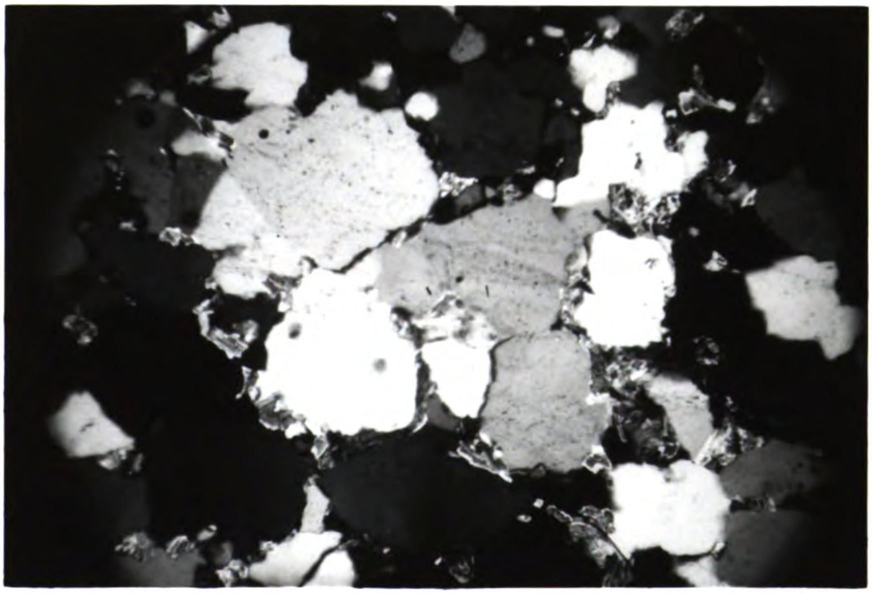


Figure 4 Photomicrograph of 26-94 showing quartzitic texture. 80 power, crossed niccols.

In several thin sections, limonite occurs as crack fillings and interstitial cement around quartz grains. The cement is limited to grains near the cracks which have served as a source. (See figure 8).

MUSCOVITE: Muscovite most typically occurs as fresh, colorless crystals corresponding in size in each section to the biotite and in some cases, the muscovite flakes are even a little larger than the biotite.

CHLORITE: Chlorite occurs as a retrograde product of biotite. (See figure 6). Most commonly it occurs as pale olive greenish gray flakes that occur in zones separated from similar biotite zones. The flakes contain opaque dust and zircon. The chlorite strongly resembles chloritoid except that the birefringence and index is a little too low.

YELLOW UNKNOWN: A systematic investigation of all mineral possibilities with reference to optical properties has failed to identify a certain yellow mineral found in almost half of the Tyler thin sections studied. (See figure 9,10). Its properties include:

(1) pale to bright yellow color

(2) lack of any noticable pleochroism

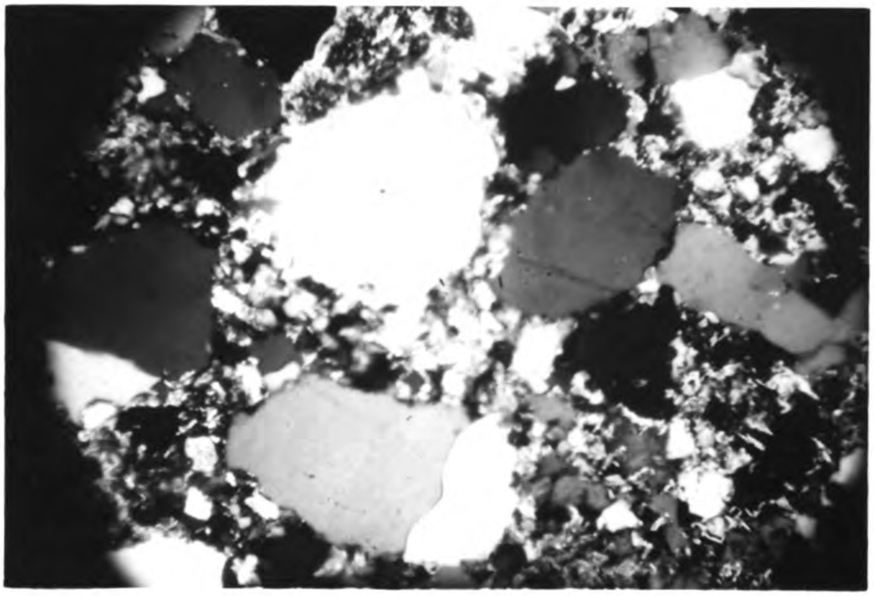
(3) extremely low birefringence with a maximum

(4) an index of refraction of about 1,653

(5) a length fast orientation

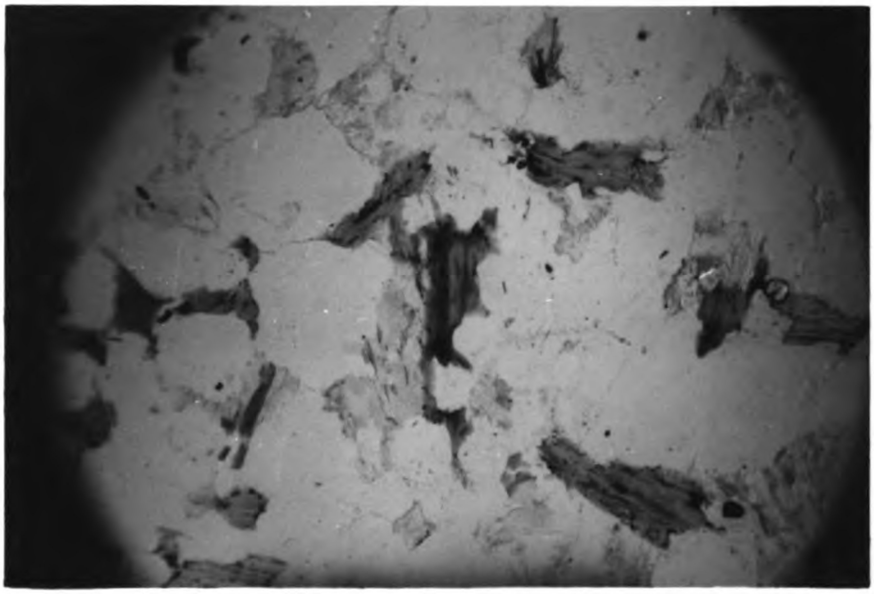
(6) parallel extinction

(7) very poor cleavage



• NOV • 64

Figure 5 Photomicrograph of 26-58 illustrating rounding of quartz grains, crossed niccols



• NOV • 64

Figure 6 Photomicrograph of 32-2 showing chlorite-biotite intergrowth, plain light

Figure 7 Photomicrograph of 26-58, illustrating a typical plagioclase grain, crossed niccols X 80 diameters

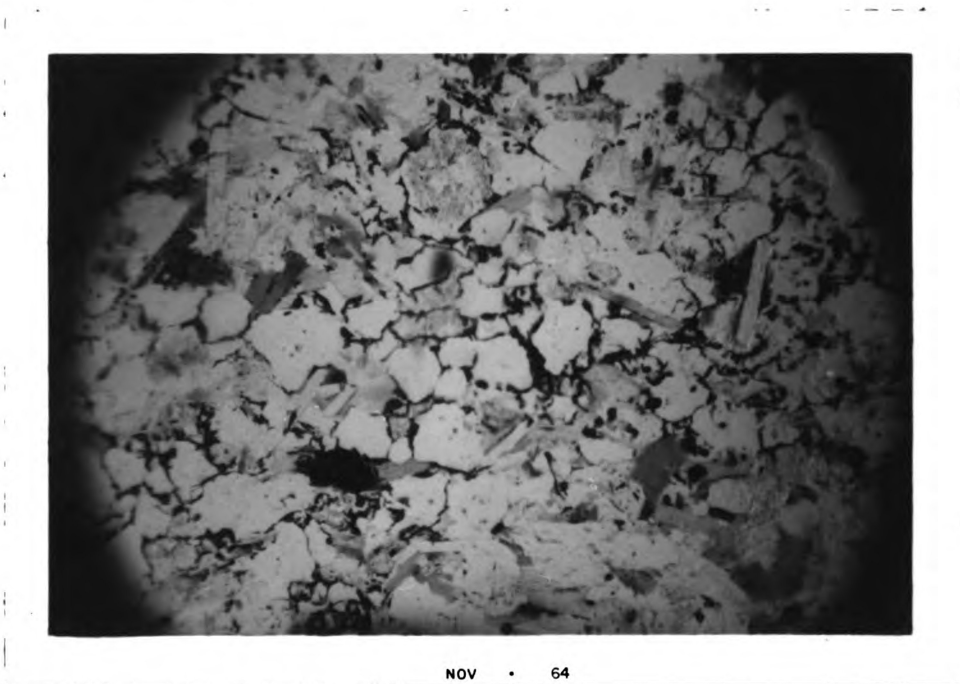


Figure 8 Photomicrograph of 32-22 illustrating limonite cement in plain light X 60 diameters

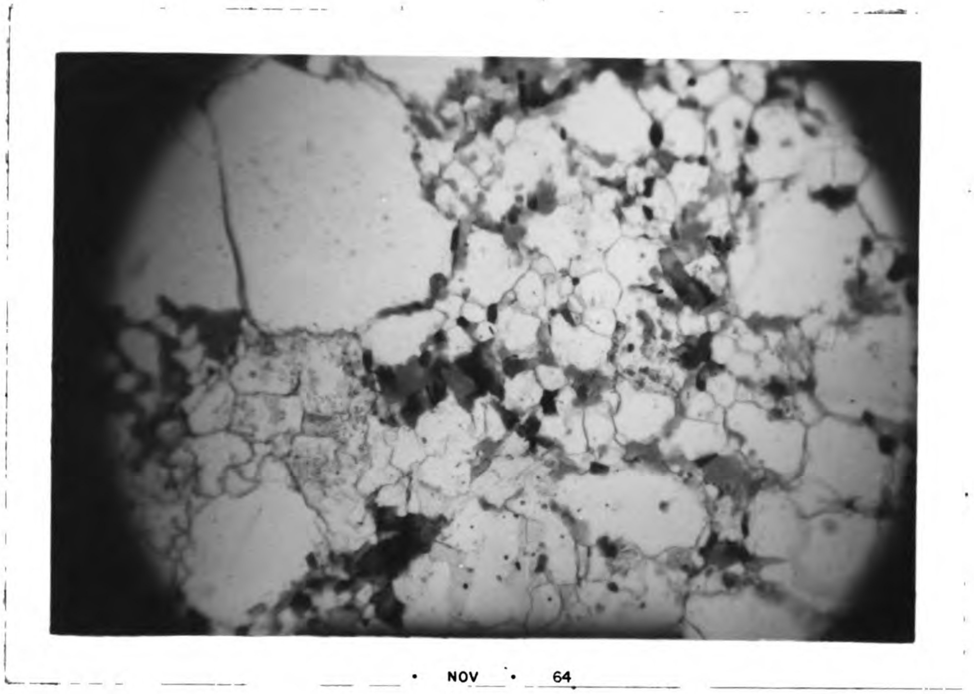


Figure 9 Photomicrograph of 32-21 illustrating yellow unknown (gray) plain light X 80 diameters

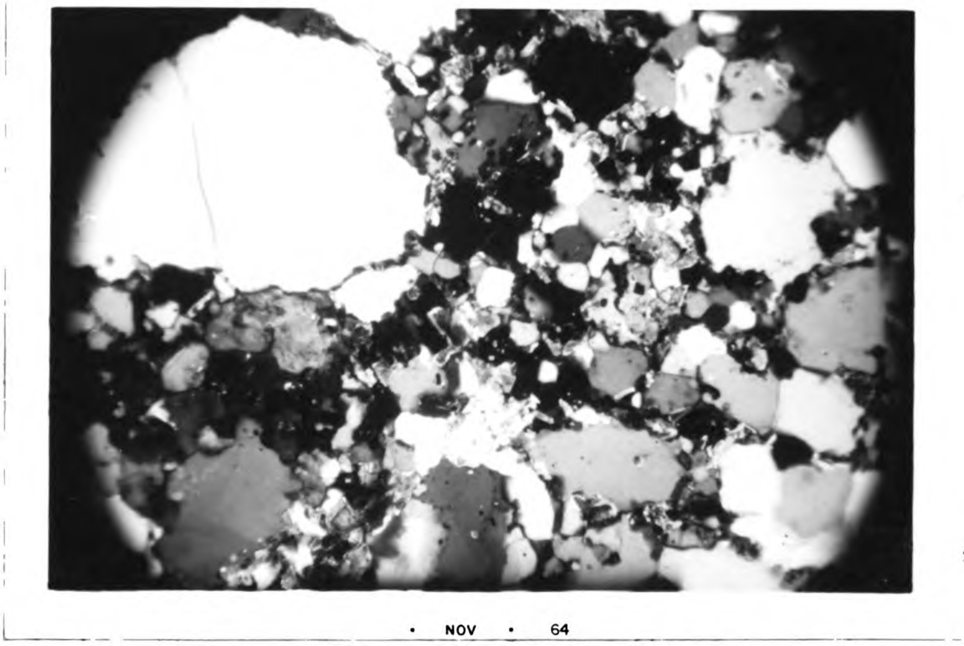


Figure 10 Same as fig. 9 under crossed niccols illustrating low birefringence of yellow unknown

Its index of refraction is not exact because of the difficulty of distinguishing it from grains of biotite normal to the c axis. Under the universal stage, the birefringence proved to be too low to permit an accurate determination of 2V or optic sign.

It is quite possibly a surface weathering effect due to the introduction of chemicals other than those involved in original deposition and lithification. The mineral may therefore have formed as a rare clay mineral or alteration product of biotite from solutions that have invaded the intersticies of the original grains. Its occurence is largely confined to samples that were taken at the surface whereas samples that were taken more than 6 inches below the surface are free from the unknown mineral.

ENVIRONMENT OF DEPOSITION

The well developed rounding and sphericity and the large percentage of quartz content of the upper Tyler quartzite facies indicates a high degree of maturity. The presence of cross-bedding is an indication of shallow water deposition. These, plus other indications, such as the fact that the upper Tyler is well sorted, indicate that the upper Tyler was deposited in a paralic environment.

The transition from a graywacke at the base of the Tyler to quartzite at the top indicates that Tyler deposition occured in water that became progressively shallower near the last stages.

METAMORPHISM

Despite the fact that many of the samples of Tyler formation were taken within 100 feet of the Mellen Gabbro intrusive contact, I have observed nothing in any of the hand specimens or thin sections that could definitely be called a contact metamorphic effect. The usual contact metamorphic minerals such as andalusite, cordierite, etc. are conspicuously absent. The probable reason for this is the resistance of quartzite to metamorphism. This resistance may be due to the low mafic content of the quartzites (see table 2). A larger amount of mafic material is needed to supply the elements for many contact metamorphic minerals. Another reason is that quartzite recrystallization causes impermeability and rigidity, thus reducing later solution or stress effects. This second reason would however, necessitate recrystallization of the Tyler Formation before intrusion of the gabbro sill. Whether the quartzite actually was recrystallized before the intrusion is uncertain. However, during the Huronian-Keweenawan time gap, this recrystallization could have occured.

Another factor to be considered is the relatively dry nature of the Mellen gabbro. Gabbro in general which does not contain as much water and other volatiles as granite has usually been found to have less extensive metamorphic effects than granite. Grout (1933) has observed a much thinner contact metamorphic zone for gabbro than for granite in the Duluth area.

MINERAL PERCENTAGES IN THE

TYLER FORMATION

Table 2

Section	Outcrop number	Quartz	Grain size in mm.	Biotite	Muscovite	Opaques	Chlorite	Zircon	Yellow Unknown	Apatite	Plagioclase	Tourmaline	Hornblende
26-94	(1)	92	.200	-	6	T	2	T	-	-	-	-	-
6-1		89	.125	6	2	-	-	T	-	-	3	-	-
26-58		88	.275	5	3	T	-	T	3	T	T	-	-
27-13		79	.250	12	7	2	-	-	-	-	T	-	-
26-072	(2)	84	.125	-	T	2	2	-	-	-	2	-	10
27-81		91	.075	-	2	-	8	-	T	-	T	-	-
32-21		83	.121	8	2	1	-	T	4	T	2	-	-
33-94		89	.100	10	-	T	-	T	-	-	1	T	-
32-65		78	.075	10	1	2	-	T	1	-	8	T	-
32-22		85	.100	4	4	2	3	-	-	-	2	-	-
31-2		91	.250	3	2	T	3	T	1	-	T	-	-
33-83		92	.275	2	4	T	1	-	-	-	1	-	-
33-103		94	.225	4	1	T	T	T	1	T	1	T	T
Average		80	.199										

(1) Lower Keweenawan quartzite

(2) Xenolith of Tyler Formation found within the gabbro

Therefore, although a quartzite should not be expected to show abundant contact metamorphic effects, a subgraywacke such as the subgraywacke facies of the upper Tyler Formation, should theoretically yield the same contact metamorphic minerals that form in argillaceous rocks. The reason that the subgraywacke facies has also evidently escaped contact metamorphism is that it has probably been sufficiently shielded from the intrusion by the overlying quartzite facies.

Below the subgraywacke in the graywacke portion of the Tyler, Van Hise and Irving have found garnet which indicates some kind of metamorphism. However, near the gabbro contact garnet has not been found.

STRUCTURE

DIP: The average of dip measurements taken along the upper Tyler is 76 degrees north. This figure agrees with what might be expected in this part of the Lake Superior Syncline. The trough of the syncline is located about 25 miles north of Mellen. The steepness of the dip is an indication of the extent to which the development of the syncline has effected the area. Hotchkiss has suggested that this syncline was formed as the result of the gradual collapsing of an underlying magma chamber. The collapsing took place during the extrusion of the Keweenawan flows and continued during the deposition of the overlying Keweenawan sediments. Evidence for this theory includes a gradual fanning of northward dips from 80 degrees at the base of Keweenawan flows to 30 degrees at the base of the overlying Keweenawan sediments. However, although this explanation has been widely accepted, it remains highly theoretical.

FAULTING: Aldrich has mapped several cross-faults passing through the Huronian and Keweenawan. Two such cross-faults were thought by him to exist in the map area of this report. The effect of both faults according to Aldrich, has been the southward displacement of a $1\frac{3}{4}$ mile wide fault block. However, on the basis of the outcrop data that I have accumulated in order to draw the northern Tyler Formation contact, such displacement would be impossible. The western fault was drawn by Aldrich on the basis of several hundred feet of alleged displacement, located in the south west corner of section 32. The eastern fault was drawn through the northwest corner of section 33 where offsetting displacement is said by Aldrich to occur, although he has also stated in 1924, that (p.227) "the actual faulting has nowhere been seen". The existence of the eastern displacement would place the northern Tyler Formation contact within section 28, however, the existence of several Keweenawan exposures south of section 28 indicates that the contact is actually located south of the northern edge of section 33.

The northward extension of both faults has supposedly isolated a rhomboid area of anorthosite. But, on the basis of my own field work, it has become apparent that the block of anorthosite actually grades gradually into a more typical type of gabbro.

THE LOWER KEWEENAWAN

After an interval of unmeasured duration that separates the Huronian from the Keweenawan, a thin sequence of Lower Keweenawan sediment was deposited. The formation is very distinctive, but in the map area of this report it is exposed only in a small area in the central part of section 26. The base contains a bed of conglomerate about 10 feet thick. The matrix of the conglomerate consists of dark gray, medium grained, silica cemented quartzite which contains $\frac{1}{2}$ to 1 cm well rounded milky quartz pebbles. Above this, the formation changes to a medium grained, pinkish gray quartzite that is well bedded. At the top just beneath the basalt flows the formation changes to a light pink, well bedded quartzite. In thin section, a sample of the pink quartzite proved to be 94 percent quartz, 4 percent muscovite, and 2 percent chlorite plus traces of zircon and magnetite. Sodium cobaltnitrite staining indicated that the pink color is not due to orthoclase content as was previously suggested by Aldrich (1929 p. 217). Instead the pink color may be caused by an impurity in the quartz or the quartz cement.

Locally the lower Keweenawan possesses the same strike and dip as the upper Tyler Formation. In Michigan, however, the Huronian-Keweenawan unconformity is much more obvious and clearly indicates that upper Huronian-lower Keweenawan deposition was not continuous.

THE KEWEENAWAN BASALTS

The basalt occurs as flow layers which vary greatly in thickness from a few feet to over 100 feet. The basalts are generally thought of as being the product of large fissure eruptions somewhere in the interior of the Lake Superior basin. Evidence to show that the lava came from the north has not been found in the map area of this thesis, but elsewhere I have observed pipe amygdules bent toward the south, and flow layers which thicken down dip.

In general, the basalts may be classified as of a typical tholeiitic type. The petrographic characteristics of a tholeiitic basalt such as little or no olivine and a prevalence of pigeonite pyroxene are both shown by the basalt in the map area. (See table 3).

The field occurence characteristics of tholeiitic flood basalts are also met by the Keweenawan lavas of Lake Superior in general. According to Turner and Verhoogen (1960), tholeiite basalts are usually:

(1) disected with contemporaneously injected swarms of diabase dikes and sills

(2) of enormous volume and extent

(3) are characteristically found in a nonorogenic continental environment

(4) take the form of thin flows

(5) are rarely associated with tuff or explosive products.

An important implication of a tholeiitic classification is that chemically there is a tendency for tholeiitic basalts to contain more SiO_2 and less Na_2O, K_2O, and MgO than typical alkaline olivine basalts.

UNALTERED BASALTS

As a norm for comparing the metamorphism of the basalt near the gabbro contact, a relatively fresh and only slightly altered exposure of basalt was found in section 14 approximately 3000 feet from the gabbro contact. The only alteration that has occurred is a relatively slight alteration of the plagioclase into paragonite and the pyroxene into chlorite. The pyroxene is apparently pigeonite on the basis of 2V measurements of 10 degrees and 12 degrees. The pyroxene occurs as interstitial material between laths of plagioclase in a well developed diabasic texture. Occasional phenocrysts of plagioclase occur in the basalt that are of the same composition as the rest of the plagioclase and this appears to be labradorite (An 63-65). Euhedral crystals of magnetite occur as the chief accessory. A single small crystal of orthoclase was found in thin section 14-2. The rock is fine grained with the average length of the plagioclase laths averaging .3mm however, grain size is variable and ranges from fine grained to very fine grained in some samples.

META-BASALTS

Unlike the Tyler Formation which shows relatively little contact metamorphic effects, the basalts near the Mellen Gabbro intrusion have been strongly contact metamorphosed. The area that best illustrates these effects occurs south of the gabbro intrusion in section 23 and 26. The series of basalt flows in section 23 and 26 is no thicker than 1100 feet at its thickest portion and pinches out completely somewhere in section 27. The zone of high ranked metamorphism is of course much thinner, being not over 500 feet thick on the basis of the outcrop data.

Southern Meta-Basalt Mass: Three contact metamorphic facies are represented in the meta-basalt near the southern contact of the gabbro intrusion. These are from the remote edge of the metamorphic aurola to the contact:

1. The Albite-epidote-hornfels facies.
2. The Hornblende-hornfels facies.
3. The Pyroxene hornfels facies.

In many ways the sequence resembles the metavolcanics of the Peavy Pond area as described by R. W. Bailey (1959), and the metabasalts in contact with the Duluth gabbro as described by G. S. Schwartz (1924).

Albite-Epidote-Hornfels facies: The basalts farthest away from the intrusion are typically dark gray,medium fine grained basalts some of which show amygdules. Also observed are small pegmatoids composed of coarse grained white plagioclase, pink orthoclase and quartz, and rimmed with hornblende. Often these blebs are stretched out in a linear fashion, or flattened. Their origin is uncertain, however, they may be a variety of segregation structure, such as described by W. Q. Kennedy. (1933). Local concentrations of water may have been responsible for their formation. They are easily noticed, quite common and very distinctive. Under the microscope (figure 11), it can be seen that during their growth magnetite grains have been "pushed" away and segregated along the edge of blebs.

Thin sections indicate that all the Keweenawan flows located south of or beneath the gabbro intrusion in the map area have undergone at least some degree of alteration. In the outermost contact metamorphic aureole, alteration consisted of recrystallization of an otherwise diabasic texture. Most of the pyroxene in the rocks of this outer aureole was converted to chlorite and uralite. The relic pyroxene is a colorless pigeonite. As the hornblende-hornfels facies is approached, the original pyroxene becomes completely uralized and chloritized, and albite appears as small rounded crystals that are often untwinned and are always free from inclusions. The remaining plagioclase is badly altered and occurs as long corroded laths which are clouded with an opaque dust. The most obvious change, however, is the development of the characteristic hornfels texture (See figure 12). Two varieties of amphiboles are present. The most common variety is the typical pleochroic brown variety. However in addition, a variety is also present that is pleochroic in pale green to yellow and possesses a smaller extinction angle. This second variety is evidently a member of the tremolite-actinolite group and because it is probably secondary after pigeonite, it may be called uralite. Usually the two varieties of amphibole do not occur in the same thin section. Another difference between the two varieties of amphibole is that the pale green variety has a more feathery or fibrous habit whereas the brown hornblende has a typical prismatic cleavage.

Two varieties of chlorite are also present. Penninite (see figure 13) occurs in thin sections 26-82, 26-83, and 26-92 (see table 3) as pale green clusters of flakes. A more typical variety of chlorite also occured in a few of the samples as very small bright grass green pleochroic flakes. This second variety of chlorite however, occured in only very small amounts.

The basis upon which the samples were classified as albite-epidote hornfels was the presence of relic diabasic texture, relic pigeonite, altered plagioclase, and the presence of epidote, clorite and recrystallized albite.

Hornblende hornfels-Pyroxene hornsfels facies: In hand specimens taken near the intrusive sill, the more strongly metamorphosed samples lack pegmatoids and amygdules. Another difference is that the hornblende hornfels rocks possess distinctive euhedral metacrysts of hornblende, about 3/4 cm across. These metacrysts typically weather out in relief and often occur in great abundance.

In thin section, the hornblende hornfels and pyroxene hornfels differ from the less strongly metamorphosed basalts in many respects. The texture is completely hornfelsic except for where the large extremely poikolitic metacrysts of hornblende occur. (See figure 14). In some of the thin sections such as 23-4, the majority of the hornblende present occurs as poikolitic metacrysts. The plagioclase is unclouded and rather than occuring as albite, it occurs largely as andesine and labradorite. The plagioclase occurs as small short stubby laths that are evenly distributed among hornblende crystals that have the same shape and size. The average size of the crystals varies greatly from sample to sample (see table 3) however, in each individual thin section, the grain size of the various component minerals is quite uniform.

Hornblende makes up a large part of the composition of the rocks of the hornblende hornfels facies. It occurs largely as small rounded individual crystals but also frequently occurs as large poikolitic metacrysts. The hornblende metacrysts are rarely free from inclusions and often inclusions are so numerous that the same crystal may be separated into several parts. However, when the hornblende metacrysts are relatively free from inclusions, they possess an euhedral shape. The hornblende is pleochroic from brown to olive green to grass green and is easily recognized by its perfect amphibole cleavage, small extinction angle, and length-slow orientation. In each case the hornblende is evenly distributed throughout the rock.

Diopside which makes its first appearance in the rocks of the hornblende hornfels facies has a similar occurance to that of the hornblende which also occurs both as individual rounded crystals and large anhedral to euhedral poikioblastic metacrysts. In the majority of the thin sections, pyroxene occurs in smaller amounts than the accompanying hornblende. However, in 2 thin sections, 27-75 and 26-90, it greatly exceeds the hornblende content and in thin section 27-12, it occurs without any accompanying hornblende. The samples in which pyroxene is the dominant mafic mineral, plagioclase increases in An content to the labradorite stage which is the same plagioclase composition found in the chill zone of the gabbro intrusive.

Several crystals have been found in the hornfels which appear to be one half hornblende and one half diopside. This observation infers either one of two explanations. Either the diopside is replacing the hornblende which has in turn altered from the original pigeonite, or the hornblende is replacing the diopside. The first interpretation would imply an intermediate hornblende stage for the diopside that is present. Although we know that it is possible through metamorphism to convert pyroxene into amphibole and amphibole into pyroxene, an alternative possibility may be a direct metamorphic conversion of one pyroxene into another which in this case would involve pigeonite and diopside. If this second explanation is accepted, then the occurence of hornblende in the combined hornblende-diopside crystals may be explained as a retrograde metamorphic product of diopside.

Magnetite together with a small amount of ilmenite are the only opaque minerals that were observed. With few exceptions, the magnetite occurs as a small anhedral grains varying in size from .050mm to .125mm. In a few cases however, large poikiolitic magnetite crystals were observed in which case biotite was found to be associated with the magnetite. The magnetite content averages three percent. However, in the case of two xenoliths of metabasalt that were found within the basic intrusive (samples 27-79 and 28-4 table 3) the magnetite content was extremely high amounting to over 12 percent. In each case, the magnetite grains occur as small evenly distributed crystals. The source for most of the magnetite was evidently the basic magma however, the reason that so much magnetite was attracted to the basalt is uncertain.

Ilmenite and bright red rutile were often present in trace amounts in several of the hornfels indicating a relatively high titanium content. Apatite was also found to be present in trace amounts in several of the samples (see table 3). In one sample, quartz was also observed in small amounts and in another sample, orthoclase was observed. The presence of these two minerals is probably the result of small relic pegmatoids or amygdules in the hornfels.

NORTHERN BASALT

North of the intrusive sill in Section 22, there occurs a group of basalt outcrops. A characteristic of the samples taken from these outcrops is that they are full of calcite amygdules. Most of the calcite has been dissolved by ground water, leaving cavities. The calcite is pink or white and is easily confused in hand specimen with orthoclase phenocrists that are also found in the basalt. The calcite amygdules are surrounded with chalcedony which in many cases make up the entire amygdule. (See figure 15) The chalcedony shows well developed radiated or cockade structure.

Chlorite occurs as very fine flakes throughout the groundmass in large amounts as a secondary mineral after pyroxene which has been largely replaced. The plagioclase laths are clouded with a fine opaque powder and shows some alteration to paragonite. The plagioclase appears to be andesine (An 25 - An 44), although clouding and alteration of the feldspar makes the determination uncertain. However, the original diabasic texture of the basalt has been preserved quite well.

The metamorphism of the northern basalts should have been even more extensive than the basalts to the south of the intrusion because of the added presence of volatiles associated with the granite differentiate. However, the lack of appreciable observed metamorphism above the sill may be explained by the probability that the rock examined is a little too far from the intrusion to have been strongly recrystallized. If in the future the northern contact is studied it may be of considerable interest to compare the metamorphic effects at the northern contact with the southern contact. A zenolith was found in the diorite zone of the basic intrusive, however in thin section it was comparable in every respect to the hornblende hornfels of the southern metabasalts.

Figure 11 Photomicrograph of 26-82 illustrating magnetite rim around a coarse grained bleb indicating post magmatic growth, plain light x 60 diameters.

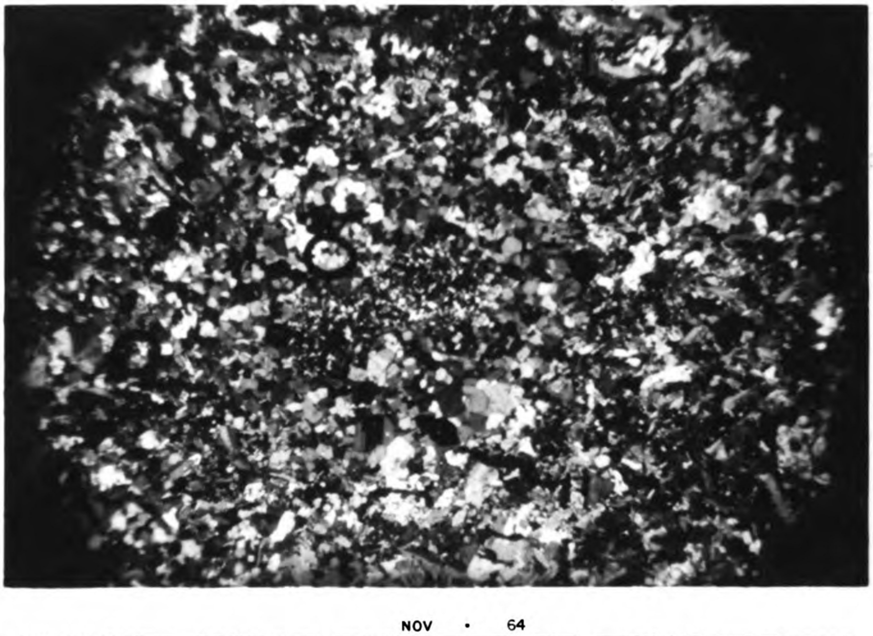


Figure 12 Photomicrograph of 26-83 illustrating hornfels texture, crossed niccols x 60 diameters.

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Figure 13 Photomicrograph of 26-92 illustrating penninite in plain light x 80 diameters.

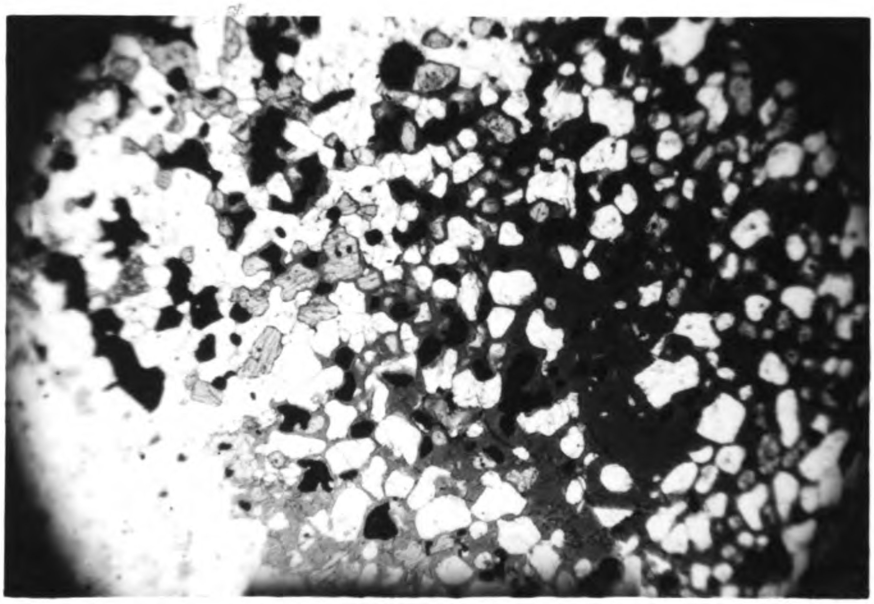

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Figure 14 Photomicrograph of 26-74 illustrating a single poikolitic hornblende crystal (dark gray) altering into pyroxene (light gray). Plagioclase is white. Plain light x 80 diameters.

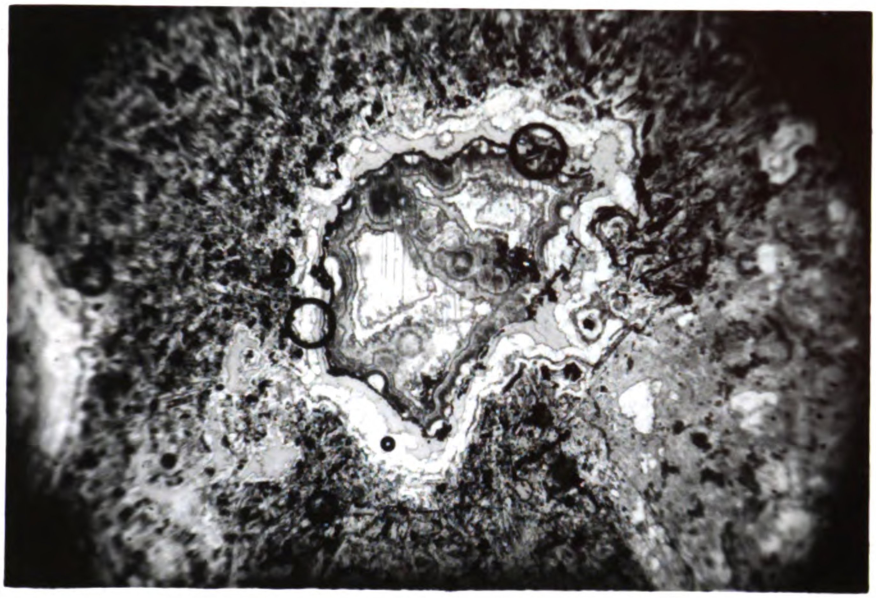

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Figure 15 Photomicrograph of 22-15 illustrating calcite-chalcedony amygdule, crossed niccols X 60 diameters.

Figure 16 Gabbro-diabase contact taken in section 31 outcrop 6.

MINERAL PERCENTAGES OF THE

KEWEENAWAN BASALTS AND META-BASALTS

Table 3

Section Outcrop	Plagioclase	Maximum % An	Average grain size in mm.	Pyroxene	Hornblende	Uralite	Olivine	Opaques	Chlorite	Apatite	Paragonite	Biotite	Quartz	Calcite	Rutile	Orthoclase	Epidote
						Fresh Basalt											
14-2	67	63	.325	25	-	-	-	4	3	-	1	-	-	-	-	T	-
14-3	62	65	.275	30	-	-	-	5	3	-	T	-	-	-	-	-	-
						Northern Meta-Basalt Mass											
22-15	50	44	.200	9	-	-	-	12	13	-	2	-	5	7	-	2	-
22-18	67	36	.750	8	-	-	-	7	14	-	3	-	1	4	-	1	-
30-40	54	35	.500	9	-	-	-	1	30	-	2	-	-	-	-	4	-
						Low Rank Meta-Basalt											
26-54	53	38	.400	-	35	-	-	1	10	-	-	1	-	-	-	-	T
26-82	41	40	.225	15	-	34	-	4	6	-	-	T	-	-	-	-	-
26-83	64	40	.500	2	24	-	-	4	6	-	-	-	T	-	-	T	T
26-91	81	38	.100	6	-	-	-	T	-	T	-	7	-	-	-	-	T
26-92	36	32	.100	-	53	-	-	3	7	T	-	1	-	-	T	-	-
						High Rank Meta-Basalt											
23-10	76	37	.200	11	4	-	-	9	-	T	-	-	-	-	-	-	-
23-4	50	50	.250	9	37	-	-	4	-	-	-	-	-	-	T	-	-
26-76	57	44	.150	6	34	-	-	3	-	T	-	-	-	-	-	-	-
26-78	5	-	.050	-	90	-	T	T	5	-	T	-	-	-	-	T	-
26-1	58	68	.150	20	20	-	-	2	-	-	-	-	-	-	-	-	-
26-74	57	54	.200	20	20	-	-	3	T	T	-	-	T	-	T	-	-
26-75	69	51	.700	22	6	-	-	3	-	-	-	T	-	-	T	-	-
26-90	67	57	.450	12	8	12	-	1	-	-	-	-	-	-	T	-	-
27-12	75	51	.500	17	-	5	-	3	-	-	-	-	-	-	-	-	-
27-79	72	43	.625	10	5	-	-	12	-	T	-	-	-	-	T	-	-
28-4	56	48	.200	18	16	-		13	-								

DIABASE DIKES

Near the contact of the Tyler Formation with the overlying intrusive Keweenawan igneous series, several diabase dikes cut the Keweenawan flows and underlying sediments. The dikes that cut the Tyler must be examined carefully to distinguish them from the graywacke which is of an identical color and grain size. Similar dikes have also been reported to cut the Huronian as deep as the Ironwood where they vary from a few inches to 90 feet thick according to Hotchkiss.

Thin sections from two such dikes, (22-14 and 26-60), reveal a diabasic texture and composition. They have grain size of .4mm and .25mm respectively and are composed of labradorite plus uralite, which seems to be secondary after pigeonite. The most distinctive feature of both samples is that their composition and texture is very similar to other exposures in the area that have a different but possibly closely related origin. Many other thick diabase dikes have been found within the igneous mass to the north of the Tyler Formation. Many of these dikes are often thick and have sharp gabbro-diabase contacts (see figures 17 and 18). However, where the exact field relationships and contacts cannot be seen, the dikes are often confused with other surrounding rock types of an identical lithologic appearance.

THE MELLEN GABBRO INTRUSIVE

The Keweenawan Mellen gabbro-granophyre intrusive complex taken as a whole, extends from a point $3\frac{1}{2}$ miles west of the Michigan border in section 7 of T. 46N., R. 2E. to section 3 in T. 44 N., R. 6W. Its length is approximately 40 miles with an average strike of approximately N.65 degrees E. The width of the intrusion varies appreciably. At one point in T. 45N., R. 2W. the width decreases to less than a mile whereas elsewhere in T. 44N., R. 4W. a thickness of about 6 miles is reached. At the town of Mellen, the intrusive complex is separated by a large mass of granite which appears to have been emplaced following the intrusion of the larger basic intrusive. The eastern contact of this Mellen granite with the Mellen gabbro is located in the map area of this report.

Since at the eastern end of the Mellen gabbro complex the Middle Keweenawan basalt is cut by the intrusion well up into the series, it appears that the intrusion was not emplaced until after most or all of the Keweenawan basalt had been extruded. The magma would not have crystallized with differentiation unless it had a thick cover of rock.

The gabbro is thought by Aldrich to have been intruded along a proposed western extension of the Keweenawan Thrust which he thought extended into Wisconsin from the Lake Gogebic area of Michigan.

The original attitude of the intrusion was probably approximately horizontal which would account for the well developed "upward" or northern differentiation, which has resulted in a basic base and an acidic top. The degree of northward tilting that has followed its emplacement is uncertain. However, dip measurements of a planar orientation of plagioclase laths taken in the map area, average about north 45 degrees. Therefore if it is accepted that the planar orientation of the plagioclase laths at the time of crystallization was approximately horizontal, then the northward dip is therefore established. However, dip of the plagioclase orientation was quite variable and may have been strongly affected by internal flowing or movement during crystallization. A 45 degree dip, being less than that of the Tyler Formation, indicates intrusion at a point in time after the regional northward inclination had begun to develop but before it had been completed.

The occurrence of banding or layering so often found in differentiated intrusives, such as the rhythmic layering of the Stillwater and Skaergaard Igneous Complex, is absent in the map area of this report. Hess (1960) has stated that its presence can be attributed to motion in the magma possibly caused by convection currents. Since the presence is attributed to motion within the magma chamber, its absence therefore implies quiescence and a lack of any convection currents. The reason for this may be the sheetlike shape of the intrusive sill. According to Hess, the ideal shape for a convection cell is one in which the horizontal diameter is only slightly larger than the vertical dimension. Therefore a sheetlike intrusion would not be expected to have had a convection cell.

Although rhythmic banding is not found in the intrusion, cryptic layering is well developed which has made possible the division of the intrusion into several zones of differentiation.

THE ZONES OF DIFFERENTIATION

An important characteristic of the basic intrusion, is the nature of its differentiation, which has developed at least four recognizable zones. The thicknesses of these zones in the map area of this report are as follows:

granite	100-400 feet thick
granodiorite-diorite	400-1,200 feet thick
gabbro-anorthosite	1,000-8,000 feet thick
chill zone	0-400 feet thick

CHILL ZONE

Hand specimen study shows the lower contact of the gabbro to be a thin, fine grained chill zone varying in thickness, but probably no greater than 400 feet thick. Although similar to the metabasalts to the east, certain differences do exist, which make recognition of this chill zone possible. The most obvious difference in hand specimens is lack of amygdules and metacrysts that are found in the basalts. Other differences are slightly coarser grain size and a fresher, less altered appearance. In some of the hand specimens large phenocrysts of a glassy plagioclase are found in the chill zone.

Diabase dikes that in no known way can be distinguished from the chill zone have been found intruding the gabbro in the map area. Since the lithology of the dikes is identical to the greater part of the chill zone, they apparently intruded along fractures while the first gabbro was crystallizing or immediately thereafter. If they had been intruded much later, their composition would be less basic due to differentiation in the magma chamber.

An important characteristic of the chill zone is its olivine content. Olivine is not present throughout the chill zone, being noticeably lacking in the very fine grained zone in contact with the Tyler Formation. However, farther from the contact where the grain size has slightly increased, but not enough to be called gabbro, olivine is present in significant amounts. Still further north, at the base of the coarse grained gabbro, olivine is also present, but is lacking in the interior of the gabbro zone. It therefore seems likely that the very first rock to crystallize did so before differentiation or gravitational crystal settling had a chance to operate and therefore reflects the true composition of the intrusive as a whole. (Thin sections 28-92, 31-6, 32-62, 32-63 represent this zone). Then before conditions became favorable for the crystallization of large plagioclase crystals, typical of the gabbro, gravitational crystal settling had already begun to take place. This may be why the interior of the chill zone contains so much olivine.

The texture of the interior of the chill zone is ophitic and resembles in every detail the base of the gabbro except for the difference in grain size.

On the basis of 2V measurement, the olivine appears to have a composition of Fo 70-Fa 30. The olivine is often very fresh (see figure 18) but in some cases magnetite and serpentine have partly replaced some of the crystals. Olivine crystals in a few samples are surrounded by what appears to be a magmatic stage reaction rim. (See figure 19). The reaction rim is composed of hornblende flakes and pyroxene in a confused fine grain pattern. The olivine is completely unzoned.

The plagioclase is labradorite in nearly all cases and is zoned. The zoning, however, is not generally continuous. The irregular shaped interior zone is more calcic than the surrounding plagioclase. Plagioclase cores of An 60-65 often have outer zones of An 35-40.

The pyroxene is all colorless in thin section and often shows well developed pyroxene cleavage. It occurs both as individual crystals and interstitially between plagioclase laths in an ophitic nature. The samples lacking olivine contain pigennite which was probably the first pyroxene to crystallize. Pigeonite was recognized by its 2V which varied from 10 to 22. In the samples containing olivine, measurements ranged from 19 to 51 suggesting that two varieties of pyroxene are present. The lower

2V measurements indicating pigeonite and the higher measurements suggesting a variety of augite. However, in the coarse grained samples of the chill zone, pigeonite was not found.

Titaniferous magnetite and a few rare crystals of pyrite are the only opaques that were found to exist in the chill zone. Quite often the ilmenite has been completely eaten away and replaced by plagioclase leaving only a skeleton of magnetite. (See figure 20).

Small euhedral apatite crystals and small, rounded, bright red rutile crystals also occur in the chill zone.

Hornblende is a frequent and sometimes plentiful constituent and occurs as fresh pleochroic crystals in browns and greens, with well developed amphibole cleavage. Its presence in large quantities suggests that water was available during the crystallization of the chill zone. Some of the water may have been supplied by the Tyler Formation in contact with the chill zone. Biotite is also found within the chill zone and is closely associated with the magnetite.

Figure 17 Xenolith of gabbro within diabase taken from outcrop 6 section 31.

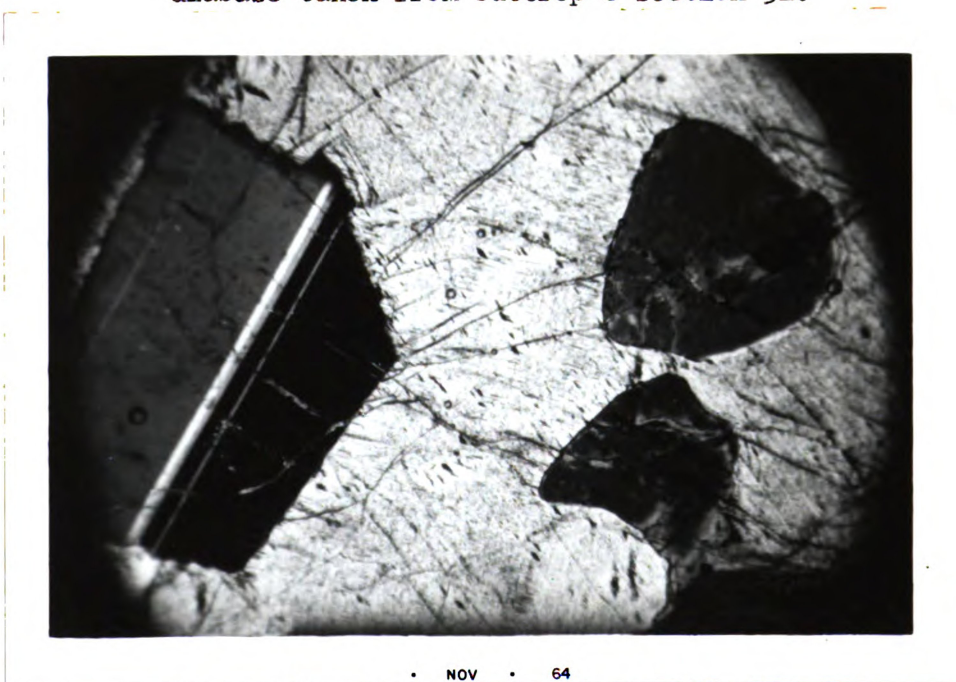

Figure 18 Photomicrograph of 32-60 showing fresh olivine and plagioclase within poikilitic augite crystal. X 100 diameters.

MINERAL PERCENTAGES IN THE

CHILL ZONE

Table 4

Section Outcrop	Plagioclase	Maximum % An	Average grain size in mm.	Pyroxene	Hornblende	Uralite	Olivine	Magnetite-Ilmenite	Chlorite	Paragonite	Apatite	Zircon	Biotite	Rutile	Calcite
6-6	70	36	.50	-	1	20	-	2	5	2	-	-	-	T	T
6-10	66	52	.40	25	-	-	5	3	T	-	-	-	T	-	-
6-42	58	55	.85	36	-	-	5	1	T	-	T	T	T	-	-
6-43	58	57	.30	27	-	2	10	3	-	-	-	-	T	T	-
26-60*	62	47	.40	-	-	33	-	5	-	-	-	-	-	-	-
27-14*	54	59	.25	5	-	35	-	1	10	-	-	-	-	-	-
27-80	66	63	.25	28	-	-	3	2	-	-	-	-	1	T	-
6-40	79	52	.80	20	T	-	T	1	-	-	-	-	T	-	-
28-90	27	49	.10	50	20	-	17	3	-	-	T	-	T	T	-
28-105	73	62	.30	15	-	-	10	2	-	-	-	-	T	T	-
30-3	66	64	.60	26	-	-	4	4	-	-	-	-	T	-	-
31-3	55	57	.60	35	-	-	5	4	-	-	-	-	1	T	-
32-13	72	55	.33	-	-	19	-	3	6	-	-	-	-	-	-
32-62	30	56	.40	-	-	40	-	T	10	20	-	-	-	-	T
32-63	71	56	.22	25	-	-	-	2	-	-	-	-	-	-	-
33-92	46	51	.30	-	-	50	-	2	-	-	-	T	2	-	-
33-100	85	56	.35	12	-	2	-	-	-	-	-	-	-	-	-
33-104	73	59	.30	12	-	-	13	2	-	-	-	-	T	T	-

* Dikes cutting Tyler Formation

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Figure 19 Photomicrograph of reaction rim around olivine grain, 32-5, crossed niccols.

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Figure 20 Photomicrograph of 32-66 illustrating magnetite skeleton left after ilmenite has been eaten away in plain light X 80 diameters.

THE GABBRO ZONE

The coarse grained gabbro intrusive differs from the chill zone in lacking olivine, containing smaller amounts of mafic minerals and a proportionately higher amount of plagioclase. (See table 5 and 6). An obvious difference is the great increase in grain size. In hand specimens, typical gabbro samples are very coarse grained and are composed largely of plagioclase. The plagioclase is a gray labradorite variety. Green silicates and occasional magnetite crystals fill the space in between the plagioclase laths producing a very attractive rock.

The gabbro is being quarried as "black granite" in section 29 and has been quarried previously at two other locations, also in section 29. The quarrying operation (see figure 21 and 22) has exposed large areas of gabbro, making possible the observation of large granodiorite and pegmatite veins that have intruded the gabbro. (See figure 23). The granodiorite - gabbro contact is extremely sharp. In an interview with Mr. Louis Jager, the quarry foreman, I was informed that most of the granodiorite intrusions dip toward the north at about 45 degrees. Test drilling has shown that the intrusions become thicker at depth.

The source of the granodiorite sills or veins is evidently the large granite intrusion west of the Bad River known as the Mellen granite. It may be that during the emplacement of the Mellen granite just west of the map area, cracking and jointing occurred in the gabbro mass. These cracks may have then been filled by apophyses from the granite magma. Granodiorite has cut the gabbro at all three quarries and at outcrops within the gabbro at several other locations. As the Mellen granite is approached, these granodiorite veins become more and more numerous. At the quarry south of Loon Lake (outcrop 12-section 29), the granodiorite contains broken off xenoliths of gabbro. Upon observing the xenolith-granodiorite relationship of the Loon Lake exposure, it is clear that there is a strong resemblance in every respect to outcrop 124 in section 30 where the Mellen granite intrusion contains numerous xenoliths of basic rock. (See figure 23 and 24).

Outcrop 33 in section 29 south of Loon Lake is located at the summit of a well exposed gabbro dome with 160 feet of relief. At this location, the gabbro possesses very unusual magnetic properties. When the Brunton compass is held four feet away from the rock surface, the needle points north as verified from a bearing taken on a church tower that could be seen in the town of Mellen, less than two miles away. However, when the compass was placed directly on the rock surface, the needle pointed due west. This is probably caused by polarity in a local concentration of magnetite occuring within the gabbro.

In thin sections, the gabbros are composed chiefly of large laths of labradorite in an ophitic texture. The grain size is quite variable. There seems to be some correlation between grain size and plagioclase content. The plagioclase is often well zoned with irregular shaped inner zones. The individual laths are often cracked and broken in a way that would seem to indicate crushing

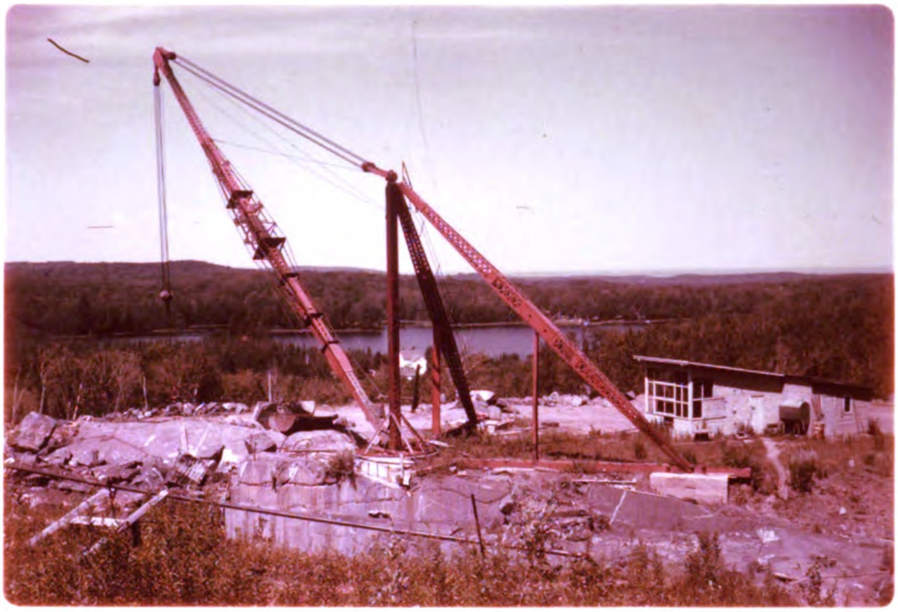


Figure 21 "Black Granite" quarry hoist with Loon Lake in the background.

Figure 22 Drill operator at work at the Loon Lake quarry.

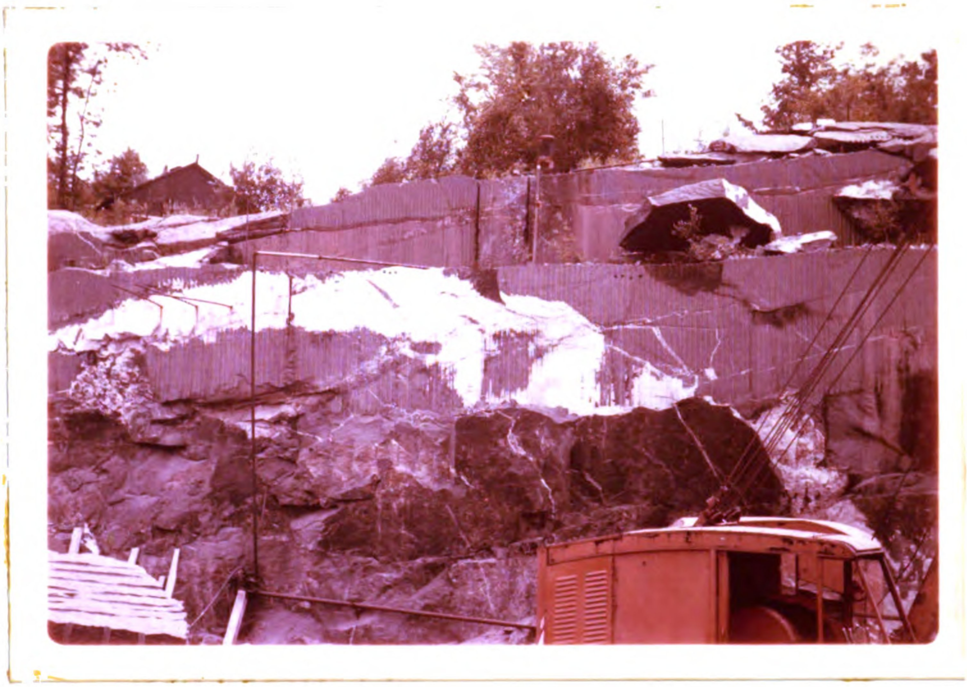


Figure 23 Quarry wall illustrating granodiorite intruded into gabbro.

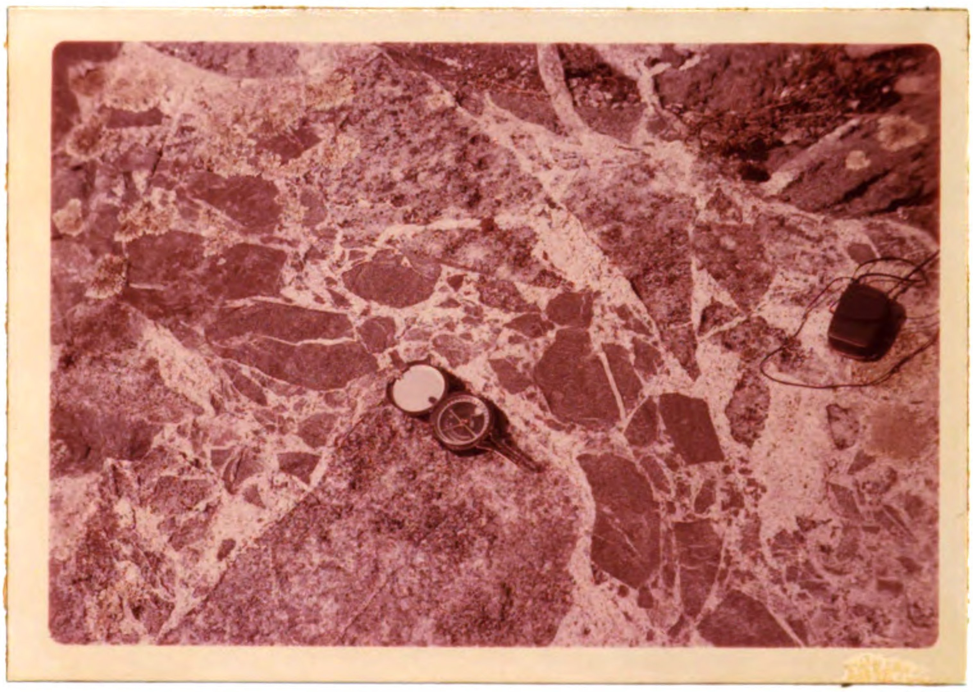


Figure 24 White granite outcrop (30-124) containing gabbro and diabase xenoliths.

before the interstitial liquid had crystallized. (See figure 25).

In an experiment performed by Wagner, Brown and Wadsworth (1960) it was shown that simple packing of aluminum tablets, (of a shape comparable with plagioclase of the type found in anorthosite) if loosely accumulated in water, the resulting void space amounted to about 45 percent. Shaking to improve the packing only decreases the voids to about 35 percent. Since the amount of plagioclase in the anorthositic variety of gabbro found in section 28, 29 and 30 reaches 95 percent, it seems probable that about 35 percent of the plagioclase grew from material supplied by the interstitial liquid after crystal settling. This reasoning assumes an origin by crystal accumulation, but in view of the gradual upward differentiation, this type of origin seems to apply. An explanation to account for the enlargement of the plagioclase has been offered by Hess (1939). He has suggested that diffusion from the overlying magma through the interstitial liquid between the crystals supplied the material necessary to continue growth. While this diffusion was occuring, a simultaneous diffusion of the unused material was occuring in the opposite direction. As growth continued, the interstitial liquid would gradually be pushed out until a small amount would be trapped. This would necessitate very slow cooling and require a thin layer of "crystal mush" in order for the diffusion to take place. As a result of this type of crystal growth, large extremely poikilitic pyroxene crystals have grown from the pore-space liquid.

Each pyroxene crystal includes within it several large plagioclase laths. It would seem that in this igneous body, plagioclase has a greater tendency to form crystal nuclei at the beginning of crystallization than pyroxene thus accounting for the ophitic texture.

The pyroxene is chiefly a colorless augite. However, hypersthene also occurs in smaller amounts. The hypersthene reveals well developed exsolution structure where augite has exsolved as oriented lamellae along the (001) cleavage direction of the hypersthene (see figure 28).

The order of crystallization making use of information supplied by the chill zone, can now be roughly stated. It appears that the first pyroxene to crystallize was pigeonite which makes up the majority of the fine grained chill zone pyroxene. As the temperature decreased slightly, augite also crystallized and exsolved from the pigeonite (see figure 26). As cooling continued while the gabbro was crystallizing, the pigeonite inverted to hypersthene while continuing to exsolve augite (see figure 27).

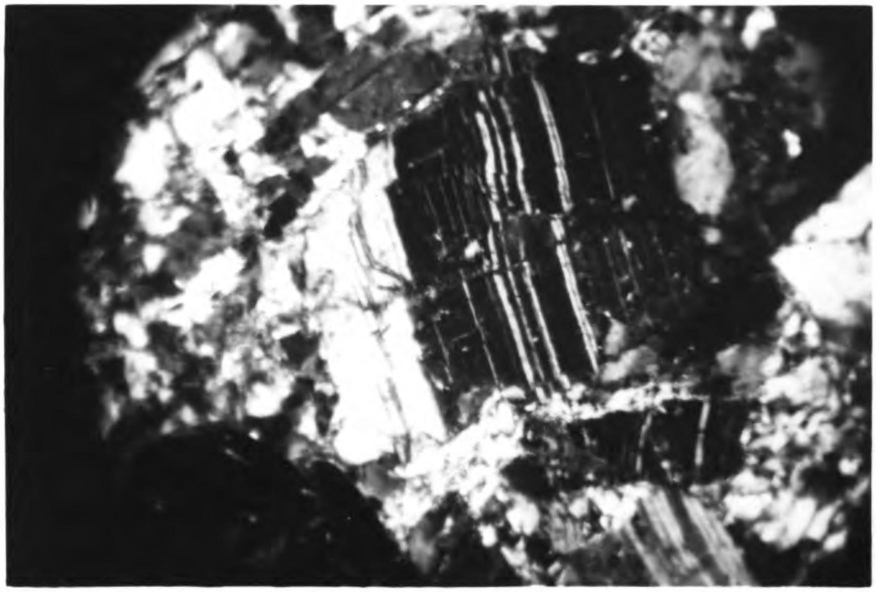
The following pyroxene contents were developed as a result of differentiation with approximate percentages:

(1) pigeonite 90% plus augite 10% = chill zone

(2) pigeonite 10% plus augite 85% plus 5% pigeonite with exsolved augite parallel to (001) lamellae = interior of chill zone and base of gabbro

(3) hypersthene 5% plus augite 90% and 5% hypersthene with exsolved augite parallel to (001) lamellae = gabbro

The presence of augite plates exsolved from pigeonite before



NOV · 64

Figure 25 Photomicrograph of 27-15 illustrating a crushed plagioclase crystal under crossed niccols.

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Figure 26 Photemicrograph of 32-61 illustrating pigeonite-augite exsolution. Crossed niccols.

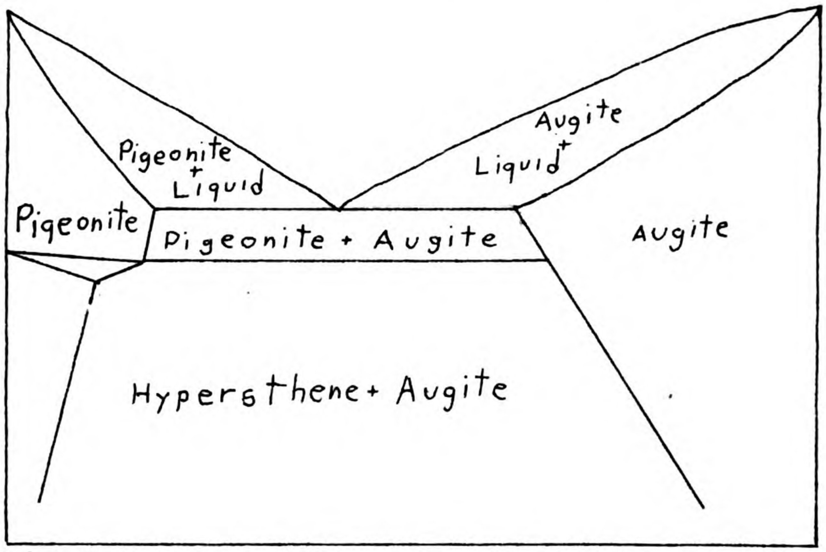

Figure 27 Equilibrium diagram of pyroxenes, after Hess (1941)

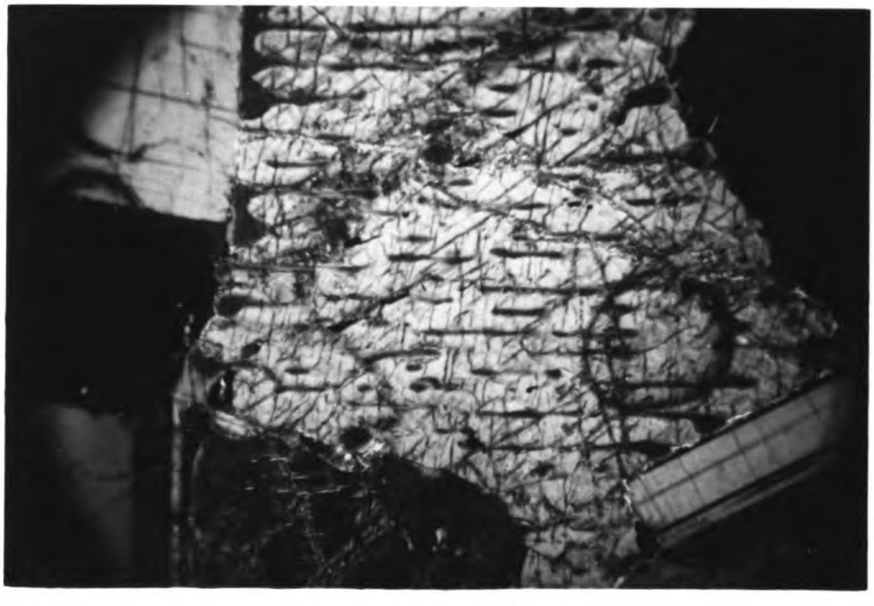

Figure 28 Photomicrograph of 32-17 illustrating hypersthene exsolving augite lamalle under crossed niccols X 100 diameters.

MINERAL PERCENTAGES IN THE

GABBRO ZONE

Table 5

Section Outcrop	Plagioclase	Maximum % An	Average length of plagioclase laths	Pyroxene	Hornblende	Uralite	Chlorite	Paragonite	Opaques	Olivine	Apatite	Zeolite	Muscovite	Calcite	Biotite
27-15	83	41	1.5	T	-	10	T	3	4	-	-	-	T	T	-
29-8a	73	65	4.0	T	-	25	T	T	1	-	-	-	-	-	1
31-131	85	64	7.5	6	-	-	T	-	1	8	-	-	-	-	-
32-17	83	62	4.0	10	-	-	T	-	2	5	-	-	-	-	-
32-8	79	57	2.5	15	-	-	-	-	2	4	1	-	-	-	-
23-120	74	56	1.0	12	8	-	T	-	4	1	1	-	-	-	-
32-6	61	36	11.8	-	-	35	T	T	4	-	-	-	-	-	-
32-12	90	64	3.5	T	-	6	-	1	3	-	-	T	-	-	-
32-101	95	67	6.0	1	-	2	-	-	1	1	-	-	-	-	-
32-66	85	64	2.5	T	10	-	2	-	3	-	-	-	-	-	-
32-60	60	58	1.5	26	-	-	-	-	2	10	-	-	-	-	2
32-61	75	55	2.5	13	-	-	-	-	1	10	-	-	-	-	1
28-106	35	59	1.2	65	-	-	-	-	T	-	-	T	-	-	T
31-5	56	54	3.0	7	-	-	-	-	2	35	-	-	-	-	-

inversion has also been described by Hess and Henderson (1949). According to Hess (1960), orthopyroxenes are not usually found in dolcrites (such as the interior of the chill zone). Instead its place is taken either by uninverted pigeonite or a variety of orthopyroxene which he calls the Palisades Type. The "Palisades Type" is caused when cooling is fast and inversion takes place before exsolution. The fast cooling therefore does not permit excess CaO from the pigeonite to become absorbed by augite lamellae and therefore causes the formation of diopside specks in the orthopyroxene. Since diopside specks were not found, it can be concluded that cooling was slow enough for the excess CaO to become absorbed by the augite lamellae or by the plagioclase.

The average 2V for the augite is only 47 degrees which indicates that it is probably diopsidic variety bordering on subcalcic variety. The augite is completely colorless in thin section. The pigeonite of the chill zone, which is also colorless, has an average 2V of 21 degrees.

Maximum extinction angles for the pigeonite averaged 34 degrees whereas maximum extinction angles for augite averaged 41 degrees.

Hypersthene was readily distinguished by its parallel extinction and faint red to colorless pleochrism. Schiller structure is well developed in most of the hypersthene and was observed in some of the augite.

In samples which contain much uralite, the pyroxene content is proportionately low. Uralitization has almost completely replaced pyroxene in several cases.

Titaniferous magnetite is the only opaque that I have observed in thin section. It occurs in amounts ranging from one to four percent. Traces of apatite have occasionally been observed in very small amounts. Biotite is seldom present, but has been observed associated with crystals of magnetite. Olivine (Fa 30), as has already been mentioned, occurs only near the base of the intrusion. Pleochroic brown to green hornblende has also been observed in two gabbro samples located near the base.

In each of the samples listed in table 6, the texture is ophitic.

DIORITE - GRANODIORITE ZONE

In traversing northwardly up dip from the dark gray gabbro, a diorite zone is encountered.

Samples taken from the diorite zone are easily distinguishable from the coarse grained gray gabbro below. In hand specimen, the diorite occurs as a medium grained rock consisting of black amphibole crystals equal in size to white feldspar crystals which make up the majority of the rock. In this section the rock is hypautomorphic granular. The composition of the diorite is represented by thin section 23-31 (see table 6). The plagioclase appears to be andesine and the chief mafic mineral is amphibole thus indicating the rock is definitely not gabbro although the sample was taken from an area that has previously been mapped as a gabbro. The amphibole is a pale green variety that is occasionally feathery but occurs chiefly as prismatic moderately pleochroic crystals.

A small amount of pyroxene which has been largely altered to amphibole also occurs in the diorite. A small amount of orthoclase was found in thin section 23-31 which occurs as small rounded blebs within the amphibole and feldspar crystals and never as distinct crystals. In the overlying granodiorite zone the orthoclase content increases.

The granodiorite is typified by sample 25 in section 23 (see table 6) where quartz makes its first appearance and total mafic content greatly decreases. The pyroxene appears to be a colorless augite. The hornblende is fresh and euhedral and is pleochroic in brown and olive green. Staining for the positive identification of orthoclase has indicated a close quartz-orthoclase association with intergrowths of quartz within the orthoclase. Magnetite is often found as euhedral crystals in contrast to its occurence in the gabbro. As the granite zone is approached it is interesting to note the high apatite content in several samples (see table 6). In some cases, the apatite occurs in fairly large grains and remains quite euhedral.

GRANITE DIFFERENTIATE

The granite zone is especially well exposed along two east-west trending ridges located along the south edge of section 21 and in the center of section 23. The granite differentiate differs from the major part of the large granite body immediately to the west of the gabbro in lacking a porphyritic texture. Certain differences have also been observed with the granite in section 30 which is not a porphyritic variety. The chief differences consist of a higher plagioclase, quartz, hornblende, apatite, and opaque content in the differentiate. (See table 6). The granite differentiate apparently differs from the granophyre described by Leighton (1954) in having a lesser development of micrographic texture and a higher percentage of mafic material in the granite differentiate. The granite differentiate is medium grained to coarse grained. The orthoclase in it is bright reddish orange. It does not contain the great number of xenoliths which may be observed in the Mellen granite to the west. However, at least two large basalt xenoliths and one medium grained xenolith of a gabbroic nature were found within it. The medium grained xenolith may represent a remnant of the upper chill zone, if such a chill zone originally developed. The upper edge of the differentiated sill was not found exposed at any place. Pegmatite (outcrop 23-22) found in contact with the granite, contains crystals ranging from 1-2cm. It is composed of roughly 50 percent red orthoclase, 30 percent

very euhedral black hornblende, and 20 percent milky quartz. The quartz weathers out strongly in relief. The pegmatite probably originated along a crack in the granite as material "sweated out" of the surrounding rock shortly following magmatic crystallization.

In thin section, the granite differentiate is best represented by sample 28-32. The texture is equigranular. The amount of orthoclase is less than one would expect after observing the rock in hand specimen. Actually, the majority of the brick red feldspar is microcline and plagioclase. All three types of feldspar are colored by a red dust that is also present in the feldspar of the granophyres described by Leighton. Leighton indicates that the coloring agent is probably hematite.

The orthoclase that is present grades into microcline which is present in large amounts. Since in hand specimen all of the feldspar is brick red, this evidently includes the plagioclase that is present. The plagioclase is albite (An 6%) and is unzoned. The red dust in the plagioclase is quite blotchy, whereas in the orthoclase and microcline it is evenly distributed. Quartz is present only in rounded, regular blebs associated with the potash feldspar, but avoiding the hornblende. The hornblende is pleochroic in green and yellows and occurs as discrete individual crystals.

Although the amount of granite probably amounts to no more than 3 or 4 percent of the total intrusive, this figure according to (Hess 1960), is quite high. Hess has stated that "In the most

MINERAL PERCENTAGES IN THE

DIORITE - GRANODIORITE - GRANITE ZONE

Table 6

Section Outcrop	Plagioclase	Maximum % An	Average grain size	Orthoclase	Microcline	Quartz	Pyroxene	Hornblende	Uralite	Biotite	Zircon	Apatite	Opaque	Rutile	Serpentine
30-2**	2	-	2.5	87	-	7	-	4	-	-	T	-	T	-	-
21-32a	29	6	1.5	8	23	19	T	15	-	-	T	2	4	-	-
21-32b	28	8	1.7	8	24	17	T	14	-	T	T	3	5	-	-
23-21	5	-	.7	45	-	35	-	-	10	-	-	-	5	-	-
28-98	71	42	2.0	6	-	8	5	6	-	-	T	3	2	-	-
21-6	69	39	1.5	9	-	5	T	9	6	-	T	T	1	T	T
23-25	76	47	1.5	8	-	2	5	5	-	T	-	T	4	T	-
22-3	60	34	1.0	8	-	9	-	15	-	-	-	-	7	T	-
22-7	78	44	1.5	3	-	1	3	5	5	-	T	3	2	-	-
23-31	66	43	2.0	2	-	-	5	25	-	-	-	-	2	-	-
29-8b*	25	-	1.5	30	10	23	-	8	-	2	-	-	2	-	-

* sample taken from granodiorite vein at gabbro quarry

** sample taken from Mellen Granite intrusive extreme cases of fractional crystallization, in which the chance of obtaining a granite residue would be most favorable, it seems very unlikely that large bodies of granite are ever derived from fractional crystallization of basalt". Despite this observation I feel that the near perfect gradation to the granite can best be explained as an acid residual of a fractional crystallization process.

THE MELLEN GABBRO-MELLEN GRANITE CONTACT

The western contact of the Mellen Gabbro instrusion with a large granite mass to the west (tentatively called the Mellen Granite), is very irregular. At no place does gabbro lithologically grade into the Mellen Granite. Instead, the contact is very sharp, with no intermediate rock type present. The most characteristic feature of the granite is the large quantity of xenoliths it contains. The larger xenoliths are usually gabbro. However, medium to fine grained basalt or diabase fragments are also found in the granite mixed in with those of gabbro.

CONCLUSION

The conclusion drawn from the above research can best be summarized by a brief discussion of the sequence of events that occurred.

The deposition of the Tyler Formation probably ended in an increasingly shallow water environment as indicated by the nature of the quartzite that resulted. The Huronian-Keweenawan time gap that followed was ended with the deposition of a thin basal Keweenawan conglomerate and quartzite layer before the extrusion of the thick Keweenawan flows that followed. While the magma chamber was emptying, a regional tilting as described by Hotchkiss (1923), may have occurred, causing the area to dip toward the northern basin thus created. Before the slumping had ceased, a large gabbro laccolith was intruded, possibily along the plane of a thrust fault that split the basaltic mass in the eastern end of the map area and followed the northern contact of the Tyler Formation in the western portion of the area.

The contact metamorphic effects of the intrusion on the Tyler Formation were slight, as indicated by the absence of contact metamorphic minerals. The reason for this fact appears to be partly because of the resistence of the recrystallized silica cemented facies of the Tyler Formation to temperature effects and its impermeability to solution effects. Also quartzites evidently lack sufficient mafic content to supply the material for the crystallization of contact metamorphic minerals. The quartzite facies has also shielded the underlying subgraywacke and graywacke facies of the Tyler Formation from any contact metamorphic effects. However, the effect of the gabbro intrusion on the Keweenawan basalt was appreciable and reaches the pyroxene hornfels facies of contact metamorphism.

As the intrusion began to crystallize, a thin chill zone was formed. Diabase dikes of an identical lithologic nature were also being intruded into the Tyler Formation as offshoots of the main gabbro mass. As the crystallization continued, olivine separated out by gravity, sinking to the bottom of the intrusive. A typical to anorthositic gabbro was then formed which makes up the bulk of the intrusive body. The gabbro, however, grades into a diorite near the top, which in turn grades into a granodiorite and finally a granite.

The last igneous event to occur in the area was the intrusion of granodiorite dikes, probably originating from the Mellen Granite, which cut the Mellen Gabbro.

SUGGESTIONS FOR FURTHER STUDY

Although it is unlikely that contact metamorphic effects will be found in any future study of the Tyler Formation, it may be very useful to examine the possibility of regional metamorphic effects on the Tyler. It is quite possible that during the Huronian - Keweenawan unconformity, some degree of metamorphism was impressed upon the Tyler Formation.

A contact metamorphic problem involving the basalt that I have left unanswered concerns the question as to whether the pigeonite was directly converted to diopside or whether it passed through an intermediate hornblende stage. This question would necessitate an explanation of the chemical changes that went on during the metamorphism. For additional field evidence, the area directly to the east of the map area of this report may prove useful. A comparison of the contact metamorphic potential of the base of the gabbro sill with the acid differentiate may also be of interest. Such a comparison would require good basalt exposure at both contacts. However, adequate exposures may exist in the area to the east of section 23.

Now that it has been demonstrated that the intrusive sill has undergone differentiation it may be useful, through a series of normative analysis, to describe the sequence of chemical changes that occurred as crystallization progressed. Such an investigation may aid in any further speculation concerning the relative importance of crystal zoning, gravity settling, and possibly partial fusion and filter pressing as differentiation mechanisms.

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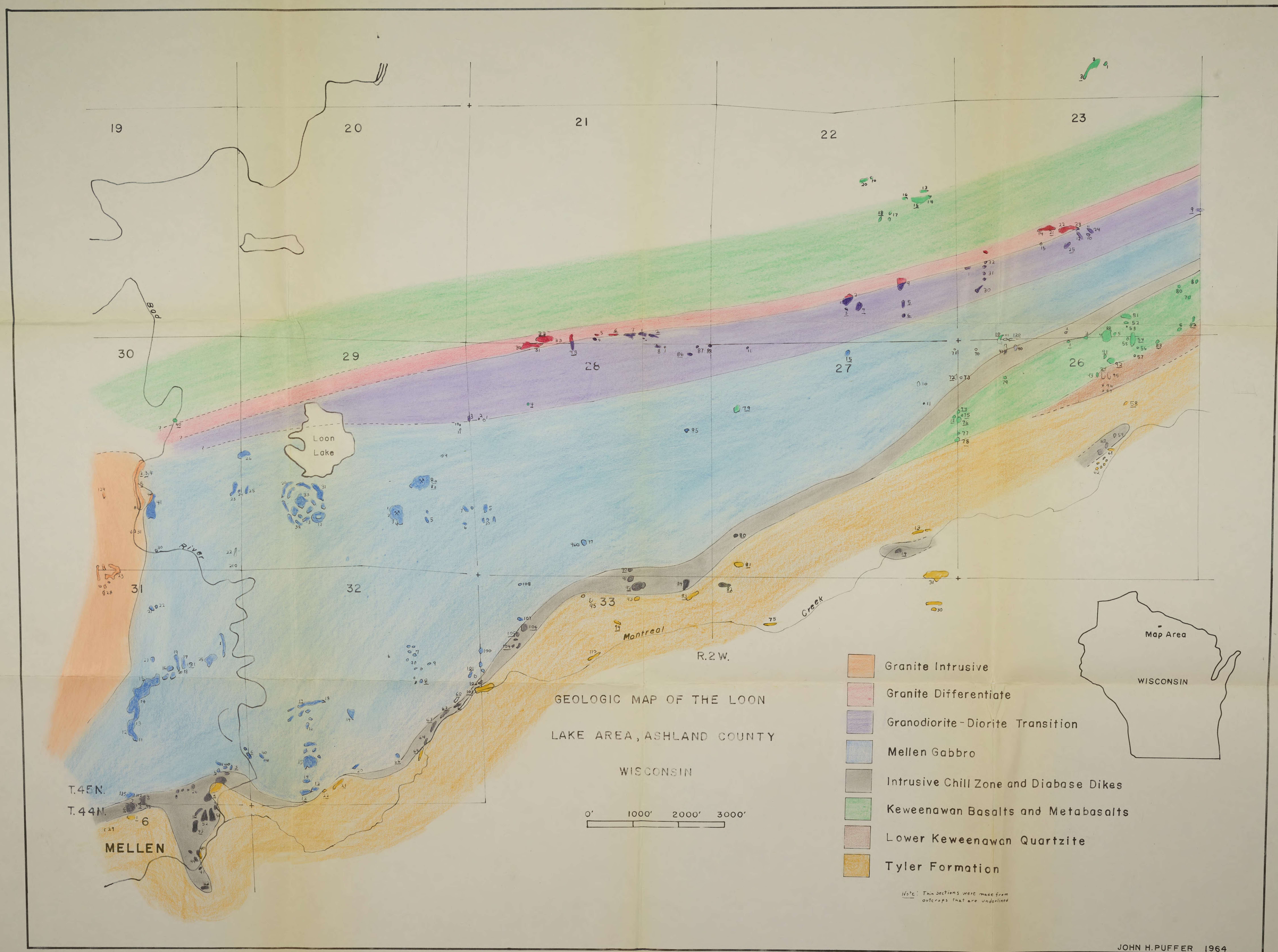
SUPPLEMENTARY
MATERIAL



GEOLOGIC MAP OF THE LOON
LAKE AREA, ASHLAND COUNTY
WISCONSIN
19
20
21
22
23
30
29
28
27
26
31
32
33
6
Loon Lake
Bad
River
Montreal
Creek
R.2W.
T.45N.
T.44N.
MELLEN
Granite Intrusive
Granite Differentiate
Granodiorite - Diorite Transition
Mellen Gabbro
Intrusive Chill Zone and Diabase Dikes
Keweenawan Basalts and Metabasalts
Lower Keweenawan Quartzite
Tyler Formation
0'
1000'
2000'
3000'
Map Area
WISCONSIN
Note: Thin sections were made from outcrops that are underlined
JOHN H. PUFFER 1964