ABSTRACT

METAMORPHIC PETROLOGY OF THE ANIMIKI SERIES
IN THE REPUBLIC TROUGH AREA,
MARQUETTE COUNTY, MICHIGAN

by James W. Villar

The Republic trough is located in southwestern Marquette County in Michigan's northern peninsula. It constitutes a tightly folded belt of Precambrian rocks which represent a southeasterly extension of the southern limb of the Marquette synclinorium. The rocks include an undifferentiated basement complex which is overlain by metasediments of the Animikie series. These are intruded by sill-like amphibolites which are themselves metamorphosed and also considered of Animikie age. Locally there are minor occurrences of unmetamorphosed diabase dikes (Keweenawan?).

The oldest clearly discernable metasediments are correlated with the Ajibik formation. Contact relationships with underlying granitic appearing rocks are transitional. The upper portions grade into iron-rich metasediments of the Negaunee. Rocks of the Ajibik are subdivided into eight principal lithologic types based on major mineral assemblages. These include quartzite, schist, and gneiss with quartz, mica, and feldspar as the most common constituents. Locally, garnet, sillimanite, andalusite, epidote, amphibole, or chlorite appear as a major phase.

The iron-rich metasediments of the Negaunee are divided into three members according to major mineral constituents. These normally reflect a close relationship between stratigraphic position and major mineral assemblage. In descending stratigraphic order the mineral assemblages of a complete section generally are: (1) quartz-specular hematite, (2) quartz-magnetite, and (3) quartz-grunerite-magnetite. The rocks are typically banded although oolitic structures occur locally. Chemically and mineralogically the upper two members are of simple composition and reveal very little relative to parent constituents. The quartz-grunerite-magnetite member provides considerably more evidence relative to the sequence of mineral development during regional metamorphism. The most apparent is the development of silicates, especially grunerite, at the expense of magnetite. This is reflected in both the bulk chemistry of the rock and mineral relationships.

Locally, a basal conglomerate which is frequently iron rich occurs between the Negaunee and overlying Goodrich formation. In addition to the conglomerate the Goodrich includes quartzite, schist, and gneiss. These are subdivided into six principal lithologic types based on salient mineral assemblages. Quartz, mica, epidote and feldspar are the most common constituents. Amphibole, garnet and sphene occasionally occur in significant quantities.

Rocks of the Michigamme formation are believed to represent the youngest metasediments of the area. Contact relationships with the underlying Goodrich are obscured by intrusives at all observable sites. Four lithologic types are recognized which include: (1) quartz-grunerite schist, (2) quartz-mica-andalusite-garnet schist, (3) quartz-mica schist, and (4) quartz-grunerite-stilpnomelane schist.

Amphibolites, which are normally sill-like, occur throughout the entire area. These are grouped into four classes: (1) amphibolite, (2) plagioclase amphibolite, (3) quartz amphibolite, and (4) pyroxene amphibolite. There is an apparent regional partitioning of these classes.

Mineral assemblages reflecting conditions of both the middle to upper greenschist and almandine amphibolite facies are present. Prograde assemblages of the greenschist facies are limited in extent. The principal indicators are stilpnomelane, actinolitic hornblende and iron chlorite. Transition from the greenschist to the lower almandine amphibolite facies (staurolite-quartz subfaces) is marked by the breakdown of stilpnomelane, appearance of epidote with intermediate plagioclase, calcite and muscovite reacting to give potash feldspar and epidote, blue green hornblende replacing actinolite, and substantial decrease in iron chlorites. There is evidence that metamorphic grades exceeding the staurolite-quartz subfacies were attained. The major indicator is the appearance of sillimanite. This marks the lower part of the sillimanite-almandine subfaces (first sillimanite isograd). There is no evidence of sillimanite formation at the expense of potash feldspar (second sillimanite isograd).

The age of metamorphism is placed at 1.61 billion years on the basis of K^{40}/A^{40} determinations on muscovite from the iron-formation. This is comparable to the Penokean orogeny between Middle and Late Precambrian.

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J.W.V.

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CHAPTER I

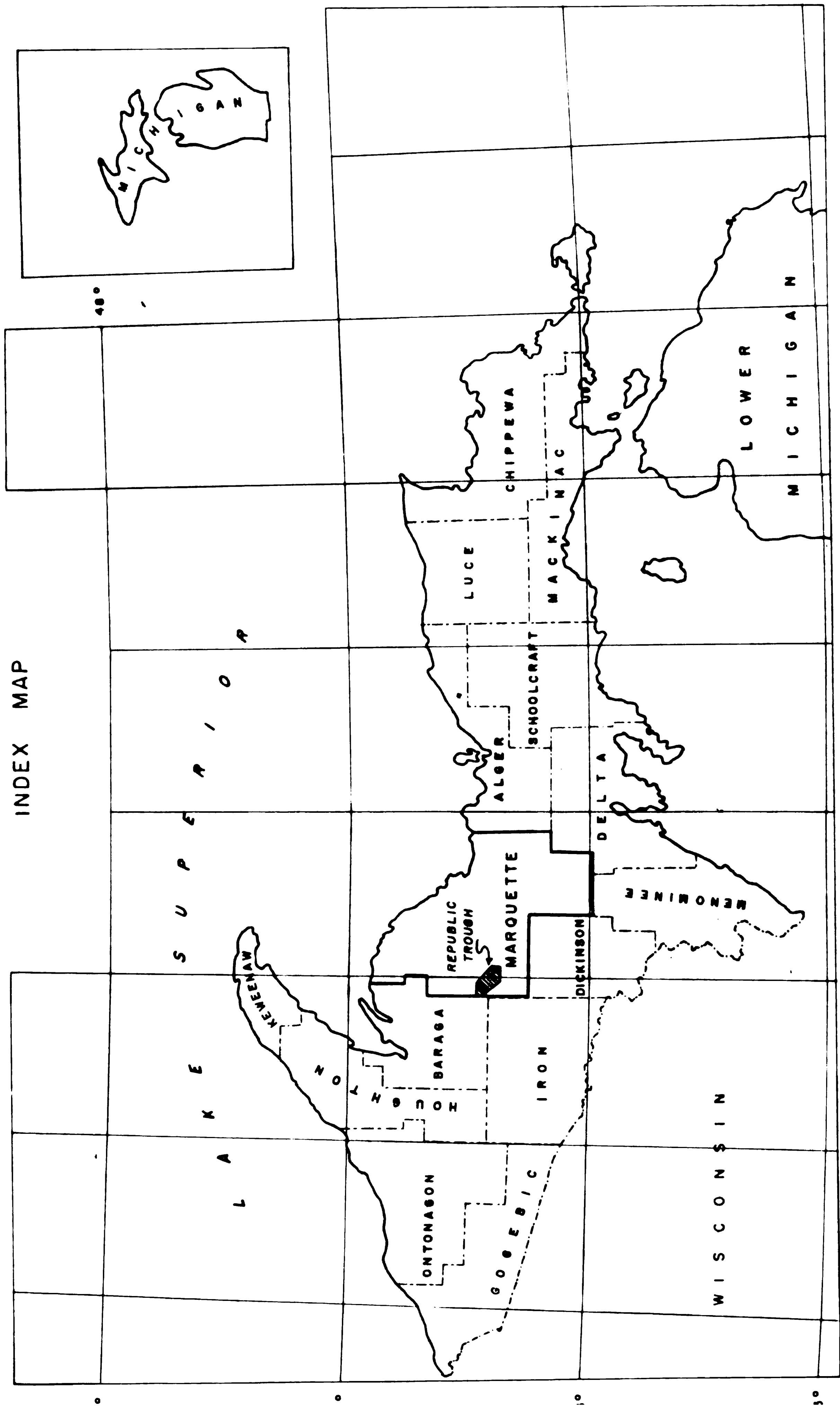
INTRODUCTION

Location and Accessibility

The Republic Trough is a narrow syncline of Animikie rocks located along the western portion of Marquette County in the northern peninsula of Michigan. Figure 1 shows its approximate location. The area that is herewith included as a portion of the trough extends from the Republic Mine northwesterly along the Michigamme River to the vicinity of the old workings of the Magnetic Mine (Sec. 20, T. 47 N., R. 30 W.). Extensions perpendicular to the major synclinal axis, which roughly parallels the Michigamme River, have been arbitrarily set to include all rocks of the Animikie series and sufficient portions of the undifferentiated basement complex to provide a structural framework. This includes an area of approximately 15 square miles.

The Village of Republic, with a population of 1600 people, is readily accessible via State Highway M-95 and several county roads. Furthermore, in conjunction with the development of the Republic Mine, an eight mile extension of the Lake Superior and Ishpeming Railroad was constructed from the Humboldt Mine (Sec. 11, T. 47 N., R. 29 W.). The central and north portions of the trough are less accessible.

FIGURE 1


INDEX MAP
LAKE SUPERIOR
MICHIGAN
KEWEENAW
HOUGHTON
BARAGA
ONTONAGON
GOGEBIC
IRON
REPUBLIC TROUGH
MARQUETTE
DICKINSON
MENOMINEE
DELTA
ALGER
SCHOOLCRAFT
LUCE
MACKINAC
CHIPPEWA
LOWER MICHIGAN
WISCONSIN
48°
47°
46°
45°
83°
84°
85°
86°
87°
88°
89°
90°

1H

Principal access is by a county road along the western edge of the Michigamme River. There are numerous logging roads but these are generally inaccessible by automobile. The area northeast of the Michigamme River can no longer be reached by automobile north of State Highway M-95. A few small bridges were constructed but these have been washed out during spring thaws and are no longer passible.

Topography and Drainage

The Michigamme River is the principal control on surface drainage in the Trough area. It flows southeasterly from Lake Michigamme and is regulated to some extent by two dams: one at the southern tip of Lake Michigamme and the other near the Village of Republic. Numerous tributaries feed the Michigamme River from the ridges along both flanks. The gradients of these smaller streams have considerable variation over short distances. This results in poor drainage with frequent swamps and marsh areas. These swamps are most extensive along the Michigamme River.

The topography of the area is characterized by numerous irregular ridges and knob-like hills which are interrupted by the lowland swamps along the Michigamme River. Maximum relief is about 220 feet. The area is, for the most part, covered with thick vegetation. This, along with the numerous swamps and irregular ridges, causes considerable difficulty in conducting continuous traverses on a set bearing.

CHAPTER II

METHOD OF STUDY

Field Mapping

The field work for this investigation was carried out primarily during the summers of 1958 through 1961. Additional mapping was conducted on a part time basis during 1963 and 1964.

A variety of base maps and mapping methods were utilized. In the vicinity of the Republic Mine field data were compiled on 1" to 50' base maps. Surveys were conducted with a transit inasmuch as the area contains numerous control stations and affords excellent visibility. In all other areas where iron formation occurrences were anticipated a plane table and telescopic alidade were employed. Traverse intervals ranging from 50 to 100 feet were maintained. The choice of interval depended largely upon the quantity of foliage. Outcrops were plotted on 1" to 200' base maps. Other formations of the Animikie series were mapped by means of pace and sundial. Traverse intervals of 200 to 400 feet were utilized and data were plotted on either 1" to 200' or 1" to 500' base maps. The majority of outcrops within the basement complex were located on aerial photographs or enlarged topographic sheets (1" = 500'). Survey control was maintained on 500 to 1000 foot traverse intervals.

A limited number of magnetic surveys were conducted to determine the continuity of several magnetite bearing units. These surveys were carried out with a Jalander, flux-gate type, magnetometer.

Sample Collection and Preparation for Chemical Analyses

In all cases where samples were collected for chemical analyses an effort was made to select areas that would represent, as nearly as possible, the entire width of the unit. Surface exposures were then channel sampled perpendicular to the strike of the unit avoiding as much as possible zones of extensive secondary alteration. Sample quantities in excess of 500 pounds were collected from each site. This composite was then thoroughly mixed and quartered. A split portion of approximately 100 pounds was stage crushed to pass 6 mesh and gain mixed. A split of approximately 5 pounds of the crushed material was compiled from the sample and cleaned with a weak magnet to remove any metallic iron contamination that may have been introduced. A one per cent portion was then pulverized by hand with an automatic type ceramic pulverizer. A similar procedure was employed when utilizing drill core. However, in this case the drill core was split in quarters and a lesser amount of total sample was collected. In most instances it was necessary to utilize more than one drill hole, in which case an effort was made to prorate sample quantities in accordance with their respective stratigraphic horizons.

Modal Analyses

The "point count" method was employed for determining the relative proportions of mineral species in thin sections. A randomized technique was chosen in that the majority of the samples exhibit a pronounced banding. Whenever possible, traverses were run nearly normal to the banding. A traversing mechanism equipped with a vernier was used and traverse intervals were randomized between one millimeter spacings. This method is similar to the "stratified random" sample described by Chayes (1956). The randomization was accomplished by arbitrarily selecting a block of numbers, appropriate for the dimensions of the measurement area, from a table of random numbers (Dixon and Massey, 1951). If, in a single analysis, the count length was less than 500, a second determination was made drawing a new set of numbers. In this manner all count lengths included at least 500 points.

In determining average modes for a particular lithologic type each thin section was not always treated with equal weight. In many instances where two or more sections were cut from one specimen, these were averaged and weighted equally with a single section from another site.

Mineral Separations

A limited number of mineral separations were made to determine specific optical and chemical properties. The usual procedure for these separations was to grind the sample in a laboratory rod mill to the desired liberation size required for the particular mineral. In the usual case, where the mineral was non-ferromagnetic, the ground sample was passed through a Davis Magnetic Tube in order to remove all magnetite. The non-magnetic fraction was then subjected to heavy liquid separation utilizing mixtures of formic acid thallous salt and malonic acid dithallous salt as the media for various gravities. In the event of fine grained separations an International Model CM type centrifuge was employed for 10-20 minute time intervals at 1500 r.p.m. to accelerate separation. The desired fraction was then cleaned by means of a Frantz Isodynamic separator. All samples were frequently inspected with a binocular microscope to determine the degree of separation.

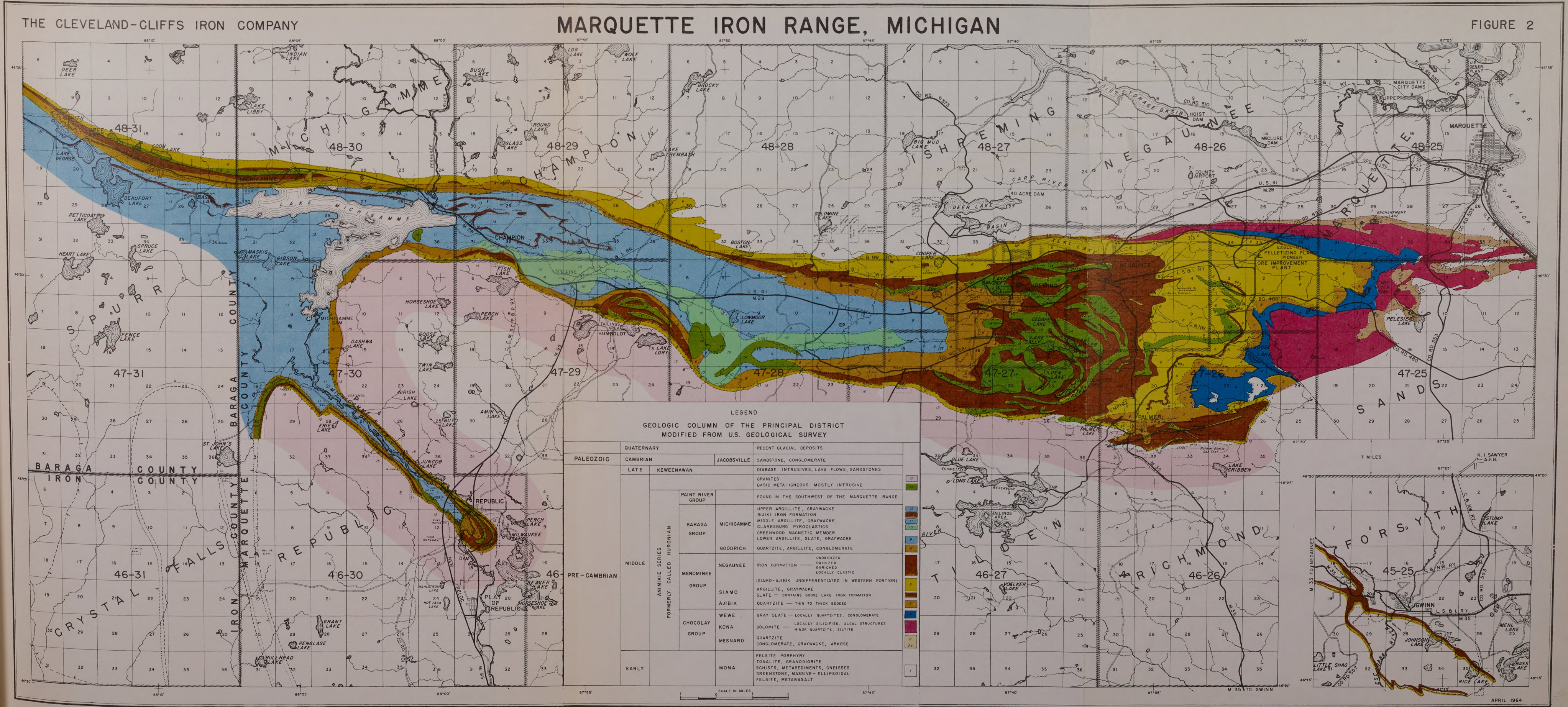
Regional Geologic Setting

The Republic Trough is a portion of a major structural feature known as the Marquette synclinorium. A brief review is presented of the gross geologic features of this synclinorium in order to provide a framework for the rock types and successions of the trough area.

The bedrock of the Marquette synclinorium consists almost entirely of Precambrian metasediments, granites and metavolcanics. These form a westerly plunging synclinorium that extends roughly 40 miles along an east-west axis (see Figure 2). The synclinorium opens up at the western end in several extensions one of which has been folded into a tight syncline known as the Republic Trough.

The Middle Precambrian metasediments of the synclinorium overlay a basement complex of lower Precambrian granites, gneisses, metavolcanics, schists, and quartzites. The Mesnard Kona and Wewe formations mark the lower portion of the succession of Middle Precambrian metasediments (Animikie series). This section of the column consists predominately of quartzite, dolomite, metagraywacke, argillite, and conglomerate. The Kona and Wewe are overlain successively by the Ajibik and Siamo formation and the Negaunee iron formation. In the western part of the synclinorium there has been no distinction made between the Ajibik and Siamo formations. These consist of quartzites, schists, metagraywackes and argillites. Locally, the Siamo contains minor occurrences of iron formation. The Negaunee iron formation has been and is the principal source of iron ore production. It consists of a variety of types but is most commonly banded with alternating layers of chert and one or more iron bearing minerals. The chief iron bearing mienrals are hematite, magnetite, iron carbonate and iron silicate. Locally, iron sulfide and goethite are found.

The Goodrich and Michigamme formations are found overlying the Negaunee iron formation. The Goodrich is comprised chiefly of quartzite and metagraywacke with subordinate quantities of schist and conglomerate. Rock types represented



POLITICAL TOWNSHIPS, GEOLOGY, MINES & EXPLORATIONS in the Michigamme formation include slates, schists, metagraywackes, pyroclastics, metavolcanics, quartzites, conglomerates and iron formation. Submembers have been recognized within the Michigamme. These include a magnetic member at the base (Greenwood), a pyroclastic horizon (Clarksburg) and an iron formation (Bijiki).

Numerous dikes and sills are found throughout the synclinorium. The least altered of these have been generally considered post Animikie and tentatively correlated with the Keweenawan.

In addition to the granitic rocks comprising the basement complex there are indications of younger granites. Pegmatites are known to cut Animikie sediments. However, the quantity of granite and gneiss that can be clearly designated late or post Animikie is problematical.

Stratigraphic Terminology

Subdivision of the Precambrian rocks in northern Michigan has undergone recent revisions (James, 1958). Various stratigraphic terminologies have been employed throughout previous studies. Although this investigation is not concerned with regional correlations a brief review is presented of the terms that have been used for the various subdivisions. This is included to avoid possible confusion. Emphasis is placed on the units directly related to the area of investigation.

James (1958) has proposed three major categories for the Precambrian rocks of Northern Michigan--Lower, Middle, and Upper. This three-fold nomenclature has been adopted by the U. S. Geological Survey and replaces the previous designations which are tabulated below. It is the division that is utilized throughout this study.

VanHise and Leith (1911)	Leith, Lund and Leith (1935)	James (1958)
Algonkian	Late Precambrian	Upper Precambrian
-----	-----	Middle Precambrian
Archean	Middle Precambrian	Lower Precambrian
-----	Early Precambrian	-----

(after James, 1958)

VanHise (1891) proposed correlation between the metasediments of the Marquette district and the Huronian series. This original correlation was later modified in a publication by VanHise, Adams, Bell, and Leith (1905) and a three-fold division of the Huronian was accepted. This sequence (see following page) had been widely used prior to the studies of James (1958).

James (1958) proposes adopting the term Animikie for the metasediments previously called Huronian. His suggestions stem mainly from extensive field work in central Dickinson County (James <u>et al</u>., 1961). This lends itself to comparative terminology for the Marquette District.

VanHise (1891)	VanHise, Adams, Bell and Leith (1905)	Marquette District
Upper Marquette Series (Upper Huronian)	Upper Huronian	Michigamme Goodrich
Lower Marquette Series (Lower Huronian	Middle Huronian	Negaunee Siamo Siamo
	Lower Huronian	Kona Mesnard

	Central Dickinson County	Marquette District
Animikie Series formerly Huronian	Baraga group	Michigamme* Goodrich*
	Menominee group	Negaunee* Siamo Ajibik*
	Chocolay group	Kona Mesnard

(after James, 1958)
*Formation names used in the Republic Trough area.

VanHise (1891)	VanHise, Adams, Bell and Leith (1905)	Marquette District
Upper Marquette Series (Upper Huronian)	Upper Huronian	Michigamme Goodrich
Lower Marquette Series (Lower Huronian	Middle Huronian	Negaunee Siamo Siamo
	Lower Huronian	Kona Mesnard

	Central Dickinson County	Marquette District
Animikie Series formerly Huronian	Baraga group	Michigamme* Goodrich*
	Menominee group	Negaunee* Siamo Ajibik*
	Chocolay group	Kona Mesnard

(after James, 1958)
*Formation names used in the Republic Trough area.

Mining History

Since 1864 there have been several periods of exploration and exploitation of the iron formation within the Trough area. The vast majority of these activities were limited in scope and duration. An exception to the aforementioned in the present day site of the large mining, beneficiating and agglomerating operation known as the Republic Mine (Sec. 7, T. 46 N., R. 30 W.).

The history of the Republic Mine dates back to 1870 at which time the Republic Iron Company was organized. Production peaks in excess of 235,000 long tons per year were recorded during the 1880's. The ore consisted of rich specular hematite "lump" which was mined underground for the most part. The Cleveland-Cliffs Iron Company obtained the property in 1914. Production of the direct shipping ore continued until 1937. Total shipments of this rich ore are recorded at 8,563,170 tons. From 1937 to 1947 the property was idle. Exploration was again resumed in 1947 when a diamond drilling program was undertaken. The emphasis was now on the low grade iron formation as potential crude ore for concentrating. A concentrating plant with an annual capacity of 650,000 long tons was put into operation during June, 1956. An expansion was completed during February, 1962, increasing the annual capacity to 1,500,000 long tons of iron ore concentrates. This expansion included a pelletizing unit designed for producing over 800,000 long tons of pellets annually. Expansion of concentrating and pelletizing facilities continued until February, 1964. The present plant is capable of producing in excess of 3,000,000 long tons of iron ore concentrates and 2,000,000 long tons of pellets annually. An areal view of these facilities is shown in Figure 3.

Exploration and development was also pursued in several other sites. The bulk of these activities took place from 1864 to 1899. The significant areas of interest are illustrated in Figure 4. Data on these properties are tabulated in Table 1.

TABLE 1.--Minor Exploration and Development of Properties of the Republic Trough Area.

Property Name and Location	Total Production Long Tons	Approximate Period of Activity
Kloman, Sec. 1 (46-30) and Sec. 6 (46-29)	94,813	1873-1883
Riverside, NW 1/4, Sec. 35 (47-30)	16,160	1888-1893
Chippewa, S 1/2, Sec. 22 (47-30)	?	?
Metropolis, NE 1/4 & SE 1/4, Sec. 2 (46-30)	289	1888
Standard, NE 1/4, Sec. 34(47-30)	?	?
Cannon, NE 1/2, Sec. 28 (47-30)	?	1876
Erie, NE 1/2, Sec. 28 (47-30)	9,194	1876-1883
Magnetic, NW 1/4, Sec. 20 (47-30)	1,136	1864-1899
NW Republic, SE 1/4. Sec. 19 (47-30)	?	1885-1890
Norman, SE 1/4 Sec. 19, & NE 1/4 Sec. 39 (47-30)	?	?

Figure 3.--View of Republic Mine area including pit, concentrator and pellitizing plant. Trough area extends to northwest (upper left of photo).

FIGURE 4

OCATION MAP

ACTIVE AND INACTIVE

TION AND DEVELOPMENT SITES

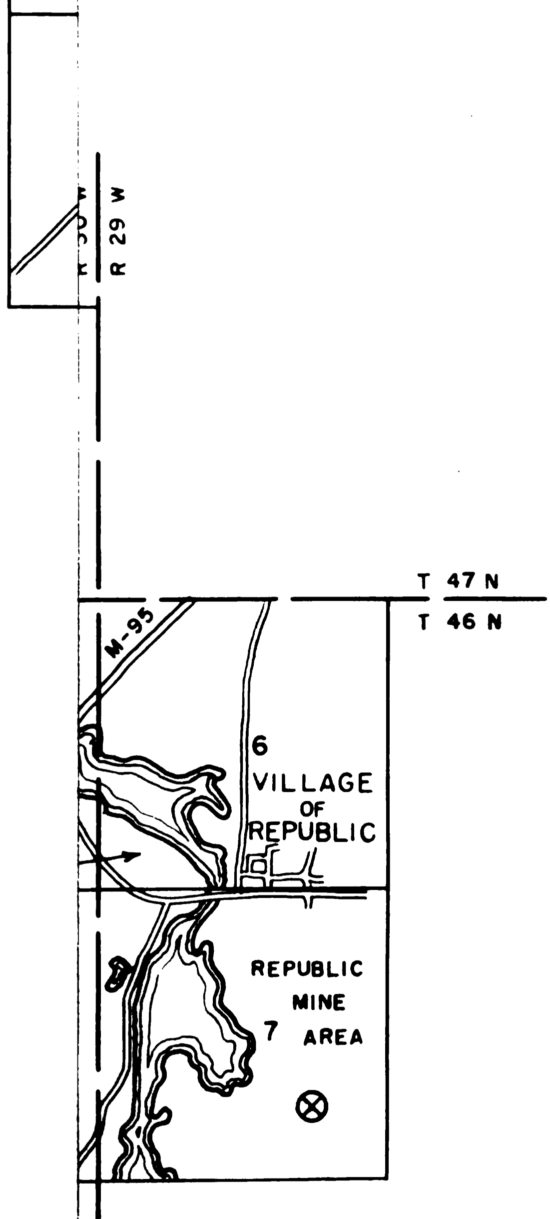
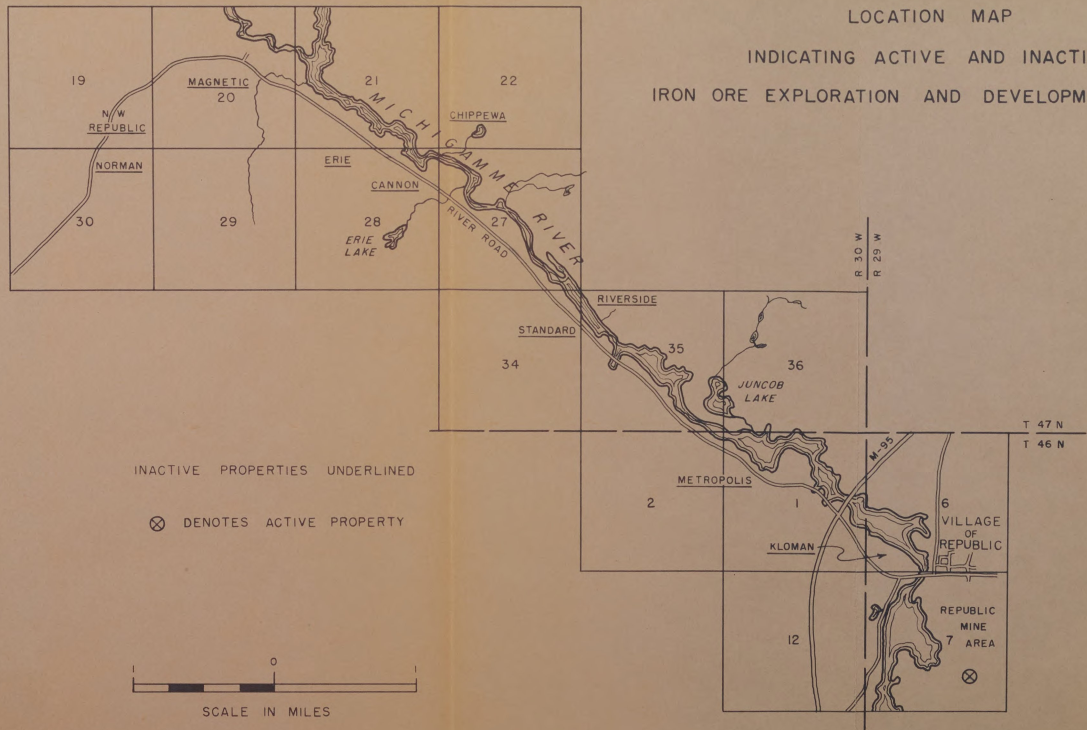


FIGURE 4

LOCATION MAP

INDICATING ACTIVE AND INACTIVE

IRON ORE EXPLORATION AND DEVELOPMENT SITES



CHAPTER III

AJIBIK FORMATION

General Information

The oldest clearly discernable metasediment of the area is assigned to the Ajibik formation. This designation is based primarily on stratigraphic position and not with respect to lithologic correlation. The so-called "Ajibik quartzite" was originally described by VanHise and Bayley (1897). The type location is in the vicinity of the Ajibik Hills northeast of the Village of Palmer (T. 47 N., R. 26 W.). At this and other localities the rock is predominantly a quartzite. However, in the Republic Trough area there are a variety of rock types comprising the Ajibik and hence the term "formation" is considered more appropriate.

Along the eastern portions of the Marquette Range a slate formation (Siamo) is commonly found between the Ajibik and overlying Negaunee iron formation. However, as a general rule, this rock type is not distinguished as a separate unit in the western portion of the Range where its thickness is greatly reduced.

The Ajibik has been reported as lying unconformably upon Archean (Pre-Animikie) rocks (Smyth, 1897). Later

Lamey (1937) cited evidence which he claimed indicated that the granitic rocks at Republic to be younger than the overlaying quartzites. Neither view can be supported on the basis of the outcrops and diamond drill core examined throughout this study. The contact appears to be transitional within the areas investigated. This is indicated on the geologic map and sections (Plates 1 through 5). The contact has been arbitrarily located between rock that appears predominantly granitic and those that exhibit definite metasedimentary characteristics.

Generally a quartzitic member is found grading into a sericitic quartzite which contains progressively more feldspar as the so-called "granite" is approached. In some cases a zone resembling migmatites is encountered. In any case no distinctive break in lithologies was observed.

The upper contact appears conformable. The transition from clastic metasediments to iron formation is in part gradational. Most frequently as the Negaunee iron-formation is approached, the Ajibik becomes progressively more schistose with increasing amounts of iron silicates and iron oxides. In some areas garnetiferous zones are present. Furthermore, the ratio of recrystallized chert to clastic quartz increases. However, it should be noted that the contact areas are often masked by basic intrusive sills occurring between the typical clastic metasediments and iron-formation.

The Ajibik appearing as typical metasediment ranges from zero to 1000 feet in thickness throughout the area that was mapped. Some of the best exposures are found in the vicinity of the old Magnetic Mine (Section 20, T. 47 N., R. 30 W.) and south of the Republic Mine (Section 18, T. 46 N., R. 29 W.). In addition, scattered outcrops occur throughout the bulk of the area. Diamond drill holes have also penetrated the Ajibik to a minor extent. Although the majority of exploration drill holes were terminated after encountering the clastic metasediments, a few relatively complete sections were cored. A composite of Ajibik metasediments was compiled from three drill holes in Section 2, T. 46 N., R. 30 W. This composite represented the bulk of lithologic types. Chemical data and normative minerals of the composite are given in Table 2 on the following page.

Lithologic Types

Eight principal lithologic types are recognized within the Ajibik formation. These include micaceous quartzite, quartz-biotite-sillimanite-andalusite-garnet schist and gneiss, quartz-mica schist, quartz-feldspar-mica schist and gneiss, chloritic micaceous quartzite, quartz-garnet-biotite schist, quartz-garnet-amphibole schist, and quartz-zoisite-hornblende-mica gneiss. Subdivision is based primarily on major mineral assemblages which are readily identified in hand specimen. Only those varieties that appear in significant quantities are included as a distinctive phase.

TABLE 2.--Chemical and Normative Composition of Ajibik Formation Within Section 2, T. 46 N., R. 30 W.

Per Cent by Weight*		C.I.P.W. Norm	
SiO_2	76.54		
Al_2O_3	11.87	Q	57.81
Fe_2O_3	1.09	C	7.75
FeO	3.77	or	16.14
MgO	1.73	ab	4.20
CaO	0.42	an	0.83
Na_2O	0.50	hy	9.73
K_2O	2.69	mt	1.62
H_2O+	0.31	il	0.46
TiO_2	0.20	pr	0.18
MnO	0.10	cc	0.40
S	0.10		
CO_2**	0.18	(molar quantities of less than 0.002 are omitted)	

*Run on dry basis with H_2O^- (105°C.) = 0.23%.

**Calculated on basis of total C as CO_2 (W. Pasich, Jones & Laughlin Steel Co., Negaunee, Michigan Analyst).

Micaceous quartzite.--Quartzites containing varying quantities of mica represent the most abundant phase of the Ajibik. Numerous specimens from outcrop and drill core were examined. Stratigraphically the rock type is not restricted to any particular position. However, it occurs most frequently in the intermediate sectors.

Generally the rock exhibits some laminations, the extent of which is a function of the development of mica.

The mica is predominantly muscovite which occurs both as fine aggregates and as well defined plates. A minor amount of biotite is present in most specimens. In thin section it is pale brownish green. There is a considerable range in the grain size of quartz. In single thin sections diameters of from 0.1 mm to over 1.0mm were recorded. The most common quartz size is in the vicinity of 0.3 mm. Minor amounts of feldspar and garnet are also present. The garnet is fresh and generally appears in clusters. The only feldspar definitely identified is microcline which appears relatively fresh. A few samples contain a mineral entirely altered to clay which could well represent a pre-existing feldspar. Accessory minerals include tourmaline, sphene and apatite. An average modal analysis is presented in Table 3.

Quartz-biotite-sillimanite-andalusite-garnet schist and gneiss.--Several samples of sillimanitie bearing schist and gneiss were observed. These were found only in drill core and restricted to the lower portions of the Ajibik. The best examples came from Section 2, T. 46 N., R. 30 W.

The rock appears both schistose and gneissic and is commonly associated with micaceous and feldspathic quartzites. Quartz and biotite normally account for over 50 per cent of the rock volume. In thin section the quartz is relatively equigranular averaging 0.3 mm in diameter. Two varieties of biotite are present. The most common has a greenish brown color and is generally associated with garnet and andalusite. A subordinate variety exhibits a more greenish color and is found only in zones where garnet and andalusite are sparse or absent. Very limited chloritization was observed in either variety.

Andalusite, sillimanite, garnet, and muscovite constitute the remaining major minerals. Andalusite appears relatively fresh exhibiting only minor alteration to sericite. Cross-sections range from 0.2 mm to 2.0 mm. Sillimanite occurs both as fibers and prismatic crystals. Alteration to pyrophyllite is conspicuous in some specimens. This replacement is pseudomorphic with the typical sillimanite transverse fractures being well preserved. Garnet frequently occurs as large poikiloblasts up to 2 mm in diameter with numerous quartz and biotite inclusions. Chloritization is rare. Muscovite was not observed in all specimens. When present it occurs as both a fine aggregate and as distinct plates. Association with andalusite is common. Accessory minerals include tourmaline and apatite.

Modal analyses of three specimens from Section 2, T. 46 N., R. 30 W., are presented in Table 4. Mineral associations are illustrated in Figures 5 and 6.

Quartz-mica schist.--Schistose rocks consisting predominantly of quartz and muscovite occur intermittently throughout the entire formation. Stratigraphically they commonly grade into micaceous quartzites or feldspathic gneisses and schists. Excellent exposures are found in Sections 20 and 28, T. 47 N., R. 30 W.

In thin section quartz is present in two distinct habits consisting of a fine (less than 0.2 mm) and a coarse (greater than 2.0 mm) fraction. The coarse variety is commonly ellipsoidal exhibiting dimensional orientation. It is characterized by marked undulatory extinction. The fine fraction is equigranular and constitutes, in part, interstitial material between the "augen like" quartz. The mica is predominantly muscovite which occurs both as coarse plates and fine aggregates. In a few instances remnants of biotite were also believed present. However, extreme alteration to cholorite (var. penninite) impedes definite identification. A minor amount of microcline was also found in one area. Additional mineral constitutents include tourmaline, sphene, apatite and hematite. The tourmaline (var. schorlite) is found almost exclusively in contact with muscovite.

Modal analyses of three common occurrences of quartz-mica schist are presented in Table 5.

Quartz-feldspar-mica schist and gneiss.--Rocks rich in quartz, feldspar and mica account for a substantial quantity of the Ajibik formation. This phase is present as both schist and gneiss which appear interlaminated in part. In general the gneissic variety predominates at the stratigraphic base of the formation. Gradational transition into micaceous quartzite or quartz-mica schist is characteristic.

Microscopically, quartz appears inequigranular with diameters varying from less than 0.2 mm to over 3.0 mm. The coarser fractions exhibit strain features and are in part fractured. A portion of the finer fraction forms inclusions within the various porphyroblasts. The quantity and type of feldspar varies between samples. Potash feldspar was recognized only in samples void of garnet. The apparent incompatibility of garnet and potash feldspars in these rocks is discussed more fully in a later section. Plagioclase feldspar is present in all the samples. It is typically twinned with estimated compositions ranging between Ab_5 to Ab_{20}. Combined Carlsbad and albite twins were observed in some sections. Perthitic intergrowth with microcline is also locally present. Alteration of plagioclase is common but fresh crystals are not unusual. The potash feldspar includes both microcline and orthoclase with the former appearing most frequently. Crystals range from 0.5 mm to over 4.0 mm in diameter. Late seritization is conspicuous. Mica as muscovite is ubiquitous in varying quantities. Plates measuring over 3.0 mm parallel to 001 are not uncommon. Brownish biotite was found in only one assemblage. Garent, when present, appears only in quantities averaging one per cent by volume. However, where present it occurs as fresh porphyroblasts with diameters in excess of 0.6 mm. Patches of carbonate (calcite) were observed in a few thin sections. They are closely associated with muscovite. This relationship is considered in a later section. In one assemblage several large crystals of tourmaline were noted. These appear as skeleton crystals with quartz and calcite. Accessory minerals include epidote, apatite, chlorite and sphene. The chlorite occurs in small patches of probable secondary origin.

Modal analyses of six frequently observed assemblages are tabulated in Table 6. Salient mineral associations are illustrated in Figures 7 and 8.

Chloritic micaceous quartzite.--The occurrence of micaceous quartzite which chlorite as a phase of its major assemblage was found along the northeastern flank of the Trough. The best samples are available from exposures in Section 6, T. 46 N., R. 29 W. Limited outcrop impedes positioning this unit stratigraphically within the Ajibik. However, it appears to occur near the base immediately above feldspathic gneiss and rocks resembling granite.

Rounded grains vary from 0.1 mm to 0.8 mm in diameter. The majority are in the range of 0.3 mm and in general the rock is considered equigranular. Much of the chlorite appears as fresh porphyroblasts. This is not considered a product of post-metamorphic alteration. Pleochroism is from nearly colorless to pale green. Interference colors are mostly of the anomalous brown type which according to Albee (1962) would indicate a magnesium rich variety (S_{P40} At_{60}). Association with opaques is clearly manifest with suggestions of iron oxide released from chlorite. However, coarse magnetite crystals were also noted throughout the specimens. A few scattered patches of garnet were observed. This garnet is fresh with little or no alteration. Plates and aggregates of muscovite are also present. These are frequently associated with chlorite.

Figure 9 illustrated a typical microscopic view. A modal analysis is given in Table 9.

Quartz-garnet-biotite schist.--A few examples of schistose rock consisting largely of quartz, biotite and garnet were found exclusively in the upper portions of the Ajibik. The best samples were taken from Section 34, T. 47 N., R. 30 W. Although the rock is normally schistose, it may also appear somewhat gneissic as foliation planes become obscured.

As seen in thin sections, quartz appears equigranular (0.2-0.3 mm). Garnets are concentrated in bands up to 2 cm in width. This compositional layering is most conspicuous in the least foliated rocks. Biotite occurs as aligned plates exhibiting a pronounced pale to dark brown pleochroism. Fine grained aggregates of what appears to be muscovite are also present. These are undoubtedly a pseudomorphic alteration product but identification of the original mineral could not be ascertained due to the extensive replacement.

An average mode of the aforementioned schist is given in Table 10.

Quartz-garnet-amphibole schist.--A series of schists rich in garnet and amphibole commonly occur in the vicinity of the contact between Negaunee iron-formation and Ajibik formation. In part these schists are interpreted as constituting a portion of the Ajibik. They differ from the typical silicate iron-formation (Negaunee) by a paucity of iron oxides (less than 5 per cent). In addition, quartz grains appear preponderantly clastic. There are relatively few dusty nuclei which characterize much of the recrystallized chert of the Negaunee. However, it should be noted that this is somewhat of an arbitrary division in that similar appearing zones have been found within the iron-formation.

In those phases designated as Ajibik, the quartz is characterized by a considerable variation in size. A fine fraction averages 0.2 mm while a coarser variety commonly exceeds 1.0 mm. Garnets generally show some peripheral alteration to chlorite. The amphibole is in the cummingtonite-grunerite series. Precise identification relative to the FeO:MgO ratios was not determined. Optic angles of

nearly 90 degrees were estimated and both positive and negative crystals are believed present. A conspicuous quantity of chlorite also appears pseudomorphic after what resembles a sheet silicate.

Two modes from typical occurrences are tabulated in Table 7.

Quartz-zoisite-hornblende-mica gneiss.--A banded quartzose rock rich in zoisite, hornblende and muscovite occurs locally near the stratigraphic center of the formation. It seldom accounts for thicknesses in excess of 15 feet and ordinarily grades into micaceous and feldspathic schists and gneisses. Banding is made conspicuous by compositional layering which is largely dependent upon the relative quantity of quartz.

In thin section quartz grains appear elongated and in subparallel dimensional orientation. Short and long diameters average 0.5 and 1.0 mm respectively. Planes of liquid inclusions are frequently present. Amphibole and zoisite occur in close association. The amphibole is believed to be hornblende with pleochroism from nearly colorless to green. Its optic sign is negative with a moderate 2V. The zoisite exhibits anomalous blue interference colors. In part it includes another epidote mineral resembling pistacite. The paragenetic implications relative to the amphibole-zoisite association are considered in a discussion on metamorphism.

Muscovite is present in two forms. The dominant variety occurs as matted aggregates resembling an alternation product. Coarse porphyroblasts are present but rare. Small quantities of calcite were also observed. The most common occurrence is in close association with hornblende. Minor amounts of chlorite are present as a surface alteration of amphibole. Magnetite and traces of sphene constitute the remaining mineral phases. An average modal analysis is given in Table 8. A typical microscopic view is illustrated in Figure 10.

MODAL ANALYSES OF VARIOUS LITHOLOGIC TYPES FROM THE AJIBIK FORMATION

TABLE 3 *Mode of typical micaceous quartzite.*

MINERAL	PERCENT VOLUME
Quartz	83
Muscovite	11
Biotite	2
K-Feldspar	2
Garnet	1
Tourmaline	X
Sphene	X
Apatite	X
Opaques	X

TABLE 4 *Modes from three varieties of quartz-biotite-sillimanite-andalusite-garnet schist and gneiss.*

MINERAL	PERCENT VOLUME		
Quartz	38	62	37
Biotite	17	17	19
Andalusite	19	8	6
Sillimanite (includes pyrophyllite)	12	4	22
Garnet	8	8	2
Muscovite	5	—	8
Tourmaline	—	X	—
Apatite	X	X	—
Opaques	X	X	6

TABLE 5 *Modes from three types of quartz-mica schist.*

MINERAL	PERCENT VOLUME		
Quartz	71	67	64
Muscovite	28	21	29
K-Feldspar	—	2	—
Chlorite (biotite alteration)	X	9	X
Tourmaline	—	—	X
Apatite	X	—	X
Opaques	X	X	6

TABLE 6 *Six modes of quartz-feldspar-mica schist and gneiss.*

MINERAL	PERCENT VOLUME					
Quartz	45	41	29	35	28	48
K-Feldspar	–	–	26	24	39	18
Plagioclase (Ab5-20)	24	46	26	28	22	22
Muscovite	28	9	16	8	8	6
Biotite	—	—	—	—	—	6
Garnet	1	1	—	—	—	—
Calcite (secondary)	—	2	X	3	X	—
Tourmaline	—	—	2	—	—	—
Epidote	X	—	—	—	—	—
Chlorite	X	X	X	1	2	—
Sphene	X	—	X	—	X	—
Apatite	X	—	X	—	—	—
Opaques	X	X	—	X	—	—

TABLE 7 *Modal analyses from two common varities of quartz-garnet-amphibole schist.*

MINERAL	PERCENT VOLUME	
Quartz	83	15
Garnet	7	41
Amphibole (cummingtonite-grunerite)	5	38
Chlorite (secondary)	3	2
Opaques	1	4

TABLE 8 *Mode of quartz-zoisite-hornblende-mica gneiss.*

MINERAL	PERCENT VOLUME
Quartz	39
Zoisite (in part pistacite)	26
Hornblende	16
Muscovite	15
Calcite	1
Chlorite	X
Sphene	tr.
Opaques	2

TABLE 9 *Mode of chloritic micaceous schist.*

MINERAL	PERCENT VOLUME
Quartz	66
Chlorite	15
Muscovite	9
Garnet	1
Sphene (?)	tr.
Opaques	9

TABLE 10 *Average modal analyses of quartz-garnet-biotite schist.*

MINERAL	PERCENT VOLUME
Quartz	62
Garnet	18
Biotite	14
Muscovite (alteration product)	5
Opaques	X

tr. exceedingly rare as fine grains. X less than one percent but frequently observed.

Figures 5 through 7.--Photomicrographs of Rocks from the Ajibik Formation.

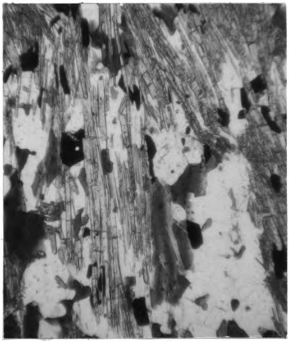


Figure 5

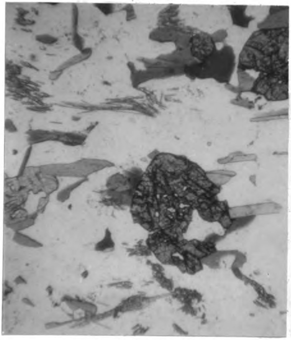


Figure 6

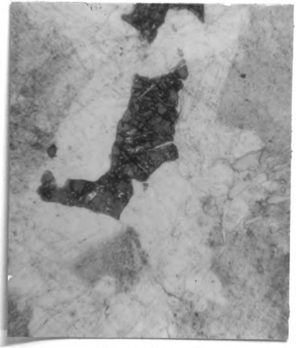


Figure 7

5.--Sillimanite schist and gneiss

Sillimanite blades (cross fractures) with quartz and biotite. Sillimanite in part replaced pseudomorphically by pyrophyllite

6.--Sillimanite schist and gneiss

Fibrous sillimanite with garnet, biotite, quartz and andalusite (center left).

7.--Quartz-feldspar-mica schist & gneiss

Tourmaline (var. schorlite) with microcline, plagioclase (slightly altered), muscovite and quartz.

Note: All figures, ordinary light, x52.

Figures 8 through 10.--Photomicrographs of Rocks from the Ajibik Formation

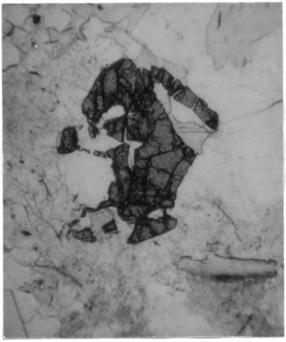


Figure 8

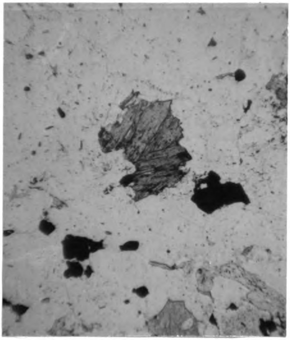


Figure 9

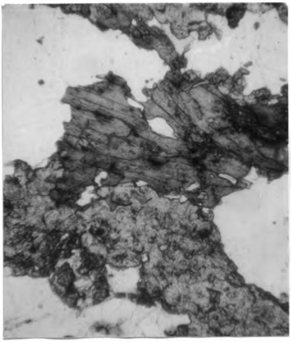


Figure 10

8.--Quartz-feldspar-mica schist & gneiss

Development of garnet with muscovite and plagioclase. Garnet occurrence appears to restrict formation of potash feldspar.

9.--chloritic micaceous quartzite

Magnesium rich chlorite porphyroblast with quartz and muscovite.

10.--Quartz-zoisite-hornblende-mica gneiss

Association of hornblende with zoisite (in part pistacite).

Note: All figures, ordinary light, X52

CHAPTER IV

NEGAUNEE IRON FORMATION

General Information

The banded iron-formation occurring above the Ajibik formation has been correlated with the Negaunee (Smyth, 1897). The type locality for this iron-formation is in the vicinity of the City of Negaunee where thicknesses in excess of 2,000 feet are attained. At the type location the major iron bearing minerals are earthy hematite, martite, magnetite, iron carbonate and iron silicate.

In the Republic Trough area the greatest thicknesses are attained at the Republic Mine (see Plate 2) where the formation is well exposed as a result of mining activity. On the northeast limb of the trough the iron-formation can be readily traced by outcrop through Section 6, T. 46 N., R. 29 W. and Section 1, T. 46 N., R. 30 W. There are excellent exposures at the Kioman property (SW 1/4, Section 6). Along this limb, farther to the northwest there are very few exposures. Limited outcrops were observed at the Riverside Mine (NW 1/4, Section 35, T. 47 N., R. 30 W.) and the Chippewa exploration (SW 1/4, Section 22, T. 47 N., R. 30 W.). Magnetic surveys between these occurrences substantiate a partial continuity of the iron-formation; however, thicknesses are greatly reduced.

Along the southwest limb the Negaunee appears to be absent immediately northwest of the Republic Mine area. Magnetic anomalies have been recorded but these may be attributed to magnetite enrichment in the Goodrich. The first positive evidence of iron-formation is in Section 2, T. 46 N., R. 30 W. This area is known as the Metropolis Mine. Samples of Negaunee were studied in both drill core and outcrop. Progressing northwest along this limb the next major occurrence of iron-formation is in the NE 1/4, Section 34, T. 47 N., R. 30 W. (Standard Exploration). Although outcrops are rare the existence of iron-formation has been proven through diamond drilling. Further to the northwest the iron-formation is again exposed in Section 28, T. 47 N., R. 30 W. (Caonnon Exploration and Erie Mine). Diamond drilling had been conducted in this section; however, there was no drill core available for study. The extreme northwest end of this limb (Section 20, T. 47 N., R. 30 W.) is marked by numerous exposures of iron-formation. This area is known as the Magnetic Mine and limited diamond drilling had been undertaken. The core from this drilling program was available for examination. The iron-formation is known to extend beyond the Magnetic Mine through Section 19, T. 47 N., R. 30 W. (Northwest Republic Exploration) and Section 30, T. 47 N., R. 30 W. (Norman Exploration). Although the Magnetic Mine markes the terminus of this study, limited mapping and drill core examination was conducted in these extensions.

In addition to the aforementioned, there are two unusual occurrences of iron-formation along the southwest limb of the trough. One of these occurs in Section 35, T. 47 N., R. 30 W., where an outcrop of banded magnetic iron-formation lies within the basement complex. The outcrop contains a zone of iron-formation approximately 50 feet wide which is bounded on the east by a coarse granitic appearing rock and on the west by amphibolite and mica schist. The contacts are roughly parallel to the strike of the banded iron-formation. Magnetic surveys across this outcrop revealed very little extension along strike. The writer considers this a faulted segment of the Negaunee. This is suggested by extensive shearing in adjacent rocks. The only alternate interpretation would be to postulate a Pre- Animikie iron-formation for which supporting evidence could not be found.

A second occurrence of iron-formation which is also apparently within the basement complex occurs in Section 7, T. 46 N., R. 29 W. Granitic appearing rocks are exposed adjacent this outcrop but contact relationships are masked by overburden. The appearance of this iron-formation differs somewhat from typical Negaunee. However, there are portions of the lower iron-formation which resemble this rock and, therefore, it is also considered a faulted segment of the Negaunee. This interpretation is based primarily on the absence of evidence for alternate explanations and is tentative at best.

The contact relationships between the Negaunee and underlying Ajibik formation have been discussed. Relationship with the overlying metasediments is considered in a following section on the Goodrich formation.

Lithologic Types

The Negaunee iron-formation of the trough area can be subdivided into three basic lithologic types according to major mineral constituents. These normally reflect a close relationships between stratigraphic position and major mineral assemblage. In descending stratigraphic order the mineral assemblages generally are: quartz-specular hematite, quartz-magnetite and quartz-grunerite-magnetite. Transition from one type to another is not necessarily abrupt and, therefore, there are several intermediate types. For example, when passing from quartz-specular hematite to quartz-magnetite there is generally a transitional zone of increasing ferrous to ferric iron ratios. However, for the most part the rocks falls into fairly well defined groups. Figure 11 illustrates the fields for each group as delineated on a portion of the Fe_2O_3-FeO-SiO_2 plane. The boundaries are drawn on the basis of seventy-five chemical analyses taken from samples that are considered representative of each group.

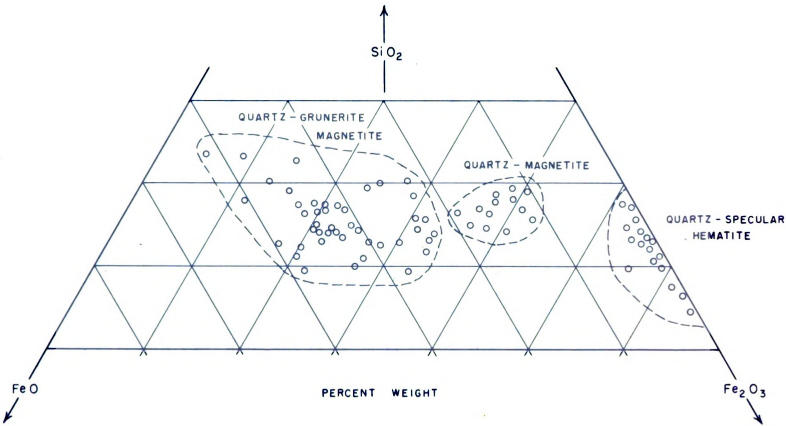
Quartz-specular hematite member.--The most extensive development of the quartz-specular hematite member is within

FIGURE 11

SEVENTY FIVE IRON FORMATION ANALYSES

PLOTTED ON A PORTION OF THE $Fe_2O_3 - FeO - SiO_2$ PLANE

SHOWING FIELDS OF VARIOUS LITHOLOGIC TYPES



the southern sector of the trough area. It is also found in lesser quantities throughout the northern sector. When occurring with other types of iron-formation it almost always appears in the upper stratigraphic horizons.

The rock is typically banded with alternating layers rich in specular hematite and quartz (see Figure 19). The bands vary from 0.1 to several centimeters in width. Quartz bands are often reddish in color as a result of finely disseminated micron size hematite. Ellipsoidal islands of quartz are frequently found within the iron rich bands. In the highly foliated portions of the iron-formation bands of rich specular hematite are often found cutting across quartz layers.

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The most common constituent other than quartz and specular hematite is muscovite. Locally it accounts for as much as 15 per cent of the rock volume but is normally less than 5 per cent. Chlorite, apatite, epidote, tourmaline and garnet also occur in minor quantities of generally less than one per cent. An average modal analysis of over 100 thin sections and polished surfaces from the Republic Mine area is given in Table 11.

TABLE 11.--Average Modal Analysis of Quartz-Specular Hematite Member.

Hematite Member	% Volume
Quartz	43
Hematite	48
Muscovite	4
Magnetite	4
Garnet	x
Apatite	x
Tourmaline	tr.
Epidote(s)	x
Chlorite(s)	x
Sphene	tr.
Carbonate(s)	tr.

x = less than one per cent but frequently observed.
tr.= trace
(s) = normally occurs as an alteration product or late fracture filling

A considerable variation was noted in the grain size of quartz. Diameters from less than 0.01 mm to over 0.06 mm occur within single thin sections. All efforts to relate grain size variations to specific zones or horizons proved fruitless. With the exception of a few clastic grains the vast majority of the quartz is considered a recrystallized chert. It is characterized by inclusions of submicron size iron oxide particles which often form a dusty appearing nucleus. Clastic quartz is very rare and found most frequently near the stratigraphic hanging wall.

The specular hematite normally occurs in two habits. A coarse variety (0.1 to 2.0 mm) is common within the iron rich bands while a finer fraction (less than 0.05 mm) ordinarily occurs with the quartzose bands. The coarse plates of specular hematite are frequently twinned. The twin planes, which may be construed as evidence of shearing, often reflect in fine striations on the surface of the mineral.

Locally, specular hematite occurs with quartz in elliposidal aggregates that strongly resemble oolites (see Figure 20). These occurrences are found most frequently in the upper stratigraphic horizons. However, oolitic-like structures were also observed in the quartz-grunerite-magnetite assemblages of the lower Negaunee.

A minor amount of magnetite is normally found with the specular hematite. For the most part it occurs as discrete grains exhibiting varying degrees of oxidation (see Figures 21 and 22). In addition there are examples of what resembles magnetite and hematite intergrowth. A third occurrence is as remnants within plates of specular hematite. This can be observed to a limited degree in Figures 21 and 22. Such occurrences are very suggestive relative to the paragenesis of the specular hematite. This topic is considered in a later section.

Muscovite generally occurs as coarse plates between quartz grains in subparallel orientation. It is often partially replaced by hematite. This replacement feature is especially common in the Metropolis area.

Garnet was found to occur with specular hematite at the Republic Mine. Positive identification of this garnet was not attained due to the extreme difficulty in obtaining a clean separation for chemical analysis. In all cases the crystals contain numerous inclusions of specular hematite (see Figure 23). It appears very similar to the almandine garnets found elsewhere. If this is truly almandine it would have serious implications relative to equilibrium conditions of the iron-formation during metamorphism. The writer has observed similar o-currences at the Humboldt Mine.

A minor amount of apatite and tourmaline occur locally. They appear most frequently with muscovite. This is especially true of tourmaline and suggests a dependency upon muscovite for its formation. Such a situation would prevail if boron solutions permeated the rocks. These solutions would then precipitate tourmaline upon contact with an aluminous rich mineral such as muscovite.

The chemistry of the quartz-specular hematite member is remarkably uniform when considering a natural system. For the most part the quartz plus hematite combinations account for over 95 per cent of the rock weight. The range of iron and silica within this member is also largely restricted to relatively narrow limits. This is illustrated in Figures 12 and 13. These results represent 181 analyses on 3882 feet of sample from holes drilled perpendicular to the strike of the quartz-specular hematite horizon.

The oxides present in addition to hematite and quartz include minor amounts of FeO, MgO, CaO, MnO, Al_2O_3 and P_2O_5. Phosphorus is nearly a constant ranging from 0.011 to 0.058 per cent over 175 samples of typical formation. Quantities as high as 0.105 per cent are present in small veins of rich hematite (+60 per cent Fe); however, these occur along fracture planes or near the Goodrich contact and are considered a product of secondary enrichment. It is interesting to note that if the phosphorus content of these occurrences is diluted by the normal quantity of silica in the formation it recalculates to amounts that very nearly approximate the average range.

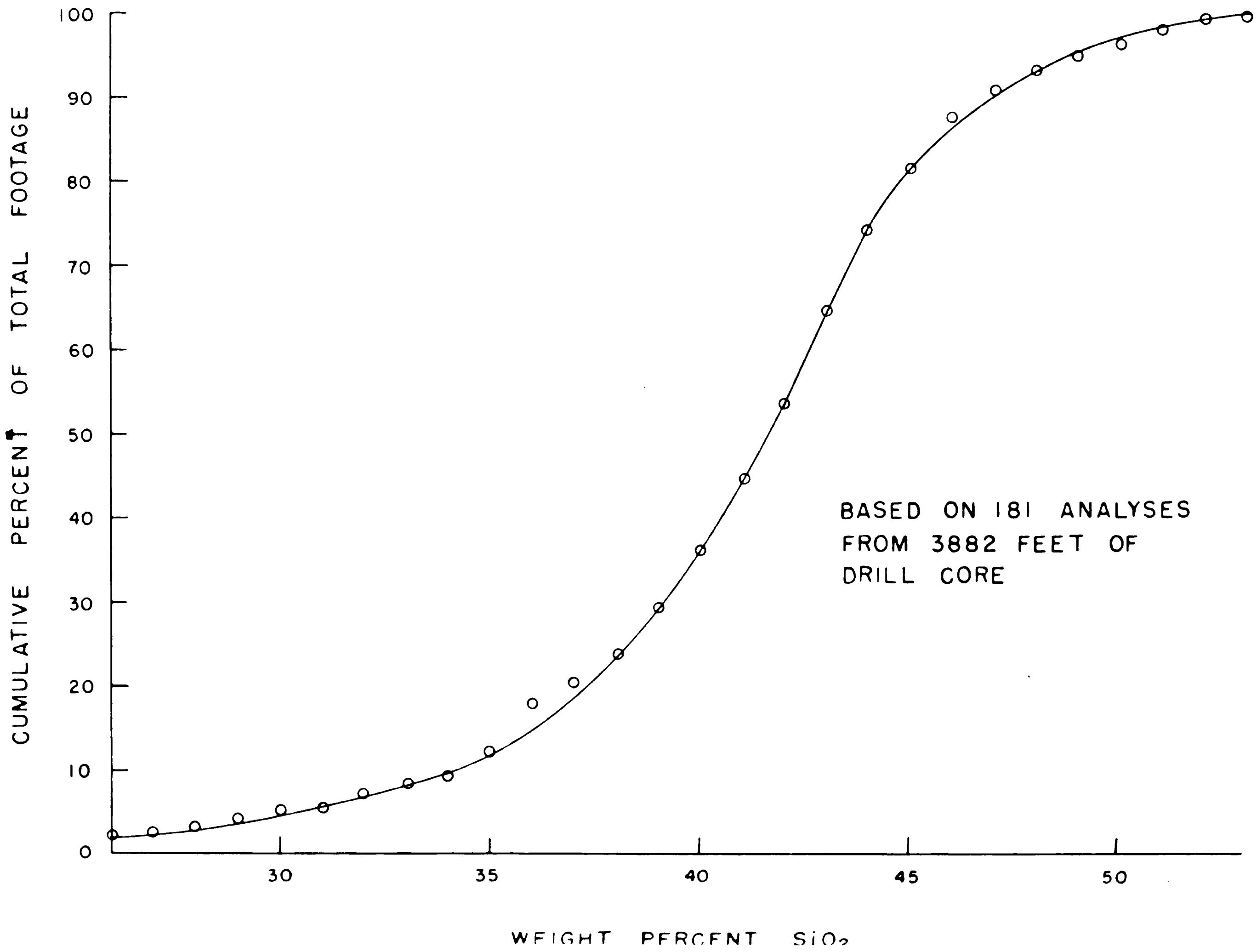
Only limited data were obtained on MnO contents. These indicate a small variation from 0.05 to 0.15 per cent by weight.

The presence of FeO within this horizon is generally limited to less than 2 per cent. However, it should be noted that quantities in excess of this may be encountered throughout the transition zones between quartz-specular hematite and quartz-magnetite members. The division between these types has been more or less arbitrarily set

VARIATION IN SiO_2 CONTENT

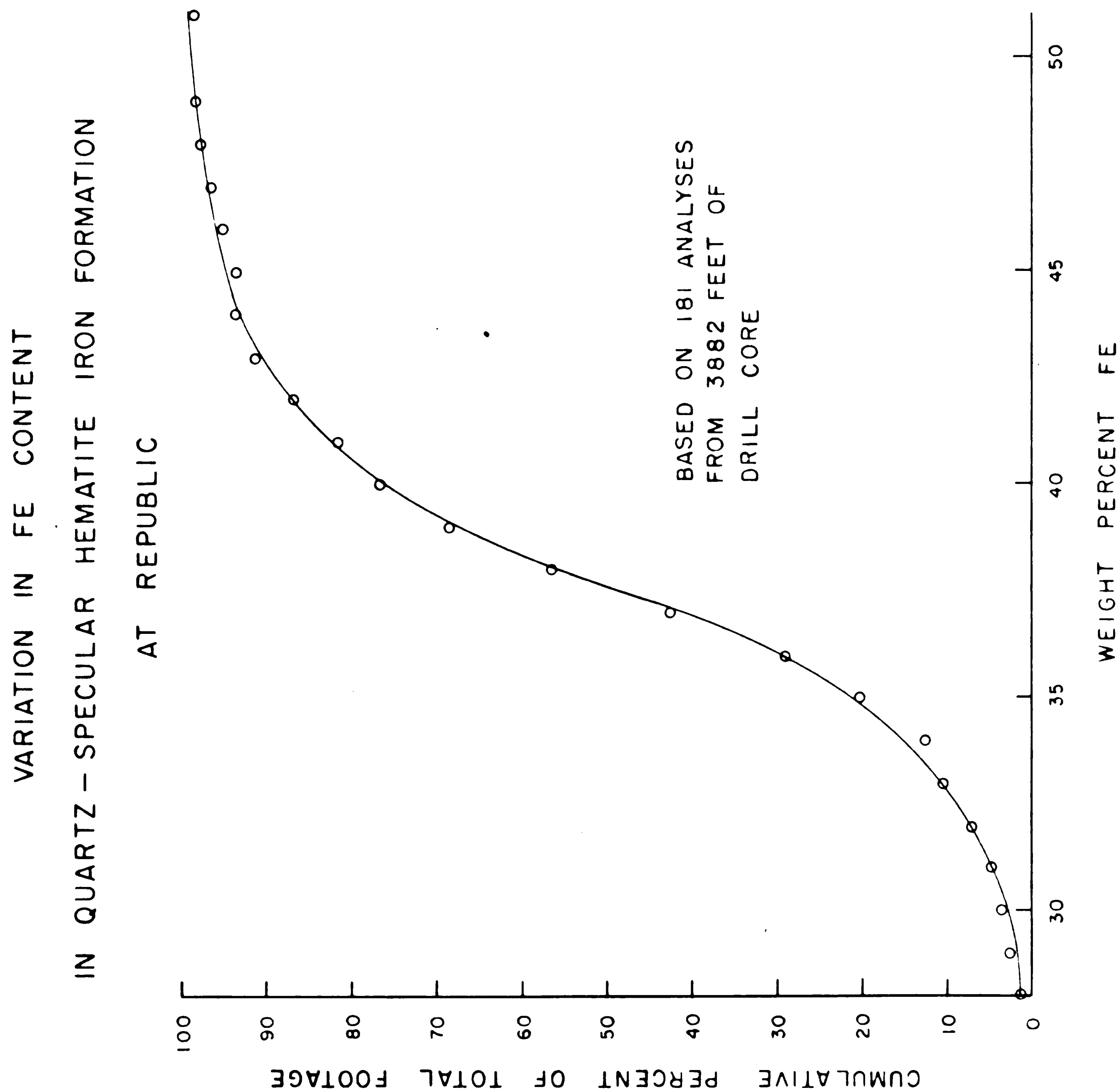
IN QUARTZ - SPECULAR HEMATITE IRON FORMATION

AT REPUBLIC



FIGUR

FIGURE 13


VARIATION IN FE CONTENT
IN QUARTZ - SPECULAR HEMATITE IRON FORMATION
AT REPUBLIC
BASED ON 181 ANALYSES
FROM 3882 FEET OF
DRILL CORE
CUMULATIVE PERCENT OF TOTAL FOOTAGE
WEIGHT PERCENT FE
0
10
20
30
40
50
60
70
80
90
100
30
35
40
45
50

and therefore exceptions would be anticipated. As a general rule there appears to be a tendency for the ferrous iron content to increase from the upper to the lower portions of the quartz-specular hematite horizon.

Variations in the weight per cent of other oxides were also noted with a range of 0.07 to 0.32 for CaO, 0.04 to 0.44 for MgO and 0.39 to 0.91 for Al_2O_3. Although the data are insufficient to postulate any systematic variation relative to stratigraphic position, there appears to be a relationship between the quantities of several oxide pairs. This is illustrated in Figures 14 and 15, where a direct functional relationship is indicated for MgO to CaO and FeO to Al_2O_3.

Analyses for sulfur were also conducted on six samples. The content is extremely low averaging less than 0.003 per cent. The hydrated water content is also very low as indicated by a loss on ignition of merely 0.24 per cent weight.

Quartz-magnetite member.--Rocks consisting of essentially quartz and magnetite with only minor quantities of either hematite or grunerite are quantitatively the most limited of the iron-formation types. However, their occurrence is widespread throughout the trough area. They normally occur immediately above the quartz-grunerite-magnetite member. The best examples in the south sector occur at the Republic and Kloman Mine areas. In the north sector the most extensive development is throughout the

FIGURE 14

RELATIONSHIP OF SOME MINOR OXIDES

WITHIN QUARTZ-SPECULAR HEMATITE IRON FORMATION

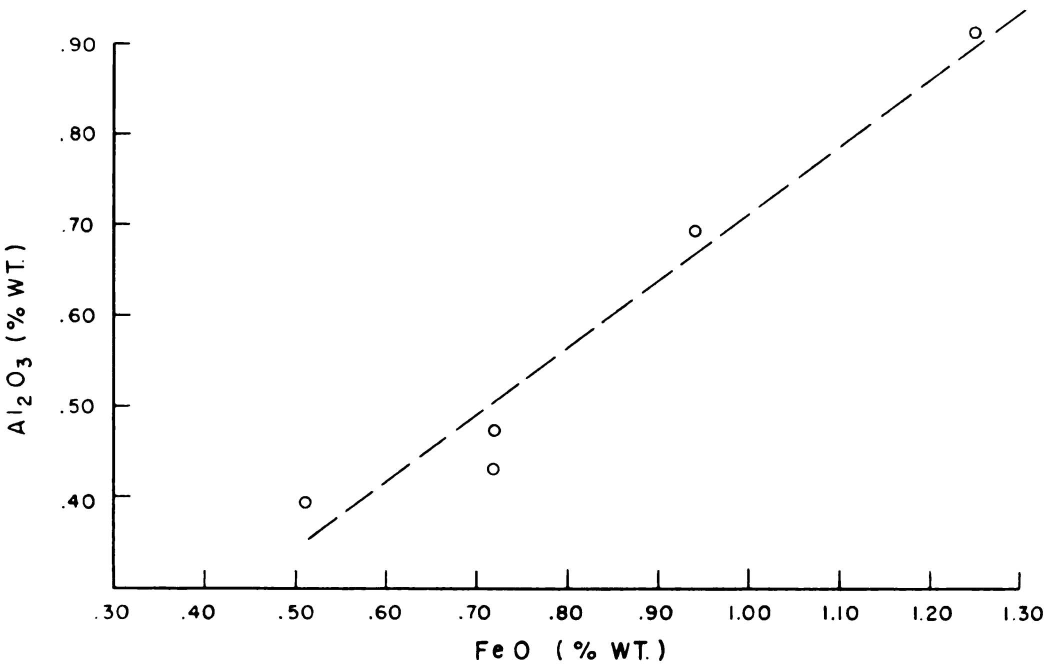
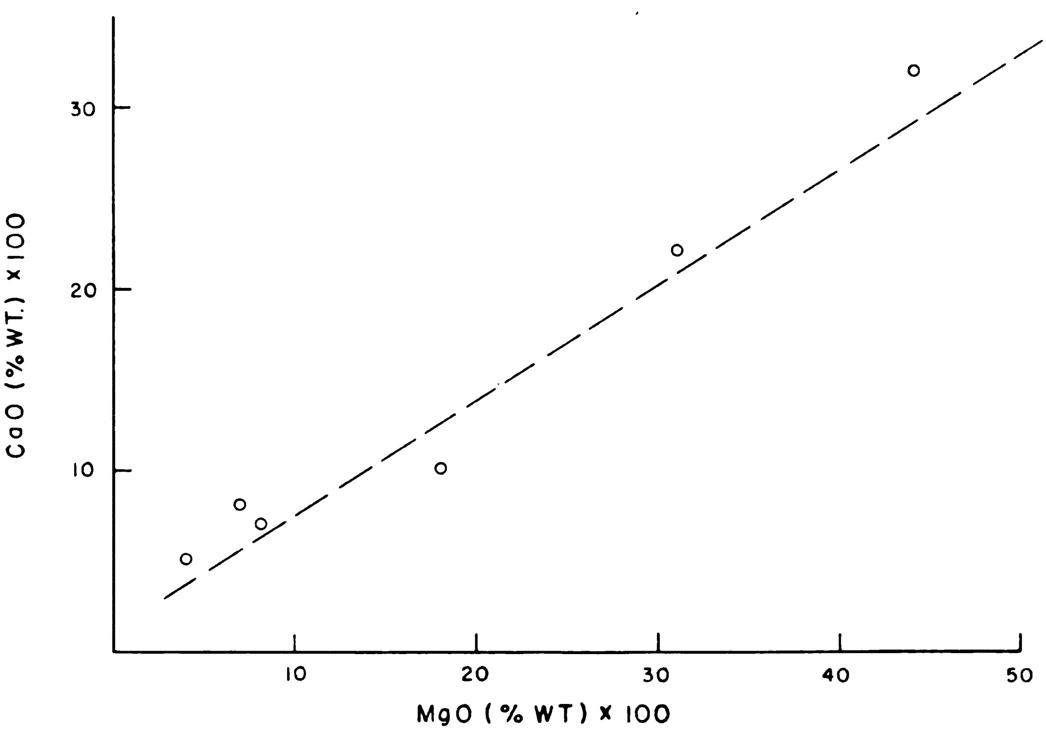


FIGURE 15



Standard and Magnetic Mine areas. In these latter occurrences the horizon is normally free of specular hematite while in the south sector gradations into both overlying quartz-hematite and underlying quartz-grunerite-magnetite members were noted.

The rock is banded in a manner similar to that described for the quartz-specular hematite member. However, in this case the quartzose bands are either clear or dark gray resulting from inclusions of fine grained magnetite rather than hematite (see Figure 19). In addition to the typical banded formation there are local developments of iron rich veins which transect the normal bands. The magnetite in these veins is generally coarse (+0.1 mm) and frequently oxidized to martite (see Figures 24 and 25).

Minerals in addition to quartz and magnetite include hematite and muscovite in the upper zones and grunerite and occasionally hornblende in the center and lower zones. Varying quantities of garnet, chlorite, apatite and carbonates occur throughout the entire member. Average modes of the upper and lower zones are tabulated in Table 12 as shown on the following page.

In general, the assemblages containing grunerite are free of specular hematite with the exception of several localized examples which are clearly related to post-metamorphic processes. These occurrences are discussed in a forthcoming section.

TABLE 12.--Average Modal Analysis of Quartz-Magnetite Member

Quartz-Magnetite	Per Cent Volume	
	Upper Zone	Lower Zone
Quartz	49	42
Magnetite*	12	37
Hematite	33	--
Muscovite	4	--
Grunerite	--	3
Hornblende	--	x
Garnet	1	3
Chlorite(s)	x	x
Apatite	tr.	tr.
Carbonates(s)	tr.	tr.

* = includes martite
x = less than one per cent but frequently observed
tr. = trace
(s) = normally occurs as an alteration product or late fracture filling

The magnetite within this member occurs in two distinct size fractions as did the specular hematite in the overlying horizons. A coarse variety which is normally over 0.10 mm. occupies the iron rich bands while a fine fraction of micron size is distributed throughout the quartzose bands These minute crystals resemble the pre-metamorphic magnetite found elsewhere on the Marquette Range. Both the coarse and fine fractions exhibit varying degrees of oxidation to martite. Figure 26 illustrates a typical microscopic view of the quartz-magnetite member.

For the most part the textural features and chemical relationships of this member are merely an extnesion of

those observed in the quartz-grunerite-magnetite type. These characteristics are, therefore, applicable to both types and will be considered in the discussion related to the latter member.

Quartz-grunerite-magnetite member.--The quartz-grunerite-magnetite member of the Negaunee represents the most abundant type of iron-formation within the trough area. It is well exposed at the Republic Mine and in the vicinity of the old workings at the Magnetic Mine. Both occurrences of iron-formation within the basement complex contain grunerite and resemble this rock type. In addition it occurs as a major phase of the iron-formation in Section 6, T. 46 N., R. 29 W., and Section 1, T. 46 N., R. 30 W., on the northeast limb and throughout Section 34, T. 47 N., R. 30 W., on the southwest limb. In all cases where data are available on adjacent iron-formation types, it occupies the lower stratigraphic horizon. Therefore, it is most likely present in nearly all areas containing iron-formation. The only known exception is in Section 2, T. 46 N., R. 30 W., where diamond drill core passed directly from a quartz-specular hematite-magnetite rock into Ajibik formation.

Sill-like amphibolites are commonly associated with the grunerite rich rocks. This is exemplified in the Republic Mine area where a series of amphibolites divide the lower portion of the iron-formation into three discrete zones (see Plate 2). In other areas the amphibolites appear as dikes as well as sills. This is especially true in areas of intense folding such as the nose of the trough where the aforementioned zones lose their identity.

The rock is typically banded as a result of compositional variations in the ratios of quartz, magnetite and grunerite. Islands of quartz commonly occur within the iron rich bands. Furthermore, bands of grunerite and magnetite frequently transect quartzose layers. These features are illustrated in Figure 27 which represents by far the most typical of the quartz-grunerite-magnetite rock types. Figures 28 through 30 illustrate lesser varieties that were found locally. These include a highly oxidized sample from the Magnetic Mine (Figure 28), a rich magnetite band with coarse grunerite from the Standard area (Figure 29), and the banded formation from within the basement complex in Section 35, T. 47 N., R. 30 W. (Figure 30).

The mineralogy of the quartz-grunerite-magnetite member is far more complex than either of the aforementioned members. Minerals in addition to quartz, grunerite and magnetite include garnet, hornblende, pyroxene, stilpnomelane, minnesotaite, calcite, hematite and an unidentified brownish green silicate. These minerals represent at least four generations of development. Scattered grains of clastic quartz and some very fine grained magnetite appear to have survived transformation and are considered pre-metamorphic. Regional metamorphism promoted the growth of some magnetite and quartz, and developed grunerite, garnet, hornblende and pyroxene. Stilpnomelane, minnesotaite, hornblende and calcite are considered products of retrograde metamorphism. Minerals attributed to post-metamorphic processes include fracture fillings of quartz-calcite, quartz-hematite and a brownish green silicate. Pseudomorphic replacements of magnetite by martite and grunerite by hematite and quartz are also considered post-metamorphic.

Quartz occurs in several distinct habits. As in the case of the other iron-formation members, the vast majority is considered a recrystallized chert. However, there are occasional grains that exhibit original clastic features. For the most part, these grains are well rounded with limited undulatory extinction. The quartz occuring as recrystallized chert is extremely variable relative to grain size. Measurements across diameters ranged from less than 0.05 mm to over 0.3 mm in single thin sections. Normally the iron rich bands contain the finer fractions. Cursory examination indicated an overall tendency for grain size increase as a function of quartz clarity. That is, the quartz grains relatively free of magnetite and other impurities are the coarser. However, a systematic study of this possible relationship was not conducted.

A few local examples were found of grunerite crystals pseudomorphically replaced by quartz. In this case the fibrous outlines of the amphibole are completely preserved. Hematite is a ubiquitous associate and usually occurs along grain boundaries and cleavage planes.

The magnetite of this formation is also characterized by extreme variations in size. Diameters ranging from 0.05 to over 0.8 mm. are common. The extremely fine variety appears most frequently in the quartzose bands and as partially replaced remnants within silicates. The former also occurs within and surrounding the oval shaped oolites. This may well represent a pre-metamorphic state of the magnetite. The coarser crystals appear to have formed through the recrystallization and assimilation of finer grains. They frequently contain impurities but all degrees of crystal development were observed.

Magnetite crystals that occur within grunerite commonly exhibit outlines that are extremely frayed (Figures 29 and 30). This feature is also common to magnetite occurring within other silicates but to a lesser degree.

Grunerite is the characteristic mineral of this iron-formation member. It is developed most extensively between magnetite and quartz bands. This is illustrated in Figures 31 and 32. The crystals tend to penetrate the magnetite bands. These usually contain numerous magnetite inclusions (Figure 33). It was noted that where grunerite penetrates magnetite rich bands it frequently is euhedral in contrast to anhedral outlines in areas surrounded by quarts. The degree of crystal perfection may well be a function on the availability of iron units. Grunerite developed between the quartzose and iron rich bands tends to form perpendicular to the banding (Figure 34).

Grunerite also occurs within the magnetite rich bands. In this case the crystals are either randomly arranged or in subparallel orientation with the banding (Figures 35 and 36). In these occurrences magnetite incluses are very common as illustrated in Figure 36.

Numerous attempts were made to obtain sufficiently clean concentrates of grunerite for chemical analyses. Only two samples were considered pure enough to give reliable data. The results of these analyses are given in Figure 16. In addition, the molecular ratios of MgO, FeO and MnO are plotted for comparison with a nomenclature suggested by Klein (1964). These analyses indicate a possible range of compositions for the grunerites. The manganoan variety (D.D.H. #18) originated from the nose of the Republic Trough in an area of intense shearing and folding. The second sample (D.D.H. #19) was collected from an area of lesser deformation.

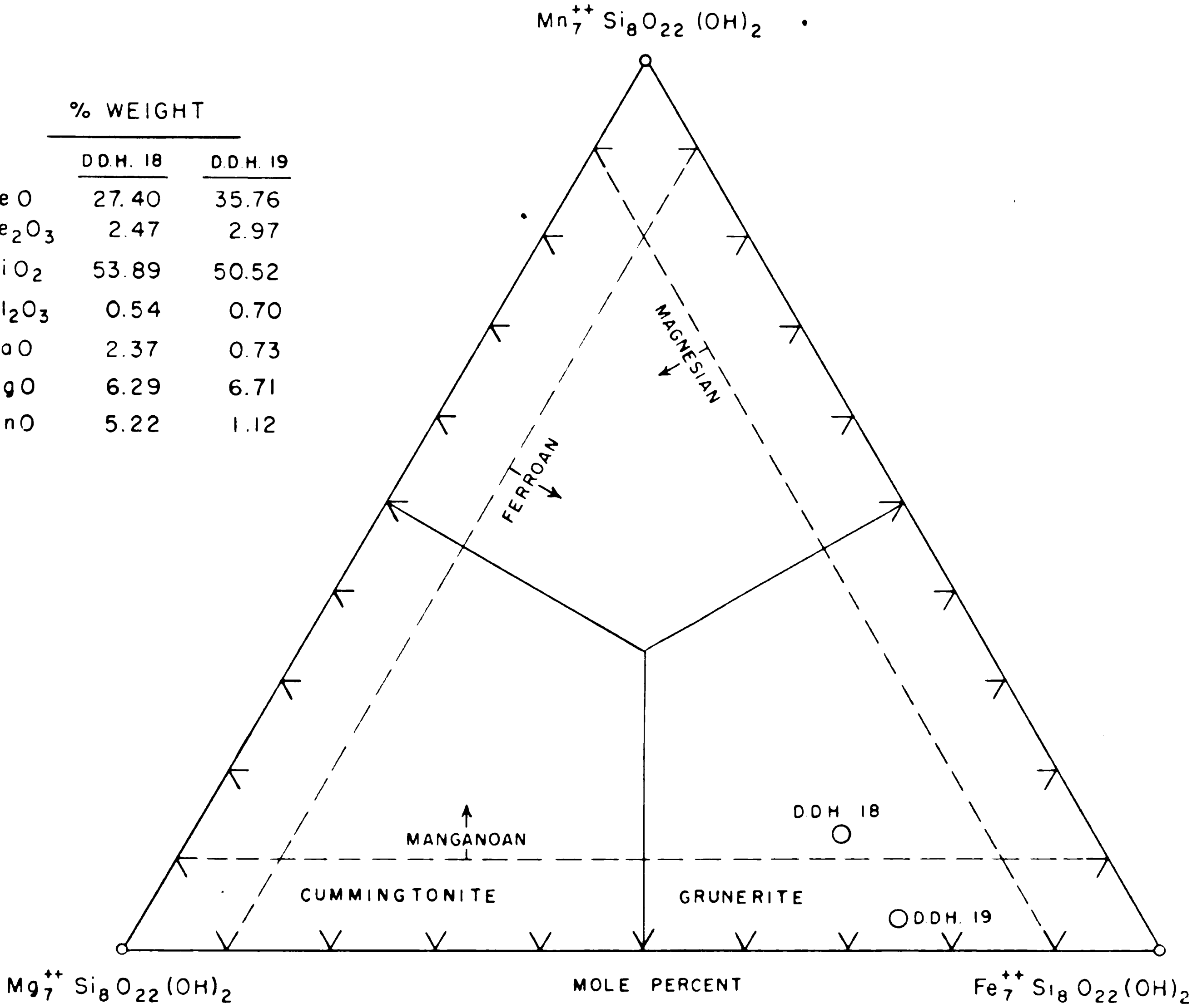
Features related to the possible origin of grunerite are considered in a forthcoming discussion.

FIGURE 16

POSITION OF ANALYZED GRUNERITES RELATIVE TO NOMENCLATURE SUGGESTED BY KLEIN (1964)

% WEIGHT

	D.D.H. 18	D.D.H. 19
FeO	27.40	35.76
Fe_2O_3	2.47	2.97
SiO_2	53.89	50.52
Al_2O_3	0.54	0.70
CaO	2.37	0.73
MgO	6.29	6.71
MnO	5.22	1.12



Garnet is a relatively common constituent of this iron-formation member. It occurs most frequently within the iron rich bands and generally contains numerous inclusions of magnetite (Figure 37). In some instances remnants of the magnetite band can be traced through garnet prophyroblasts. As in the case of grunerite, there is a noticeable decrease in the quantity of magnetite within the garnet as compared to surrounding positions.

Garnet appears to have formed later than grunerite, This is suggested by inclusions of grunerite within garent. Furthermore, many grunerite crystals are truncated by garnet porphyroblasts.

Pyroxene is a relatively rare constituent. It was observed most frequently along the northeast flank of the Republic Mine area. Remnants of grunerite within pyroxene are very common. This would suggest that pyroxene formed after and possibly at the expense of grunerite.

Although carbonates are relatively rare, there are a variety of occurrences which would indicate more than one generation of development. For the most part, the carbonate is highly calcic as revealed on a series of differential thermal analysis curves. It was found as a principal constituent of some bands between magnetite-grunerite layers. In these instances it occurs with either magnetite or garnet as equigranular grains in apparent equilibrium with adjacent minerals. There are no indications of reaction rims or

replacement textures. A second occurrence is as irregular grains and minute blades replacing silicate-magnetite bands or as secondary veinlets (Figure 38). Such replacements are normally localized and marked by their irregularity. Finally, carbonate rarely occurs as a major constituent of some oolites embedded in quartz. In this case the quartz and possibly some magnetite within the oolite are being replaced by the carbonate.

Stilpnomelane occurs only within localized areas, which are marked by intense shearing and alteration. It is found most frequently within grunerite crystals and is considered a retrograde product.

Hornblende is also considered a product of retrograde metamorphism. It was found as a peripheral replacement of grunerite, garnet and pyroxene. Where found with grunerite it exhibits a bluish-green coloration while a more brownish hue is more common for occurrences with garnet and pyroxene. This color variation appears to reflect the compositional differences of the host mineral.

A few clusters of a brownish-green layered iron silicate were observed within several quartz grains. Identification of this silicate could not be ascertained but it strongly resembles minnesotaite. This mineral was also found within several garnets where it appears as a retrograde or later alteration product.

Chemically the quartz-grunerite-magnetite member is the most complex of the iron-formation types. Fifty chemical analyses for Fe++, Fe+++, SiO_2, MgO, Al_2O_3, and CaO were conducted on drill core samples representing the major occurrences in the Republic Mine area. The average oxide composition with respect to these analyses is given in Table 13. This table also lists the extremes that were noted.

TABLE 13.--Partial Composition of the Quartz-Grunerite-Magnetite Iron-Formation Based on Fifty Analyses.

Oxide	Per Cent Weight		
		Range	
	Average	Low	High
FeO	28.49	19.03	36.14
Fe_2O_3	20.53	4.00	30.46
SiO_2	40.82	35.39	48.07
MgO	2.62	1.14	4.95
Al_2O_3	0.99	0.26	4.38
CaO	1.91	0.35	4.90

This writer was unable to detect any systematic variation in the rock composition relative to stratigraphic horizons within the iron-formation member. There is a general tendency for an increasing ferrous to ferric iron ratio as one progresses towards the lower stratigraphic horizons; however, this is not clearly defined. The relative distribution of oxides within individual samples irrespective of stratigraphic position appears to relate for more consistent relationships. These are considered in a following discussion on the paragenetic relationships of some iron-formation minerals.

Paragenetic Relationships of Some Iron-Fromation Minerals

There is little evidence relative to the parent constituents of the quartz-specular hematite and quartz-magnetite members. Transitions within these rocks have been so complete that relationships indicative of the rock evolution are masked. Furthermore, these members are characterized by simple compositions wherein quartz and iron oxide account for nearly the entire assemblage. A sequence of mineral development would not be expected in such a simple system. This is especially true in lithologies where hematite constitutes a principal phase. According to Yoder (1956) hematite would appear as a stable phase only if the oxygen partial pressures were in excess of those limiting the development of most silicates. That is, the normal sequence of silicate development would not be realized throughout progressive metamorphism if hematite persisted as a stable phase. The localized occurrence of garnet within the quartz-specular hematite member (see Figure 23) appears to contradict this concept. This may represent an assemblage that is not in equilibrium, although there is no evidence of reaction borders. The chemistry of these

garnets is unknown and until such data are obtained it is presumptuous to speculate on the phase relationships.

The frequent appearance of magnetite remnants within specular hematite plates merit note. If merely textural relationships are considered this would strongly suggest that specular hematite formed at the expense of magnetite. The remnants occur most frequently within the plates and normally exhibit an irregular outline which would further support the contention that specular hematite formed after magnetite, at least in part.

The quartz-grunerite-magnetite member provides considerably more data relative to the sequence of mineral development during regional metamorphism. To a large extent these have been discussed in a previous section. One of the most significant observations seems to be the development of silicates, especially grunerite and garnet, at the expense of magnetite. The following mineral relationships support this concept:

1. preferential development of grunerite between magnetite and quartz rich bands,
2. growth of grunerite and garnet porphyroblasts within nearly pure magnetite layers wherein portions of the original band can be traced through the silicate,
3. substantial decrease in the ratio of fine grained magnetite within grunerite as compared to quartzose zones,

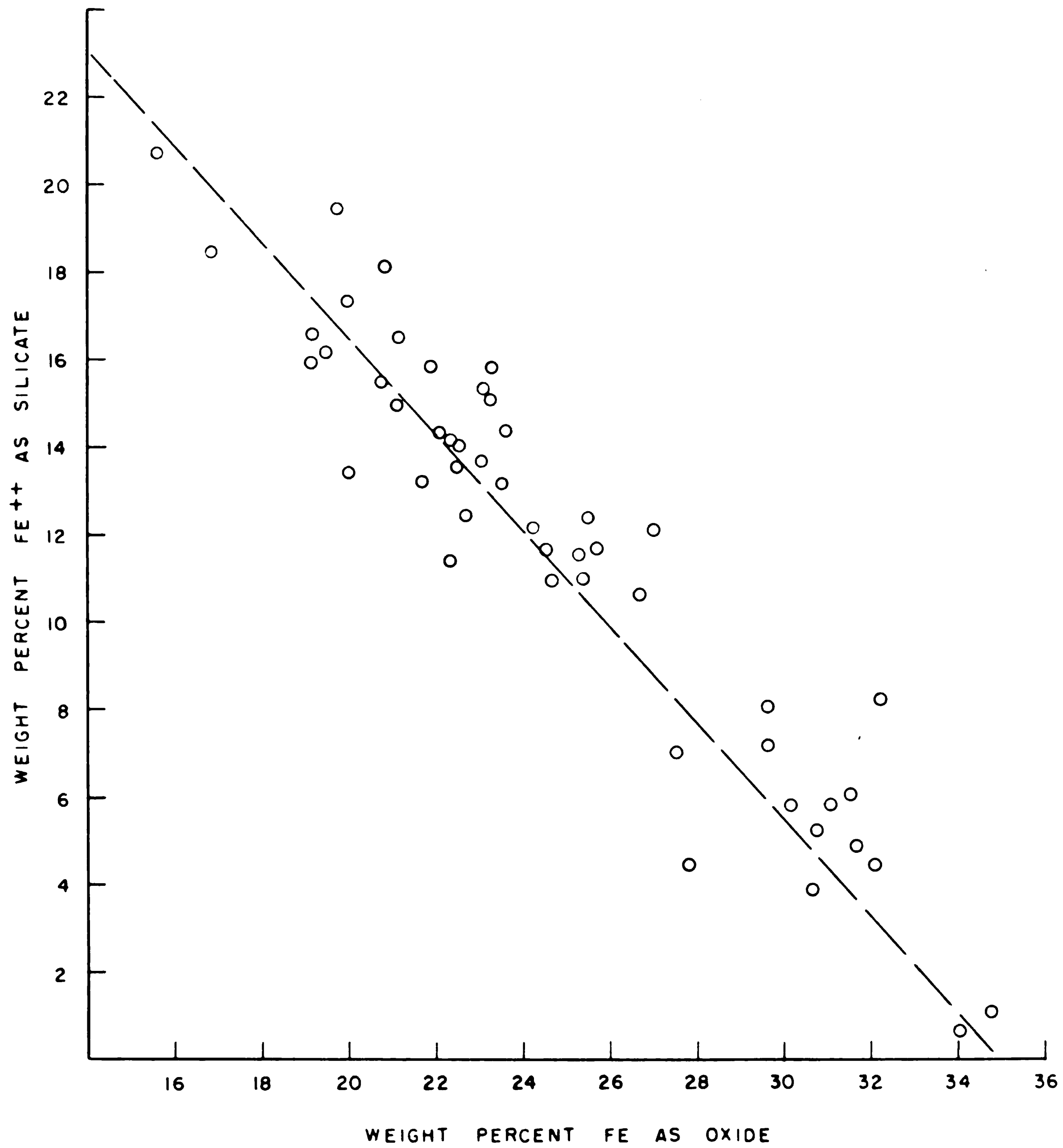
4. a depletion in the fine grained magnetite surrounding grunerite,
5. growth of grunerite adjacent magnetite veinlets that cut quartzose bands,
6. irregular outlines of magnetite grains in grunerite and garnet in contrast to subhedral and euhedral crystals in quartz, and
7. presence of quartz-magnetite remnants within grunerite and garnet.

If, as indicated by the aforementioned mineral relationships, silicates did form at the expense of magnetite, this should also be reflected in the bulk chemistry of the rock. In an effort to determine if any relationships exists between iron occurring as silicate and oxide, fifty samples representing all horizons within the member were analyzed. Each sample was analyzed for acid soluble (hydrochloric plus stannous chloride) iron and total iron (fusion method). Within this area the iron occurring as silicates is normally insoluble while that as oxides is soluble. In order to check these analyses twenty-five samples were also analyzed for total and soluble ferrous iron. In all instances the insoluble ferrous iron checked within 0.8 per cent of the total insoluble iron.

The data obtained from these samples are plotted on Figure 17. These analyses clearly indicate an inverse relationship between the iron occurring as silicate and oxide

FIGURE 17

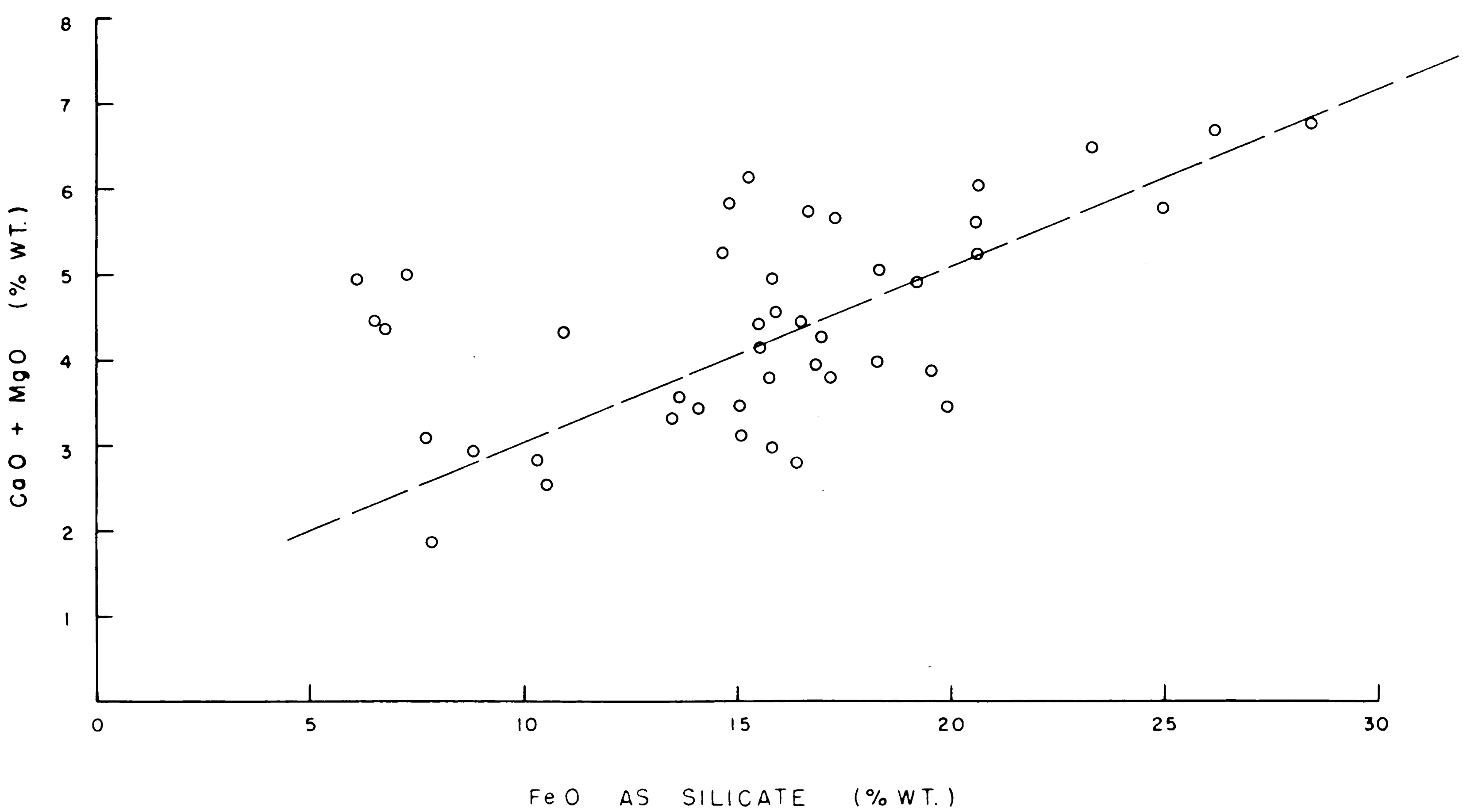
RELATIONSHIP BETWEEN THE DISTRIBUTION
OF FE IN OXIDES AND SILICATES
AS INDICATED BY FIFTY ROCK ANALYSES



which strongly supports the contention that grunerite, garnet and possibly other silicates formed at the expense of magnetite. This does not preclude the participation of other reactants such as carbonates and layered iron silicates. Some source would be needed to satisfy the elemental requirements of the particular silicate. Such minerals may have been the controlling factor relative to the extent of reaction. That is, the quantity of available oxides such as CaO and MgO may have determined the amount of magnetite that was consumed in the reaction. In order to investigate this possibility the aforementioned fifty samples were also analyzed for CaO and MgO. These quantities were then compared with the amount of FeO occurring as silicate. A slight trend was detected as indicated in Figure 18; however, this relationship is far less positive than that noted in Figure 17. To some extent this may reflect in varying silicate compositions which is certainly suggested on the basis of the two grunerite analyses given in Figure 16. In any event, reactions independent of magnetite are not considered paramount in the formation of silicates in the quartz-grunerite-magnetite member. This does not exclude the possibility of grunerite development independent of magnetite in other lithologies. Reactions depending mainly on minnesotaite and stilpnomelane are considered for rocks of the Michigamme formation which is discussed in a forthcoming section.

FIGURE 18

RELATIONSHIP BETWEEN THE QUANTITY OF CaO + MgO IN THE ROCK AND FeO OCCURRING AS SILICATE



Silicate formation at the expense of magnetite is not a new concept. However, within the trough area it appears to have taken place on a relatively wide scale. This does point out that the treatment of oxygen as a fixed component throughout all grades of progressive metamorphism is not applicable in every instance. Any reaction producing grunerite at the expense of magnetite would require a reduction in the oxygen partial pressure. The ferric iron content of the grunerite is insufficient to account for any major transition.

An additional clue related to the sequence of mineral development is the common remnants of grunerite within garnet and pyroxene suggesting that these latter mienrals formed late during progressive metamorphism. To what extent grunerite participated in their formation could not be ascertained.

Figure 19.--Contact between banded quartz-specular hematite (left photo) and quartz-magnetite (right photo) iron formation types.

Figure 20.--Oolitic appearing aggregates of specular hematite (white) in quartz (dark gray) with a minor amount of magnetite (light gray). Polished surface, x80.

Figure 21.--Typical quartz-specular hematite iron formation member. Note relationship between hematite (white) and magnetite (light gray). Polished surface, x80.

Figure 22.--Coarse specular hematite plates associated with finer grained partially oxidized magnetite. Note a few remnants of magnetite (light gray) within specular hematite. Polished surface, x100.

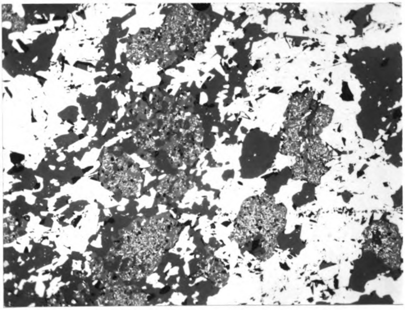


Figure 23.--Garnet poikiloblasts in quartz-specular hematite member at the Republic Mine. Note numerous inclusions of specular hematite within the garnets. Polished surface, x80.

Figure 24.--Rich coarse magnetite vein cutting quartzose layer. Occurrence is typical of intensely folded areas.

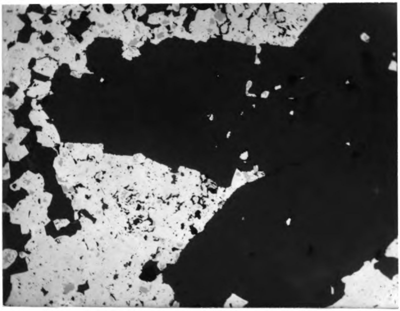


Figure 25.--Portion of rich magnetite band almost completely oxidized to martite. Note small patches of magnetite (light gray). Polished surface, x80.

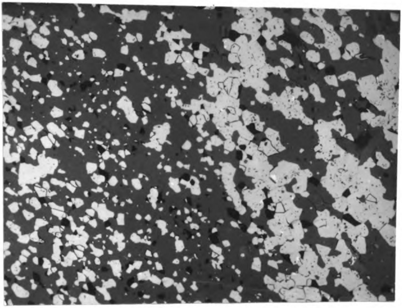


Figure 26.--Typical quartz-magnetite iron formation member. Note variation in grain size of magnetite. Polished surface, x80.

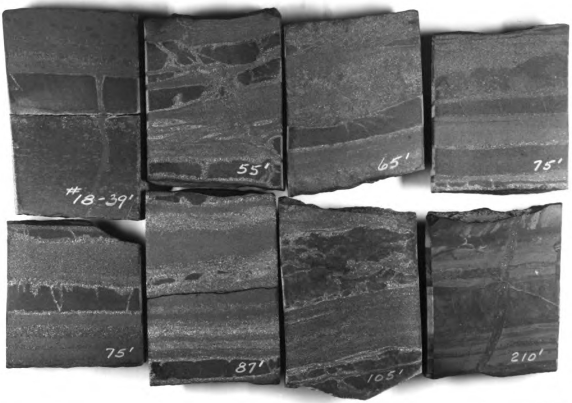


Figure 27.--Drill core specimens of typical quartz-grunerite-magnetite type iron formation. Note iron rich bands cutting quartzose layers and some quartz islands within grunerite-magnetite band. Also note extensive grunerite development along quartz-magnetite interface.

Figures 28 through 30.--Various minor lithologic types of quartz-grunerite magnetite type iron formation.

Figure 28

Figure 29

Figure 30

28.--Highly oxidized and partially hydrated sample from the Magnetic Mine.

29.--Rich band of magnetite with coarse grunerite from the Standard area.

30.--Banded formation within basement complex in Section 35, T.47 N., R.30 W.

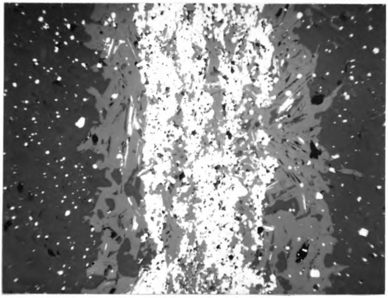


Figure 31.--Typical occurrence of grunerite (light gray) along contact between quartz (dark gray) and magnetite (white). Note frayed appearance of magnetite with grunerite in contrast to subhedral to euhedral crystals elsewhere. Polished surface, x80.

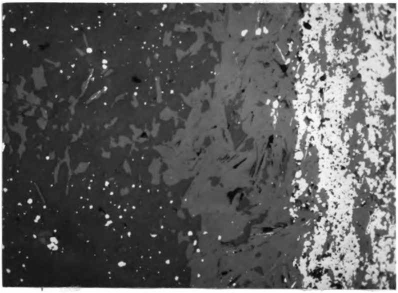


Figure 32.--Preferential development of grunerite between quartz and magnetite band. Note slight decrease of fine grained magnetite in the vicinity of grunerite within quartz band. Polished surface x80.

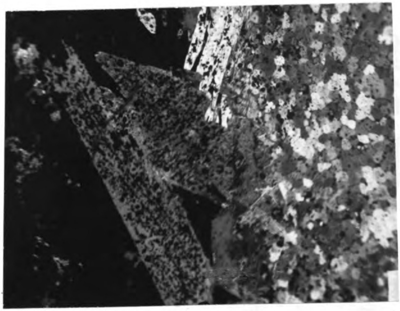


Figure 33.--Grunerite crystals penetrating magnetite rich layer. Note fine grained inclusions of magnetite within grunerite. Thin section, crossed nicols, x80.

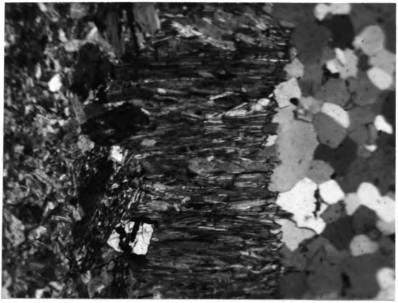


Figure 34.--Formation of grunerite between quartz and iron rich layers. Note long axes orientation of grunerite perpendicular to direction of banding. Thin section, crossed nicols, x80.

Figure 35.--Random growth of grunerite in magnetite band. Polished surface x80.

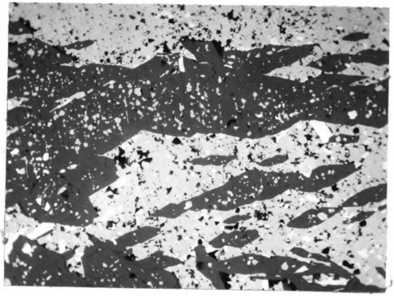


Figure 36.--Development of grunerite, in subparallel orientation to direction of banding, within magnetite band. Note magnetite inclusions within grunerite. Polished surface, x80.

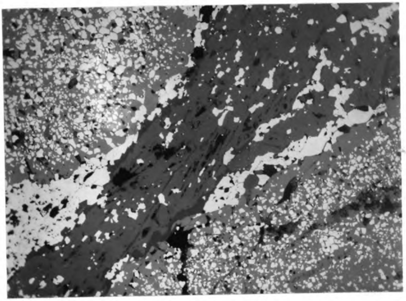


Figure 37.--Poikiloblastic garnet with numerous inclusions of magnetite. Garnet appears to have formed at the expense of magnetite and later than grunerite. Polished surface, x80.

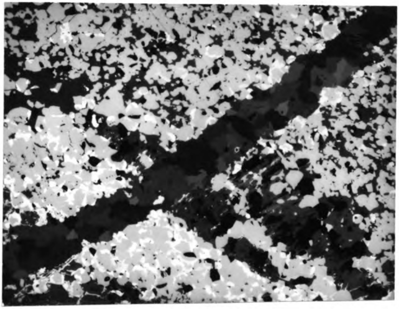


Figure 38.--Carbonate vein cutting quartz, magnetite and grunerite. Note partial oxidation of magnetite. Polished surface, crossed nicols, x100.

CHAPTER V

GOODRICH FORMATION

General Statement

The metasediments occurring immediately above the Negaunee iron-formation were designated by VanHise, Bayley, and Smyth (1897) as Goodrich Quartzite. The type locality for this formation is approximately 3-1/2 miles southwest of the City of Ishpeming. The reference exposures are adjacent to the Goodrich Mine (Section 19, T. 47 N., R. 27 W). In this vicinity the rock is essentially conglomeritic at the base consisting of mostly iron-formation pebbles in a quartz-mica matrix. The conglomerate grades upward into micaceous and feldspathic quartzite.

In this study all the metasediments occurring stratigraphically above the Negaunee iron-formation and below the Michigamme formation are considered Goodrich. These rocks include conglomerate, schist, quartzite and gneiss of various composition (see below). Therefore, the term "formation" is preferred. Elsewhere on the Marquette syncline, formations such as the Greenwood and Clarksburgh have been described as mappable units occurring between the Goodrich and Michigamme (Swanson, 1931; Zinn, 1931; Hase, 1957). Field evidence did not justify this distinction within the Republic Trough area. Zones of magnetic highs exist at or near the Goodrich-Michigamme contact (Sections 20, 21, 27, and 28, T. 47 N., R. 30 W.) but these are limited in scope and the rock types were not observed in either outcrop or drill core. Furthermore, the contact zones between these formations are masked, for the most part, by sill-like intrusives.

Angular unconformities in the range of 15 degrees have been reported for the Negaunee-Goodrich contact (e.g., VanHise, Bayley, and Smyth, 1897; Hase, 1957). Unequivocal evidence for an angular discordancy related to original sedimentary conditions was not observed during field mapping of the trough area. Variations in the attitude of adjacent bedding planes within either formation often exceeds that observed for the overall discordancies at the contact area. Such differences could easily be attributed to differential movement of parallel beds during folding. Furthermore, in areas of lesser deformation, a general rule of parallelism was noted.

The Goodrich attains thicknesses in excess of 1,000 feet at the southern extremity of the Trough. This includes some 400 feet of conglomerate. The rock is well exposed in the vicinity of the Republic Mine (Section 7, T. 46 N., R. 29 W.). Elsewhere within the trough the Goodrich commonly constitutes 200 to 700 feet of thickness. However, the conglomeratic member is generally absent and where present seldom attains thicknesses in excess of several feet. The marked development of conglomerate at the nose of the trough certainly suggests, by virtue of localization, an extremely irregular topography prior to Goodrich deposition.

The continuity of Goodrich along the southwest limb (see Plates 1 and 2) is substantiated by scattered outcrop and several diamond drill holes. Continuity along the northeast limb is less certain due to very few outcrops north of the Kloman Mine (Section 6, T. 46 N., R. 29 W.). However, old test pit data and diamond drill hole records justify delineating a continuous extension.

Samples of Goodrich representing 338 feet of stratigraphic thickness were composited from diamond drill core. Six holes from Section 2, T. 46 N., R. 30 W. and Section 34, T. 47 N., R. 30 W., were used in this compilation. The core did not include the aforementioned conglomeratic member. Chemical data and normative minerals of the composite are presented in Table 14 (see following page).

Lithologic Types

The Goodrich formation is subdivided into six basic rock types based on salient mineral constituents. These types include micaceous quartzite and quartz-mica schist, quartz-feldspar-mica schist and gneiss, quartz-feldspar-mica-epidote-amphibole schist and gneiss, quartz-feldspar-mica-epidote schist and gneiss, quartz-feldspar-amphibole-epidote gneiss, and quartz-mica-epidote schist.

TABLE 14.--Chemical and Normative Composition of Goodrich Formation Occurring in Section 2, T. 46 N., R. 30 W., and Section 34, T. 47 N., R. 30 W.

Per Cent by Weight*		C.I.P.W. Norm	
SiO_2	60.20		
Al_2O_3	12.59	Q	19.89
Fe_2O_3	3.27	C	0.71
FeO	7.34	or	15.59
MgO	2.44	ab	22.03
CaO	4.48	an	16.97
Na2O	2.61	hy	15.10
K_2O	2.68	mt	4.63
H_2O+	0.25	il	2.58
TiO_2	1.38	ap	0.67
P_2O_5	0.30	pr	0.09
MnO	0.25	cc	1.20
S	0.07	(molar quantities of less than 0.002 are omitted)	
CO_2**	0.51		

*Run on dry basis with H_2O^- (105°C.) = 0.21.

**Calculated on basis of total C as CO_2 (W. Pasich, Jones and Laughlin Steel Co., Negaunee, Michigan, Analyst).

In addition the conglomertic phase constitutes a major member. Cursory examination indicates a considerable variation in mineral constituents for this rock type. No attempt was made to subdivide the conglomerate into specific types due to limited data; however, the iron rich phases may be roughly divided into quartz-muscovite-specular hematite and quartz-chlorite-magnetite members. It was noted that the former occurs almost exclusively at the southeast nose of the trough while the latter is the common type along either limb. Figures 39 through 41 illustrate a few examples of these members.

Micaceous quartzite and quartz-mica schist.--The most abundant rock type within the Goodrich consists of micaceous quartzite and quartz-mica schist. These rocks are found throughout the extent of the formation. Compositionally there is no unique partitioning between the quartzitic and schistose phases. This appears to be more a function of deformational environment than mineral assemblage.

Transition into different rock types is generally graditional. Common associates are micaceous feldspathic quartzite and quartz-feldspar-mica schist occurring both with and without epidote. Over short distances there can be considerable variation in the relative proportions of major mienrals. However, the rock is characterized by the absence of both feldspar and epidote.

Quartz generally accounts for over 60 per cent of the rock volume. The individual grains in the quartzitic phases are relatively equidimensional ranging from 0.2 to 0.3 mm. Two size ranges are common in the schistose variety. One is normally less than 0.2 mm while the other often exceeds 1.5 mm. The coarser quartz fraction is characterized by a pronounced undulatory extinction and occasionally exhibits granulated borders. Muscovite is the characteristic mica and is ubiquitous in this rock type. It occurs predominantly as subparallel plates often found engulfing coarse elliptical quartz grains. Varying quantities of olive to brownish green biotite are also frequently present. However, locally this mica may be rare or absent. In the more schistose phases it usually exhibits partial alteration to chlorite. Minor quantities of sphene, apatite and tourmaline occur infrequently.

Average modal analyses from seven locations are presented in Table 15.

Quartz-feldspar-mica-schist and gneiss.--A rock type similar to the quartz-mica schist previously described occurs intermittently throughout the formation. Presence of feldspar and paucity or absence of biotite are the distinguishing features. Two typical assemblages are given in Table 16. One contains both plagioclase and potash feldspar while the second type contains only the latter.

In this section both assemblages exhibit quartz grains with a considerable variation in size. Two habits are clearly distinguishable. The first averages less than 0.2 mm in diameter and generally forms as a matrix. A larger fraction, averaging over 1.2 mm, appears very similar to the so-called "augen" that were described for certain varieties of Ajibik schist. The composition of plagioclase is estimated at An_{15}. Some crystals appear poikiloblastic with numerous inclusions of quartz and muscovite. These are commonly over

2 mm and generally exhibit frayed edges. Smaller crystals (0.2 mm) of plagioclase are also present. There appears to be no pronounced compositional variation between the two occurrences. However, calcite was noted within several of the larger crystals which suggests a possible releast of the CaO molecule. The potash feldspar occurring with plagioclase is believed to be orthoclase. In rocks void of plagioclase, microcline was the only feldspar identified. Muscovite is present both as an alteration product of feldspar and as distinctive plates. Chlorite occurs pseudomorphically after what is believed to be biotite. Minor remnants of material resembling biotite were observed within several masses of chlorite. Where biotite was positively identified it exhibits dark olive green to pale green pleochroism.

Quartz-feldspar-mica-epidote-amphibole schist and gneiss.--Several zones of schist and gneiss were observed void of muscovite and containing varying quantities of potash feldspar, biotite, epidote and amphibole. The most common occurrence was noted in Section 2, T. 46 N., R. 30 W. In this area the rock type accounts for at least 130 feet of stratigraphic thickness. Megascopically it is grayish and resembles a metagraywacke. As a general rule, secondary alteration appears more pronounced as the iron-formation is approached. Schistose phases were also observed more frequently in proximity to the iron-formation contact.

In thin section, quartz appears to be relatively uniform in size, averaging 0.2 mm across diameters. Biotite in the least altered phases is brownish green to pale buff. Preferred orientation along 001 is conspicuous. The amphibole is hornblende exhibiting strong pleochroism from bluish green to pale green. Excellent development is characteristic. Minor amounts ofcarbonate were often found associated with the amphibole. Epidote is a major constituent in all the specimens. Grains up to 0.9 mm were observed. It appears predominantly as pistacite; however, subordinate quantities of zoisite were recognized in several samples. The feldspars are, for the most part, altered. This impeded positive identification, although the presence of microcline was ascertained. The existence of plagioclase is uncertain. A few small altered grains exhibit what appears to represent relic albite twin planes. Sphene was found in most specimens and frequently in amounts up to 3 per cent. Polysynthetic twinning was noted in some of the larger grains.

Average modes from three occurrences are presented in Table 17. Figure 42 illustrates a typical microscopic view.

Quartz-feldspar-mica-epidote schist and gneiss.--
Numerous samples of quartzose schist and gneiss with varying quantities of feldspar, mica, and epidote were observed

throughout the Goodrich. Both schistose and gneissic textures were noted within single outcrops. Textures appear to be mainly a function of the quantity of mica. The gneissic phases are generally well banded with alternating layers rich in quartz. Individual bands vary from 1.2 to 3.0 cm in width. They are often discontinuous along strike. Although the rock type is common, it is not believed to represent a unique stratigraphic horizon within the Goodrich. Samples occur intermittently along strike and dip throughout the entire formation.

In the majority of thin sections quartz exhibits a relatively equidimensional character. Grains average between 0.2 and 0.3 mm across diameters. In some of the more schistose phases two size fractions were noted. These include a fine variety averaging less than 0.2 mm and a coarse fraction in the range of 0.6 mm. Mica is present as both biotite and muscovite. Biotite was observed in all but one case. In this instance chlorite is present and believed to represent an alteration product of pre-existing biotite. Muscovite is a common constituent in the majority of occurrences. However, it was not found in specimens containing over 20 per cent epidote. The implications of this apparent restriction are considered during the discussion on metamorphism. Microcline was the only feldspar positively identified. This, however, does not preclude the presence of plagioclase. Minor amounts of highly altered grains suggest a plagioclase parent. Epidote, as pistacite, is a characteristic constituent. Occasionally zoisite can be observed in subordinate quantities. Its appearance generally markes the presence of calcite.

Average modes from specimens collected over nine localities are tabulated in Table 18.

Quartz-feldspar-amphibole-epidote gneiss.--Zones of quartzose gneiss with feldspar, amphibole and epidote as common constituents were found in limited quantity near the base of the formation. A complete absence of mica, other than that representing late alteration, characterizes this lithology. Generally the rock is banded although discrete compositional layering is somewhat subtle in hand specimen. The rock is best exposed in Section 7, T. 46 N., R. 30 W. and Section 27, T. 47 N., R. 30 W.

Microscopically, quartz is equidimensional within individual thin sections; however, size variations ranging from 0.1 to 0.4 mm were noted for samples collected from different localities. Potash feldspar is present both with and without plagioclase. Microcline was the only feldspar noted in assemblages void of plagioclase. In specimens containing plagioclase the potash feldspar is believed to be orthoclase. However, this identification is questionable due to extensive secondary alteration. Very few of the plagioclase crystals were amenable to compositional determination by extinction angle methods. Measurements on a few grains indicated a sodic content of less than Ab_{80}. The amphibole is well developed and considered hornblende. It is pleochroic from green to pale brownish green and lacks the bluish tint noted in hornblendes characteristic of other lithologic types. Epidote (mostly pistacite) is present in varying quantities. It is generally found associated intimately with hornblende.

Table 19 relates average modes of assemblages with and without plagioclase. Mineral relationships are illustrated in Figure 43.

Quartz-mica-epidote schist.--Quartzose micaceous schists with epidote were found widely distributed throughout the Goodrich within the Trough area. Numerous samples were collected from Section 6, T. 46 N., R. 29 W.; Section 12, T. 46 N., R. 30 W.; and Sections 28 and 34, T. 47 N., R. 30 W. Quantitatively the rock type appears most prevalent at the stratigraphic center of the formation. However, limited examples were also noted in the upper and lower portions. The rock is distinguished from other epidote bearing schists by the absence of feldspar. It is, however, marked by a considerable variation in mineral constituents. Amphibole is present in several assemblages and garnet was recognized in one locality. Mica may constitute anywhere from 9 to 45 per cent of the rock volume.

In thin section the quartz grains are fairly uniform averaging from 0.15 to 0.30 mm across diameters. Mica is normally present as both muscovite and biotite; however, a few specimens were found to contain only the latter. Biotite is typically olive green to brownish green in assemblages lacking garnet. It exhibits a more pronounced brownish hue when found with garnet. Muscovite appears both as large subparallel plates and in fine grained aggregates. The bulk of the epidote is pistacite with minor quantities of zoisite. Poikilobastic garnet up to several millimeters is present infrequently. Iron oxides and quartz are common inclusions. The amphibole found in a few samples is identical to the blue green hornblende observed in other Goodrich lithologies. It is generally well developed with cross-sections in excess of 0.8 mm. Numerous quartz inclusions are common.

Modes representing six variations of the rock type are given in Table 20. Several mineral constituents are illustrated in Figures 44 and 45.

MODAL ANALYSES OF VARIOUS LITHOLOGIC TYPES FROM THE GOODRICH FORMATION

TABLE 15 *Modes from nine composites of micaceous quartzite and quartz-mica schist.*

MINERAL	PERCENT VOLUME								
Quartz	79	65	63	58	64	75	91	72	89
Muscovite	18	12	16	28	23	23	6	24	7
Biotite	—	18	12	14	11	X	X	—	—
Chlorite(s)	X	—	—	—	—	—	—	—	4
Sphene	X	—	—	—	—	tr.	X	—	X
Apatite	X	—	—	—	—	tr.	X	X	—
Tourmaline	tr.	X	—	—	—	—	—	—	—
Opaques	2	4	9	—	2	X	2	3	X

(s) alteration product.

TABLE 16 *Modal analyses from two varieties of quartz-feldspar-mica schist and gneiss.*

MINERAL	PERCENT VOLUME	
Quartz	62	64
K-Feldspar	6	6
Plagioclase	22	—
Muscovite	9	21
Biotite	—	1
Chlorite(s)	1	—
Calcite	X	—
Apatite	—	X
Opaques	X	7

(s) alteration of biotite.

TABLE 17 *Average modes from three occurrences of quartz-feldspar-mica-epidote-amphibole schist and gneiss.*

MINERAL	PERCENT VOLUME		
Quartz	31	31	61
K-Feldspar	19	21	7
Plagioclase	1	X	—
Biotite	19	19	11
Hornblende	11	6	5
Epidote	12	17	12
Calcite	3	X	X
Sphene	3	X	3
Apatite	tr.	X	tr.
Opaques	tr.	5	X

TABLE 18 *Modes of quartz-feldspar-mica-epidote schist and gneiss from nine locations.*

MINERAL	PERCENT VOLUME								
Quartz	43	62	53	61	61	46	63	61	66
K-Feldspar	3	1	5	9	2	8	1	2	12
Muscovite	—	—	15	5	12	3	23	22	9
Biotite	23	16	17	14	—	24	7	5	—
Chlorite(s)	—	—	—	—	11	—	—	—	X
Epidote	28	21	5	3	10	15	2	4	9
Calcite	—	—	—	—	3	1	—	—	—
Sphene	—	—	—	—	X	2	X	X	—
Apatite	—	—	tr.	—	tr.	X	X	—	—
Tourmaline	—	—	X	X	—	—	—	—	—
Opaques	3	—	5	7	X	X	3	5	3

(s) in part appears as alteration product.

TABLE 19 *Modal analyses of typical quartz-feldspar-amphibole-epidote gneiss.*

MINERAL	PERCENT VOLUME	
Quartz	63	49
K-Feldspar	8	9
Plagioclase	—	10
Hornblende	12	25
Epidote	14	1
Opaques	3	5

TABLE 20 *Six average modes of quartz-mica-epidote schist.*

MINERAL	PERCENT VOLUME					
Quartz	53	56	49	39	45	46
Muscovite	3	16	5	4	—	20
Biotite	42	17	29	22	9	22
Chlorite(s)	—	—	—	—	—	3
Garnet	—	—	—	6	—	—
Hornblende	—	—	—	8	41	—
Epidote	1	10	12	16	2	8
Calcite(s)	—	—	—	—	X	—
Sphene	—	—	—	—	2	X
Apatite	—	—	tr.	—	—	—
Opaques	X	X	4	4	1	1

(s) alteration product

tr. exceedingly rare. X less than one percent but frequently observed.

Figures 39 through 41.--Iron-Rich Members of Goodrich Conglomerate.

Figure 39

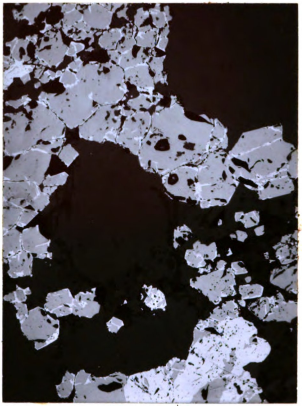


Figure 40

39.--Sample of magnetic conglomerate from the Kloman Mine.

40.--Partially oxidized magnetite and chlorite surrounding clastic quartz in magnetic phase of conglomerate at the Kloman Mine. Polished surface, x80.

41.--Quartz-muscovite-specular hematite phase of conglomerate from the Republic Mine area. Polished surface, x80.

Figures 42 and 43.--Photomicrographs of Rocks from the Goodrich Formation.

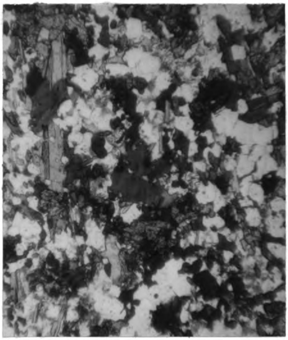


Figure 42

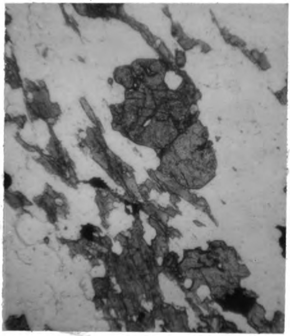


Figure 43

42.--Occurrence of biotite, pistacite, quartz and feldspar in quartz-feldspar-mica-epidote-emphibole schist and gneiss. Note minor presence of sphene.

43.--Typical development of pistacite and hornblende in quartz-feldspar-amphibole-epidote gneiss.

NOTE: Both figures, ordinary light, x52.

Figures 44 and 45.--Photomicrographs of Rocks from the Goodrich Formation.

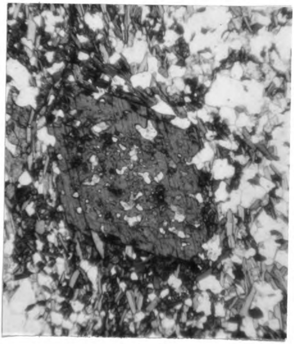


Figure 44

Figure 45

44.--Local development of poikiloblastic hornblende in quartz-mica-epidote schist. Note concentration of epidote along periphery of amphibole crystal.

45. Local development of garnet prophyroblast in quartz-mica-epidote schist. Note band of iron oxides extending through garnet.

NOTE: Both figures, ordinary light, x52.

CHAPTER VI

MICHIGAMME FORMATION

General Statement

Rocks of the Michigamme formation are believed to represent the youngest metasediments of the Republic Trough area. This formation outcrops extensively throughout the western end of the Marquette syncline. Specially in the vicinity of Lake Michigamme where the type locality was designated by VanHise, Bayley, and Smyth (1897). At that site it is predominantly slate and mica schist. The formation is also well exposed immediately north of the Republic Trough. There it consists chiefly of garnetiferous mica schist with local development of abundant staurolite and andalusite. Several excellent exposures were found along the Michigamme River in Sections 17 and 18, T. 47 N., R. 30 W. Although these outcrops are beyond the area delineated by Plates 1 and 2 they are believed to represent the upper portion of the Michigamme as it exists throughout the northern sector of the Trough. Channel samples were taken from these outcrops representing 45 feet of stratigraphic thickness. Chemical data and a calculated norm from these samples are given in Table 21.

TABLE 21.--Chemical and Normative Composition of Upper Michigamme Formation throughout the Northern Sector of Republic Trough.

Per Cent by Weight*		C.I.P.W. Norm	
SiO_2	61.52		
Al_2O_3	17.84	Q	32.75
Fe_2O_3	1.14	C	12.13
FeO	7.34	or	20.60
MgO	3.70	ab	5.24
CaO	0.50	an	2.50
Na2O	0.62	hy	20.72
K_2O	3.48	mt	1.62
H_2O+	0.54	il	1.37
TiO_2	0.69	pr	0.09
P205	0.16	(molar quantities of less than 0.002 are omitted.)	
MnO	0.14		
S	0.05	NOTE: cc not considered in norm with 0.30 per cent weight of carbon assumed organic.	
CO_2**	1.10		

*Run on dry basis with H_2O^- (105°C.) = 0.12

**Calculated on basis of total C as CO_2 (W. Pasich, Jones and Laughlin Steel Co., Negaunee, Michigan Analyst).

Within the actual trough area there are very few exposures of metasediments above the Goodrich. The most likely location for these outcrops is in proximity to the axial plane of the syncline. However, this area is marked by abundant swamps and in part contains the Michigamme River.

These features are believed to reflect the relative erodability character of the underlying bedrock.

The best specimens of Michigamme that were obtained from within the northern sector of the trough came from diamond drill core (Section 20, T. 47 N., R. 30 W.). These consist predominantly of mica schist with a subordinate iron bearing member. Stratigraphically the core represents the lower portion of the formation.

Throughout the southern sector of the trough the Michigamme outcrops infrequently in several sections. The most extensive exposures occur in Section 6, T. 46 N., R. 29 W., and Section 1, T. 46 N., R. 30 W., where the rock is typically schistose. Fifty pounds of chip samples were composited from a series of outcrops occurring in the vicinity of Highway M-95 (new) approximately 1,400 feet south of the new bridge (Section 1, T. 46 N., R. 30 W.). Chemical analyses were conducted on a split portion of this composite. These data, along with a calculated norm, are tabulated in Table 22, on the following page.

It should be noted that the actual contact between the Goodrich and Michigamme was not observed. These contact relationships have been obscured by sill-like intrusives at all potential observation sites.

TABLE 22.--Chemical and Normative Composition of Michigamme Formation in Section 1, T. 46 N., R. 30 W.

Per Cent by Weight*		C.I.P.W. Norm	
SiO_2	61.44		
Al_2O_3	8.03		
Fe_2O_3	2.59	Q	33.95
FeO	15.48	C	4.28
MgO	3.13	or	9.46
CaO	1.16	ab	6.29
Na_2O	0.76	an	2.23
K_2O	1.60	hy	32.77
H_2O+	0.37	mt	3.70
TiO_2	0.55	il	1.06
P_2O_5	0.17	pr	0.44
MnO	0.12	cc	1.30
S	0.28	(molar quantities of less than 0.002 are omitted)	
CO_2**	0.59		

*Run on dry basis with H_2O^- (105°C.) = 0.34.

**Calculated on basis of total C as CO_2 (W. Pasich, Jones and Laughlin Steel Co., Negaunee, Michigan, Analyst).

Lithologic Types

Four lithologic types were recognized on the basis of limited outcrop and diamond drill core specimens. This subdivision is again in accord with dominant mineral assemblages. The basic types include quartz-grunerite schist, quartz-mica-andalusite-garnet schist, quartz-mica schist, and quartz-grunerite- stilpnomelane schist.

Quartz-grunerite schist.--Quartzose schists rich in grunerite were found throughout the southern portion of the trough. These rocks commonly contain varying quantities and combinations of biotite, garnet and hornblende as major constituents. The aforementioned exposures in Section 1, T. 46 N., R. 30 W., and Section 6, T. 46 N., R. 29 W., typify this rock type. These schists are well banded, reflecting compositional variations, particularly in the quartz and iron silicate ratios. The bands are generally extremely contorted and often discontinuous along strike.

Miscroscopically quartz occurs in two habits in most specimens. These consist of a coarse and fine fraction measuring 0.6 mm and 0.1 mm across diameters. In a few samples a relatively equigranular habit was noted. These average approximately 0.2 mm. Grunerite crystals measuring up to several millimeters in length are common. Surface alteration to a hydrated iron oxide was noted locally. Polysynthetic twinning is very prevalent. Interference figures revealed a very large 2V (80-90°). The majority of the crystals appear to be optically negative, although the existence of subordinate cummingtonite cannot be precluded. Garnet was found in all but one outcrop area. It frequently occurs as coarse euhedral poikiloblasts over 2.0 mm in diameter. Iron silicates and quartz are common inclusions. Chloritization is rare and limited to fracturs and peripheral areas. Biotite is a common constituent in all assemblages except those containing hornblende. This restriction is further considered in a following section. The biotite is normally olive green to pale yellow brown. It is generally fresh, although minor chloritization was observed locally. A blue to pale green amphiobole, thought to be hornblende, is present in one outcrop area. It is frequently intergrown with grunerite. Extinction angles on longitudinal sections are in the range of 20 degrees. The optic sign is negative with a moderate 2V. A limited quantity of plagioclase is present in a few specimens. Extinction angle measurements on albite twins suggest a composition near andesine. Precise determination was not possible due to the sparce occurrence.

Modal analyses of specimens from four outcrop areas are tabulated in Table 23. Figure 46 illustrates the relationship between amphiboles.

Quartz-mica-andalusite-garnet schist.--A few scattered outcrops of micaceous schist with quartz, andalusite, garnet and chlorite were found in the northern extremity of the trough. This rock is very similar to the aforementioned schist occurring between Lake Michigamme and the Republic Trough. A noteworthy exception is the absence of saturolite.

The rock is typically grayish brown and characterized by large andalusite crystals, up to several centimeters across, in a micaceous groundmass. On weathered surfaces a knobby appearance is made conspicuous by the more resistant andalusite crystals.

In thin section quartz appears equigranular averaging 0.2 mm in diameter. Andalusite is typically poikiloblastic with numerous inclusions of muscovite and biotite. Seritization of the andalusite is only locally pronounced. Biotite also occurs as subparallel plates throughout the rock. It is pleochroic from brown to nearly colorless and frequently contains clouded centers which may well represent carbonaceous matter. Fresh garnet crystals up to 2.0 cm can be observed truncating all surrounding minerals. A chlorite mineral is generally found in the vicinity of the garnet. However, it occurs as a distinct phase and not as a product of secondary garnet alteration. There is no petrographic evidence to suggest that these two minerals are not coexisting in equilibrium. The chlorite exhibits abnormal blue to brown interference colors and is optically negative. This indicates an intermediate variety (Albee, 1962) relative to the FeO : MgO ratio.

Figure 47 illustrates a microscopic view of the rock type. An average modal analysis of the limited specimens is presented in Table 24.

Quartz-mica schist.--Intensely foliated rocks consisting almost entirely of quartz, biotite and muscovite are common throughout the formation. These occur most frequently near the Goodrich contact. The rock accounts for some 70 feet of stratigraphic thickness in Section 20, T. 47 N., R. 30 W.

Microscopically the quartz appears remarkably uniform in size (0.20 mm) and exhibits little evidence of shearing in spite of the highly foliated nature of the rock. Biotite is brown and exhibits a pronounced preferred orientation. Likewise, muscovite is well oriented. Some biotite has a clouded appearance. This seems fairly typical of the formation in the northern sector of the trough. It is undoubtedly caused by some form of carbonaceous matter. This would reflect some error in Table 21 wherein an analysis for total carbon was all calculated as carbon dioxide.

A typical mode of the rock type is tabulated in Table 25.

Quartz-grunerite-stilpnomelane schist.--A quartzose schist with coexisting grunerite and stilpnomelane was found to occur in the northern half of Section 20, T. 47 N., R. 30 W. The rock type was not observed in outcrop and samples are limited to a single drill core. It is believed to represent a portion of the aforementioned iron rich member of the Michigamme. The specimens are greenish brown and crudely banded with alternating layers rich in iron silicates and quartz.

In thin section the quartz has a more clastic appearance than the typied recrystallized chert of the Negaunee iron-formation. Some clouded grains are present but to a much lesser degree. The grains are relatively equidimensional averaging 0.30 mm across diameters. A colorless to very pale green amphibole was identified as grunerite. The mineral has a more frayed appearance than the grunerite observed elsewhere. However, polysynthetic twinning is conspicuous and the birefringence is relatively high. Interference figures relate a very large 2V with a negative sign. These figures, as well as the mode of occurrence, strongly suggest grunerite. Hesitation stems from the pale green coloration of some crystals, although this feature is not entirely absent in the grunerites of the Negaunee. Yellow brown stilpnomelane was found to occur predominantly in the gruneritic rich bands. Several examples of fibers up to several millimeters in length were noted. The mineral exhibits marked pleochroism from yellow to yellow brown. Basal plates reveal a nearly uniaxial figure with a negative sign. A typical occurrence is as radiating plates from a micaceous mass. The mineral is relatively fresh and appears to cut across crystals of grunerite.

In addition to the above mentioned constituents, apatite was found in noteworthy quantity. Clusters of grains are concentrated mostly in individual bands. These are usually closely associated with magnetite.

Figure 48 relates a microscopic view of the rock type. An average modal analysis is given in Table 26. Cursory polished section study of the opaque minerals reveal this to be mostly magnetite. Hematite was also noted along the grain boundaries of quartz. Additional opaques include pyrite, chalcopyrite and possibly pyrrhotite.

MODAL ANALYSES OF VARIOUS LITHOLOGIC TYPES FROM THE MICHIGAMME FORMATION

TABLE 23 *Average modes from four outcrop areas of quartz-grunerite schist.*

MINERAL	PERCENT VOLUME			
Quartz	27	61	42	36
Grunerite*	35	7	28	19
Hornblende	—	—	—	12
Garnet	19	—	20	28
Biotite	18	30	9	—
Plagioclase	—	1	—	3
Opaques	1	X	X	2

* possibly includes cummingtonite.

TABLE 24 *Mode of typical quartz-mica-andalusite-garnet schist.*

MINERAL	PERCENT VOLUME
Quartz	19
Muscovite	9
Andalusite	28
Chlorite	3
Biotite	32
Garnet	6
Carbonate(s)	2
Opaques	X

(s) alteration product.

TABLE 25 *Modal analysis of quartz-mica schist.*

MINERAL	PERCENT VOLUME
Quartz	53
Biotite	36
Muscovite	8
Opaques	3

TABLE 26 *Average mode of quartz-grunerite-stilpnomelane schist.*

MINERAL	PERCENT VOLUME
Quartz	33
Grunerite	38
Stilpnomelane	11
Apatite	3
Opaques	15

X less than one percent but frequently observed.

Figures 46 through 48.--Photomicrographs of Rocks from the Michigamme Formation.

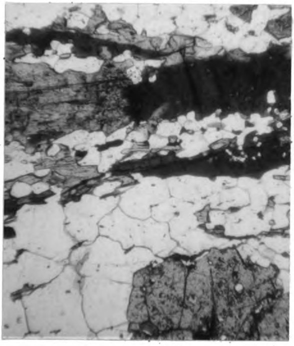


Figure 46

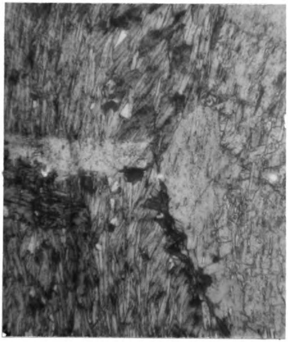


Figure 47

Figure 48

46.--Quartz-grunerite schist.--Assemblage of quartz-grunerite-hornblende-garnet. Note intergrowth of two amphiboles. Presence of darker (hornblende?) restricts formation of biotite.

47.--Quartz-mica-andalusite-garnet schist.--Large andalusite poikiloblast truncating biotite rich matrix. Note chlorite (left center) and light muscovite plate.

48.--Quartz-grunerite-stilpnomelane schist.--Stelpnomelane porphynoblast in matrix of fine grunerite and quartz.

NOTE: All figures, ordinary light, x52.

CHAPTER VII

AMPHIBOLITES

General Information

The entire Republic Trough area is marked by abundant quantities of greenish black rocks rich in amphibole. In part these include the so-called diorites of Brooks (1873). They occur predominantly as large sill-like masses; however, there are instances where adjacent beds are transected (see below). These rocks were observed within or adjacent to all the formations of the trough, including the basement complex. For the purposes of this study they have been grouped in their entirety as amphibolites. The term amphibolite is used here to designate lithologies rich in amphibole that occur as a distinctive unit. It does not include those stratigraphic members that can be clearly associated to a phase of any of the previously described metasediments. The amphibolites being considered are for the most part of magmatic parent. Evidence for this interpretation stems primarily from field observations. It was noted that in several areas the sill-like masses actually cut the adjacent bedding. Furthermore, there are examples of dikes branching from the major sills. Although chilled borders are rare they were noted in a few instances.

The actual time of the parent intrusions is undertain. Considered as a group they are certainly past early Michigamme. Also, since they all exhibit metamorphic features, they must be considered older than the major period of metamorphism. This places them somewhere between Michigamme and the end of Animikie time. The latter restriction is based on the presence of unmetamorphosed diabase dikes correlated with the Keweenawan type.

Lithologic Types

Four classes of amphibolites were observed within the trough area. These include: amphibolite (qtz. = plag. $\pm$ 10%); plagioclase amphibolites (plag. > qtz. + 10%); quartz amphibolites (qtz. > plag. + 10%); and pyroxene amphibolites. This subdivision is generally in accordance with a classification suggested by Cannon (1963). It appears to lend itself readily to field classification. Furthermore, it is especially suited for the amphibolites of the trough area in that a regional partitioning of the specific varieties is formulated.

Amphibolites.--Medium to coarse grained rocks consisting predominantly of hornblende outcrop throughout Sections 27 and 28, T. 47 N., R. 30 W. The bulk of these rocks occur immediately above the Goodrich formation. For the most part they appear conformable with adjacent formations. Thicknesses of over 350 feet are attained. In hand specimen the amphiboles appear as foliated masses in the coarser grained portions of exposures. As the grain size decreases, a more pronounced orientation becomes apparent. This feature predominates near contact areas. Locally the rock exhibits extensive alteration. This feature also occurs most frequently in proximity to contact areas.

Microscopically in the least altered specimens the hornblende is pleochroic from green (slight bluish tint) to pale brown. In specimens where alteration is more extensive the amphibole exhibits a pale green to almost colorless pleochroism. This is undoubtedly a more actinolitic variety. Breakdown of amphibole to epidote (pistacite), chlorite (penninite), and calcite is extensive in some areas. In several instances a pseudomorphic replacement was observed. Although the aforementioned alteration is most extensive along the peripheral portions of the intrusives it also occurs to a limited extent in the central sectors. However, within the interior portions alteration is generally confined to fracture zones.

Euhedral rhombic sphene is a common constituent. It is frequently associated with leucoxene and skeletal ilmenite.

Average modes of both the fresh and altered varieties are given in Table 29. Figure 49 illustrates the mineral constituents of the altered rock as it typically appears through the microscope.

Plagioclase amphibolite.--Exposures of amphibolite relatively rich in plagioclase occur extensively throughout the southern sector of the trough. The mafic sills that are present within the iron-formation at the Republic Mine (see Plate 2) typify this rock type. Exposures were also observed within the Goodrich formation. In most cases a sill-like relationships was observed. However, there are examples where the adjacent formations are definitely transected. Contact effects with surrounding rocks were not observed to any great degree. Locally garnetiferous zones are present at or near the contact planes. The rock is usually greenish black and medium grained. Occasionally it exhibits a characteristic "salt and pepper" appearance made conspicuous by the presence of light plagioclase and dark amphibole.

Channel samples were collected across the three major sills within the footwall portion of the Negaunee iron-formation at the Republic Mine. These were composited and chemically analyzed. Chemical and normative data on this composite are given in Table 27, on the following page.

In thin section the rock was found to consist predominantly of poikiloblastic hornblende. In fresh specimens this hornblende is pleochroic from bluish green to green. Unequivocal evidence for relating the amphibole to the uralitization of pyroxene could not be established. Pseudomorphs after pyroxene are absent and only limited fraying was observed along crystal boundaries. In altered samples the amphibole exhibits a green to pale green pleochroism

TABLE 27.--Chemical and Normative Composition of Phagioclase Amphibolite in Section 7, T. 46 N., R. 29 W.

Per Cent by Weight*		C.I.P.W. Norm	
SiO_2	49.20	Q	4.93
Al_2O_3	13.19	C	5.33
Fe_2O_3	3.70	or	11.69
FeO	11.51	ab	20.45
MgO	5.16	an	16.69
CaO	5.52	di	5.54
Na2O	2.44	hy	23.93
K2O	1.98	mt	5.33
H_2O+	0.43	il	5.01
TiO2	2.61	pr	0.18
P205	0.29	ap	0.67
MnO	0.19	cc	1.30
S	0.13	(molar quantities of less than 0.002 are omitted)	
CO_2**			

*Run on dry basis with H_2O^- (105°C.) = 0.27%.

**Calculated on basis of total C as CO2 (W. Pasich, Jones and Laughlin Steel Co., Negaunee, Michigan Analyst).

indicating a more actinolitic variety. This is considered a secondary product after the aforementioned hornblende. Justification for such an interpretation stems primarily from the relationship with other altered products such as plagioclase to saussurite, biotite to chlorite and ilmenite to leucoxene. In unaltered samples the plagioclase is andesine. Crystals up to one centimeter with numerous quartz inclusions were observed. Biotite is present in most specimens. When fresh it is pleochroic from dark greenish brown to pale buff. Chloritization of the biotite to varying degrees was observed locally.

The appearance of rhombic sphene crystals is characteristic of this amphibolite. Quantities up to 8 per cent of the rock volume were noted. Sphene aggregates are generally found in association with ilmenite and magnetite. These are often partially altered to leucoxene. Calcite and epidote were identified in several specimens. These represent alteration products, for the most part, with only a few restricted examples being void of observable replacement features.

Table 30 gives average modes from three localities representing relatively fresh samples and one from an intensely altered zone. Figures 50 and 51 illustrate several typical microscopic features.

Quartz amphibolites.--Amphibolites with quartz as a major constituent occur throughout the northern sector of the trough area (see Plate 1). The most prominent exposures are found in Section 20, T. 47 N., R. 30 W. In general, the rocks occur as sill-like masses and tend to pinch and swell along strike. Thicknesses of 40 to 900 feet were recorded. Along contact zones a schistose texture is prevalent while the interior portions of the sills are commonly massive.

Approximately five hundred pounds of chip samples were collected from the major amphibolite outcrops occurring above the Negaunee iron-formation in Section 20, T. 47 N., R. 30 W. These samples were composited and a representative portion was analyzed. Chemical data and a calculated norm are given in Table 28.

TABLE 28.--Chemical and Normative Composition of Quartz Amphibolite in Section 20, T. 47 N., R. 30 W.

Per Cent by Weight*		C.I.P.W. Norm	
SiO_2	52.96	Q	14.24
Al_2O_3	13.89	C	1.84
Fe_2O_3	3.93	or	12.25
FeO	7.53	ab	22.03
MgO	3.16	an	15.02
CaO	3.48	hy	17.60
Na2O	2.60	mt	5.79
K2O	2.04	il	1.21
H_2O+	0.38	cc	0.80
TiO2	0.63		
P2O5	0.06	(molar quantities of less than 0.002 are omitted)	
MnO	0.14		
S	0.02		
CO_2**	0.37		

*Run on dry basis with H_2O^- (105°C.) = 0.35%.

**Calculated on basis of total C as CO2 (W. Pasich, Jones and Laughlin Steel Co., Negaunee, Michigan Analyst).

In thin section the rock is clearly distinguishable from the other amphibolites. Equigranular quartz ranging from 0.2 to 0.3 mm across diameters is a salient constituent.

The amphibole exhibits a pale green to nearly colorless pleochroism. This is considered a highly actinolitic variety of hornblende. Bluish green hornblende is conspicuously absent. The amphibole occurs as poikiloblasts over one centimeter in length with numerous quartz inclusions. Biotite is generally present although assemblages void of mica are not uncommon. When biotite is present it occurs as brown plates in subparallel orientation. Alteration to chlorite is locally conspicuous. Twinned plagioclase was observed in all specimens. Compositionally it is andesine with a somewhat smaller proportion of An molecule than that observed in the plagioclase amphibolites to the south.

It is interesting to note that sphene, which is a characteristic constituent of the amphibolites (per se) and plagioclase amphibolites, was not found in any of quartz amphibolite specimens. This may well serve as a distinguishing feature for correlation studies within this area.

Average modal analyses of assemblages with and without biotite are presented in Table 31. A typical thin section view is illustrated in Figure 52.

Pyroxene amphibolite.--Pyroxene bearing amphibolites were found within the Ajibik formation in Section 2, T. 46 N., R. 30 W. Specimens were limited to diamond drill core samples. This variety of amphibolite was not recognized in outcrop. As a result the precise mode of occurrence could not be ascertained. The rock appears to occur in a series of narrow dikes and sills ranging between 5 and 25 feet in width. It was found most frequently near the base of the Ajibik formation. Contact planes with adjacent metasediments are ill defined and a zone of respective assimilation is common. Chilled borders were not observed in hand specimen. The rock appears relatively massive and is frequently chloritized. The degree of chloritization is most prevalent along the contact zones. The least altered portions are generally coarse grained with a greenish black coloration.

In thin section the relatively fresh samples were found to consist predominantly of amphibole and pyroxene. The amphibole is green hornblende which normally exhibits frayed crystal borders. The pyroxene is optically positive with a moderate 2V and exhibits intermediate interference colors. It is believed to be diopside. Alteration at the crystal edges and along cleavage planes is very common. Plagioclase was not observed in any of the specimens. Quartz was found in very minor quantities and usually is an isolated cluster.

The altered phases generally contain considerably less amphibole and pyroxene. Muscovite and epidote appear instead as secondary products. The epidote is dominantly zoisite with subordinate pistacite. A spectacular anomalous blue interference color is exhibited by the zoisite. Partial or complete pseudomorphic replacement of pyroxene by the epidote minerals is a common feature. Muscovite occurs both as large clear plates and in fine aggregates. For the most part it is considered a product of late alteration.

Typical modal analyses of relatively fresh and extensively altered samples are given in Table 32. Specific mineral associations are illustrated in Figures 53 and 54.

Depositional Sequence of the Animikie Series

James (1954) consideres the rocks of the Animikie series as representing a normal sequence in geosynclinal development. He notes that rocks of the lower Animikie are mostly orthoquartzites (Mesnard) and carbonates (Kona). These are the common constituents that occupy miogeosynclines (Kay, 1951) representing relatively stable orogenic conditions (Cady, 1950). Rocks of the upper Animikie include mostly conglomerates, graywackes, slates and basic volcanics which are typical of eugeosynclines. The iron rich sediments are found between these lithologies. James, therefore, concludes that the iron-formations were deposited during a transitional phase in the structural evolution of the region. This would be during a period when restricted basins prevailed as a result of offshore swells.

It is virtually impossible to determine, with any degree of certainty, the original sedimentary constituents of the metasediments within the Republic Trough.

MODAL ANALYSES FROM LITHOLOGIC VARIETIES OF AMPHIBOLITE

TABLE 29 *Average modal analyses of amphibolite.*

MINERAL	PERCENT VOLUME	(altered phase)
Quartz	8	1
Biotite	8	3
Hornblende	74	42
Epidote	–	29
Calcite	–	14
Sphene	6	9
Opaques	4	2

TABLE 30 *Four typical modes of plagioclase amphibolite.*

MINERAL	PERCENT VOLUME			(altered phase)
Quartz	11	12	15	10
Plagioclase	23	25	26	29*
Biotite	15	4	6	4
Hornblende	42	47	39	46
Epidote	–	–	1	X
Calcite	–	1	1	X
Sphene	6	7	7	8
Apatite	–	–	X	–
Opaques	3	4	4	3

*Saussuritized

TABLE 31 *Modal analyses of two varieties of quartz amphibolite.*

MINERAL	PERCENT VOLUME	
Quartz	24	32
Plagioclase	12	13
Biotite	22	–
Hornblende	38	52
Opaques	4	3

TABLE 32 *Modal analyses from two phases of pyroxene amphibolite.*

MINERAL	PERCENT VOLUME	(altered phase)
Quartz	3	4
Muscovite	–	11
Hornblende	70	19
Pyroxene	24	16
Epidote	–	48
Opaques	3	2

X less than one percent but frequently observed.

Figures 49 through 51.--Photomicrographs of Various Phases of Amphibolite.

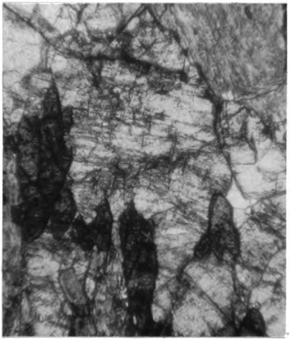


Figure 49

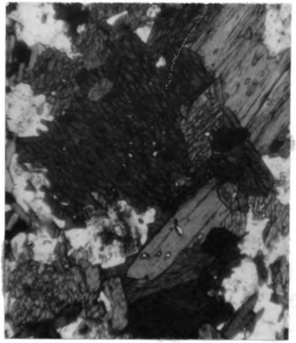


Figure 50

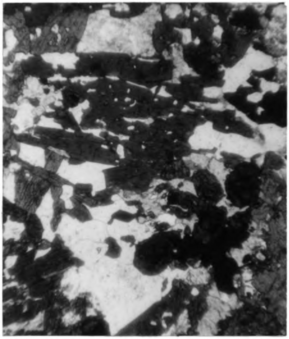


Figure 51

49.--Amphibolite.--Highly altered phase consisting of abundant epidote and rhombic sphene crystals.

50.--Plagioclase Amphibolite.--Unaltered variety showing hornblende, biotite, quartz and plagioclase.

51.--Plagioclase Amphibolite.--Hornblende-plagioclase-quartz-sphene assemblage. Note slightly altered plagioclase (upper center) and typical sphene (center.

NOTE: All figures, ordinary light, x52.

Figures 52 through 54.--Photomicrographs of Various Phases of Amphibolite.

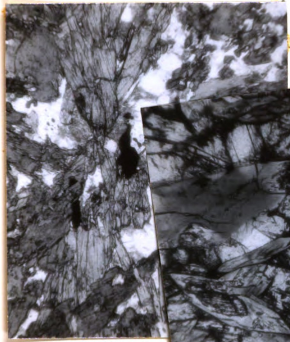
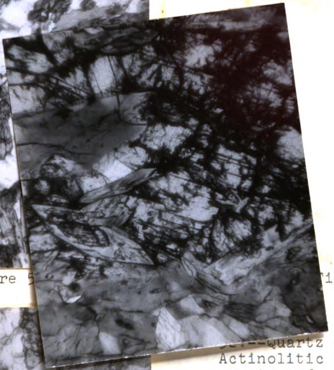


Figure 5



igure 53

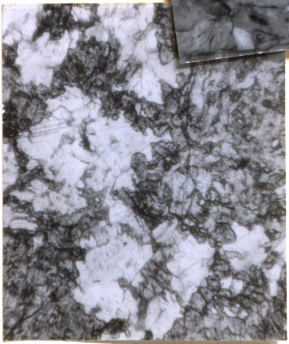


Figure 54

--Quartz amphibolite.--
Actinolitic hornblende with quartz and plagioclase (center, showing partial alteration).

53.--Pyroxene amphibolite.--
Large pyroxene (diopside) crystal surrounded with hornblende.

54.--Pyroxene amphibolite.--
Altered phase showing nearly complete replacement by epidote (pistacite and zoisite) and muscovite.

NOTE: All figures, ordinary light, x52.

Figures 52 through 54.--Photomicrographs of Various Phases of Amphibolite

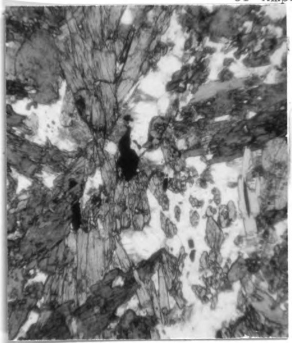


Figure 52

Figure 53

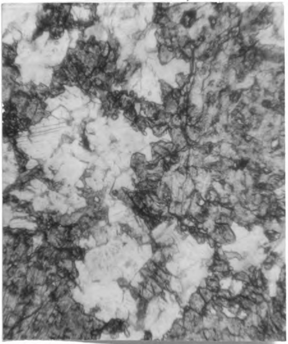


Figure 54

52.--Quartz amphibolite.--Actinolitic hornblende with quartz and plagioclase (center, showing partial alteration).

53.--Pyroxene amphibolite.--Large pyroxene (diopside) crystal surrounded with hornblende.

54.--Pyroxene amphibolite.--Altered phase showing nearly complete replacement by epidote (pistacite and zoisite) and muscovite.

NOTE: All figures, ordinary light, x52.

Recrystallization has obliterated nearly all evidence of pre-metamorphic characteristics. It would be presumptuous to correlate the present lithologies with the classes of sedimentary rock that are normally utilized. However, certain generalizations can be made on the basis of average compositions if one assumes little or no transfer of matter during metamorphism.

Representatives of the lower Animikie series are absent or completely masked throughout the trough area. The oldest clearly discernible metasediments are represented by the Ajibik which includes a variety of lithologic types. Compositions corrleative with carbonates or orthoquartzites are exceedingly rare. There is evidence in the upper portions of the Ajibik for a gradual transition from clastic to chemical sedimentation. The increasing quantity of recrystallized chert is the principal indicator. However, the major lithology appears to be more nearly of the subgraywacke type. This is also indicated on the basis of the average chemical composition (see Table 2) which satisfies most criteria set forth by Pettijohn (1963). The alumina is high (11.87%) and K_2O is substantially in excess of Ha_2O (2.69 : 0.50). However, ferric iron does not exceed ferrous and the CaO is somewhat lower than the analyses reported by Pettijohn (1963). Therefore the rock was probably on the proquartzite end of the subgraywacke type. This is further indicated by a relatively high SiO_2 content (76.54%).

The base of the Goodrich is characterized by the local development of extensive conglomerate. This corresponds with the pattern of structural evolution suggested by James (1954) for the period after deposition of iron rich beds. Many of the rock types within the Goodrich could have been of a graywacke parent. Feldspar appears to be a more common constituent than was noted in the Ajibik. Chemically the average Goodrich (see Table 14) is very similar to the average analyses of graywackes given by Pettijohn (1963). The criteria of high alumina and MgO, and excess ferrous over ferric iron are adequately satisfied. Pettijohn points out than an excess of Na_2O over K_2O is the most characteristic feature of most graywackes. Although the Na_2O/K_2O ratio (2.61 : 2.68) is slightly less than one (Table 14) it is substantially greater than any other metasediments of the trough area..

Limited exposures of Michigamme formation seriously impede interpretations relative to the parent sedimentary constituents. The rock type occurring in the south sector is highly ferruginous (see Table 22) and may represent in part a period of iron deposition during the lower part of the upper Animikie. However, the common occurrence of mica schist suggests that a variety of shale was the dominant sedimentary parent. The Na_2O/K_2O ratios (Tables 21 and 22) are substantially less than one for occurrences in both the north and south sectors. Furthermore, the composition of the Michigamme in the north sector is similar to the Pre-cambrian slates reported by Nanz (1953).

The occurrence of amphibolites, which were probably intruded during late or post-Michigamme time, seems to correspond with the volcanic activity characteristic of eugeosynclines. Therefore, the rocks of the trough area appear to generally correspond with the geosynclinal development suggested by James (1954).

Diabase Dikes (Keweenawan?)

Numerous diabase dikes were observed throughout all the formations of the trough area. No attempt was made to include these as a mappable unit in that they seldom attain thickness in excess of 10 feet. The dikes are generally fresh. They normally trend N. 65-85° East with a nearly vertical dip. Contacts with adjacent formations are sharp, and chilled zones within the intrusive are not uncommon. The age of these dikes is uncertain. However, due to the absence of either deformational or metamorphic features they are certainly post Michigamme. Diabase dikes of similar description have been reported as Keweenawan and, therefore, this age is assumed.

In thin section the rock exhibits a typical diabase texture of lath-shaped plagioclase with interstitial pyroxene. The plagioclase was identified as labradorite with a composition near An_{54}. This is based on extinction angle measurements of combined Carlsbad and albite twins. Minor zoning of plagioclase crystals was noted in several sections. The pyroxene is augite with an estimated 2V of 60°.

Modal analyses for four thin sections indicate a rock volume consisting of 45% pyroxene, 47% plagioclase, and 8% opaques. Microscopic features are illustrated in Figure 55.

Photomicrograph of Keweenawn (?) Dike

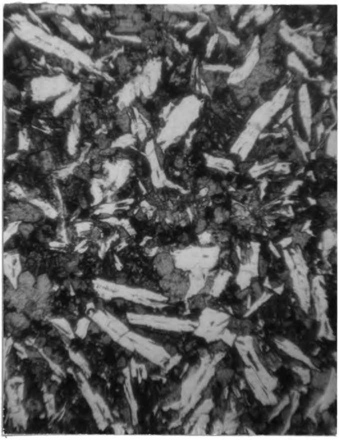


Figure 55.--Diabase Dike.--Lath-shaped plagioclase (An_{54}) with interstitial pyroxene (augite).

NOTE: Ordinary light, x52.

CHAPTER VIII

METAMORPHISM

Previous Investigations

Metamorphic effects on the rocks of the Marquette synclinorium have been recognized for some time. Reports such as those by Brooks (1873); VanHise, et al. (1897); Richarz (1927); and Snelgrove, et al. (1943) encompass notations relative to specific occurrences within the Republic Trough. However, these studies were not directly concerned with systematically subdividing regions in accordance with metamorphic gradients.

Lamey (1934) was one of the first to consider progressive transitions within mineral assemblages of the Republic Trough. He attributed these changes to contact metamorphism resulting from the intrusion of post-Animikie granites. However, since then, Lamey has concurred with James (1958) that the so-called "Republic granite" is for the most part of pre-Animikie age as originally postulated by VanHise, et al. (1897). This would then preclude any major development of contact metamorphic aureoles and the interpretations must therefore be disregarded.

The most comprehensive study of the varying degrees of regional metamorphism in northern Michigan was conducted by James (1955). He describes a pattern of metamorphic gradients over an area which includes the Republic Trough. James concludes that the entire trough area, as delineated in this study, is within the sillimanite zone. He states (James, 155, p. 1461):

> Delineation of a sillimanite zone in the Republic district is based chiefly on features shown by the iron formation, and at best the position of the isograd is highly approximate. The Michigamme slate--probably the only rock that would yield sillimanite--though not exposed is assumed to be present between Republic and the south end of Lake Michigamme, and an erratic boulder of sillimanite-bearing Michigamme slate derived from this covered area was found 7 miles west-northwest of Republic.

He attributes the presence of lower grade assemblages to widespread retrograde metamorphism. For example (James, 1955, pp. 1472-1473):

> Basic intrusives are well exposed at the town of Republic within a sillimanite zone. Green hornblende and andesine are the major constituents of the few specimens studied, but the rocks have been changed extensively by retrograde metamorphism and it is possible that some features--the color of the hornblende, for example--are now significantly different from those produced at the peak of the progressive metamorphism.

The present writer is partially in accord with the conclusions of James. There is no longer any doubt that sillimanite-bearing rocks actually occur in the area. However, data are presented in subsequent sections that indicate lesser degrees of metamorphism for much of the area. Although the influence of retrograde or later alterations is pronounced in some local zones, there are many instances where mineral assemblages do not exhibit any characteristics that are typical of these processes. In the absence of such evidence, it seems to the writer, there is no justification for regarding the various mineral phases as anything but prograde assemblages.

Bulk Chemistry

In attempting to correlate any particular mineral assemblage with respect to established metamorphic facies or zones, consideration must be given to the bulk chemistry of the host rock. Figure 56 shows the relative position of several analyzed composite samples from the Republic Trough with respect to a chemical classification of metamorphic rocks given by Fyfe, et al. (1958). The molar compositions are projected onto the Al_2O_3 + Fe_2O_3 - (Na_2O + K_2O); CaO + CO_2 - 3 (P_2O_5); MgO + FeO + MnO plane after adjusting the various oxide components for accessory minerals. This fivefold classification is somewhat arbitrary and can not be directly applied to all rock units. According to this classification five of the six analyzed samples would be termed magnesium varieties. In actuality sample #4 (Michigamme fm., S. Sector) would be more appropriately considered as ferruginous. Samples #1 (Ajibik fm.) and #3 (Michigamme fm., N. Sector) approach the pelitic field with resulting assemblages characteristic of that class. The amphibolites represented by samples #5 and #6 are most likely derivatives of basic or semibasic igneous

FIGURE 56

ACF DIAGRAM SHOWING POSITION OF ANALYZED SAMPLES RELATIVE TO CHEMICAL DIVISION OF METAMORPHIC ROCKS*

① AJIBIK FM.

② GOODRICH FM.

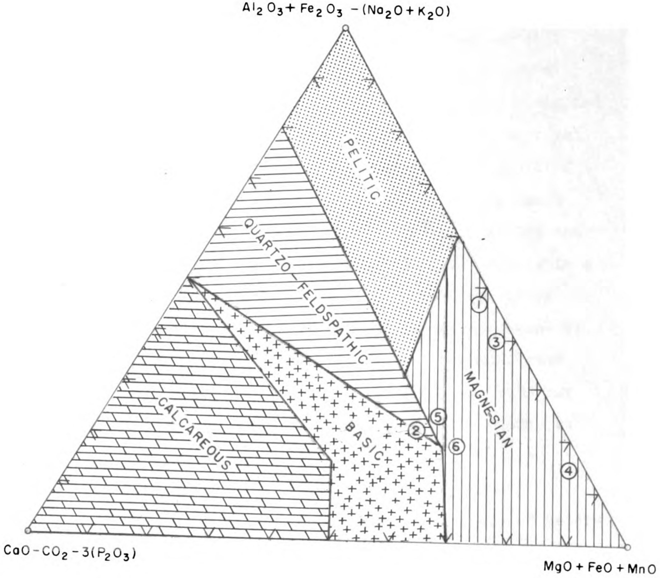
③ MICHIGAMME FM. (N. Sector)

④ MICHIGAMME FM. (S. Sector)

⑤ QTZ. AMPHIBOLITE

⑥ PLAG. AMPHIBOLITE

(POSITIONS CORRECTED FOR ACCESSORIES)



* [COMPOSITIONAL FIELDS AFTER FYFE, TURNER AND VERHOOGEN (1958)]

rocks. Sample #2 (Goodrich fm.) projects onto the join between the basic and quartzo-feldspathic fields. The writer considers the latter field as the most appropriate for the majority of rocks of the Goodrich formation.

Application of Phase Rule and Equilibria Considerations

Interpretation of various mineral assemblages must also be considered in light of equilibria conditions with respect to thermodynamic principles. The classic approach to this problem has been to evaluate the various mineral phases with regard to the restrictions imposed by Gibbs phase rule. Although the phase rule is being widely applied by metamorphic petrologists it must be considered in light of some sweeping assumptions. These are best realized if the underlying principles in the derivation of the phase rule are reviewed. Although this derivation is seldom considered in geologic literature it is admirably treated in a publicaton on the scientific papers of J. Willard Gibbs (1961) and by Glasstone (1947). It is beyong the scope of this present study precisely to define all the functions that are employed in the derivation of the phase rule but it is considered worthy of a brief review. The reader is referred to the aforementioned discussions for a more thorough treatment.

A basic requirement for equilibrium in a closed heterogeneous system at a specified temperature and pressure (equal at all phases) is that the Gibbs free energy (F) be at a minimum. If this were not the case a spontaneous process would occur in such a manner as to decrease the total free energy of the system.

$$dF_{t,p} > 0$$

Therefore, a closed system at equilibrium must have:

$dF_{t,p} = 0$ (reversible processes)

The differential Gibbs free energy for an open system may be expressed as follows:

$$dF = -SdT + VdP + \Sigma\mu_i dn_i$$

where S is the entropy, V the volume, T the absolute temperature, μ the chemical potential of each component in each phase, and n the molar concentration of each component of the system. At constant temperature and pressure this expression reduces to:

$$dF_{t,p} + \Sigma\mu_i dn_i$$

In order to apply the aforementioned conditions of equilibrium we must first close our system in the sense of its entirety. However, this does not preclude the exchange of matter throughout the various phases of that system. The requirement for equilibrium would then be:

$$dF_{t,p} \text{ (entire system)} = 0$$

and therefore,

$$\Sigma\mu_i dn_i = 0$$

That is for a closed system of a,b,...P phases and 1,2,3...C components in equilibrium the condition:

$$\begin{array}{llllll}
\text{phase (a)} & \mu_1 dn_1 & + \mu_2 dn_2 & + \ldots & + \mu_c dn_c & \\
\vdots & & & & & \\
\text{phase (b)} & \cdot & \cdot & & \cdot & \\
\vdots & \vdots & \vdots & & \vdots & \\
\text{phase (P)} & \mu_1 dn_1 & + \mu_2 dn_2 & + \ldots & + \mu_c dn_c & = 0
\end{array}$$

must hold. If the system as a whole is closed then the total quantity of each component must remain unchanged and hence the summation of dn_1 over phases a, b, ..., P totals zero. Likewise, summation of other components over all phases must also equal zero. If these conditions are met it would require that the chemical potential of individual components must be equal throughout all phases.

$$\begin{array}{ll}
\text{component 1} & \mu_a = \mu_b = \ldots. = \mu_p \\
\text{and} & \\
\vdots & \\
\text{component C} & \mu_a = \mu_b = \ldots = \mu_p
\end{array}$$

This equivalency of chemical potentials for a particular component throughout all phases at equilibrium is an essential feature of the Gibbs phase rule. The rule establishes the number of variables that must be fixed completely to define a closed system of C components and P phases in equilibrium. Such a system would have C-1 possible concentrations for each phase or P(C-1) variables over all phases. In addition the temperature and pressure must be specified. However, the equivalency of chemical potentials of a component in all phases reduces the number of variables that require definition by C(P-1). This actually fixes this number of separate equations. The remaining number of variables (f) that must be known precisely to define the system is now:

$$f = C - P + 2$$

This equation further shows that for any set number of components the phases that can coexist in equilibrium will be at a maximum if f is equal to zero. Furthermore, at a specified T and P these phases would be equal to, or less than, the total number of components. This is generally known as Goldschmidt's mineralogical phase rule.

The components of a rock system can normally be expressed in terms of its major oxide constituents. These most frequently include: SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, MnO, FeO, TiO_2, P_2O_5, K_2O, Na_2O, SO_2, CO_2, and H_2O. If a particular rock contained all these components it would be possible to have 14 phases coexisting in equilibrium. However, in the usual case, accessory minerals and opaques are not considered as indicator minerals with respect to regional metamorphism. If these phases are excluded the number of components must also be reduced in instances where a particular oxide is known to exist only within that mineral. Examples of this would be P_2O_5 in apatite or S in sulfides. The number of components may be further reduced if there are any oxides that appear in excess in a relatively pure state. Within the trough area quartz would fit these circumstances. Thompson (1957) also presents arguments for considering H_2O as a mobile component. He points out that H_2O should then be considered as an intensive variable like P and T which are externally controlled. That is, the chemical potential of H_2O would be the only defining characteristic.

Table 33 lists all the major prograde assemblages that were observed in the trough area excluding those of the Negaunee iron formation. Opaque phases are not included and accessory minerals are tabulated only in instances where they account for over one per cent of the rock volume. In the case of all the two, three, and four phase assemblages the numbers of phases are clearly less than those permitted by the phase rule. The five and six phase assemblages all appear to conform with the phase rule limitations with $P \geq C$. The seven phase assemblage can be explained by considering SiO_2, K_2O, Al_2O_3, FeO, MgO, CaO, and TiO_2 as the essential components. The appearance of plagioclase in the eight phase assemblage would permit one more phase as a result of Na_2O. Therefore, it appears that there is no violation of the phase rule restrictions and every assemblage can be considered as representing equilibrium conditions unless contrary evidence is noted on the basis of petrographic observations. It should be noted that these conditions are met without appealing to stabilizing oxides such as MnO, Fe_2O_3, ZrO_2, etc.

Table 33.--Summary of Prograde Mineral Assemblages within Metasediments* and Amphibolites.

<u>Two Phases</u>:

qtz.-musc.

<u>Three Phases</u>:

qtz.-gar.-grun.
" -epi.-horn.
" -gar.-bio.
" -musc.-bio.
" -plag.-horn.
" -horn.-pyr.
" -grun.-stilp.

<u>Four Phases</u>:

qtz.-bio.-(and.-sill.)-gar.
" -musc.-micr.-bio.
" -plag.-musc.-gar.
" -chl.-musc.-gar.
" -micr.-bio.-epi.
" -micr.-horn.-epi.
" -musc.-bio.-epi.
" -grun,-gar.-bio.
" -grun.-bio.-plag.
" -bio.-horn.-sp.
" -plag.-bio.-horn.

<u>Five Phases</u>:

qtz.-musc.-bio.-micr.-gar.
" -bio.-(and.-sill.)-gar.-musc.
" -plag.-musc.-gar.-cal.
" -micr.-plag.-musc.-tour.
" -micr.-plag.-musc.-chl.
" -micr.-plag.-musc.-bio.
" -micr.-bio.-horn.-epi.
" -micr.-musc.-bio.-epi.
" -micr.-plag.-horn.-epi.
" -bio.-horn.-epi.-sp.
" -grun.-horn.-gar.-plag.
" -plag.-bio.-horn.-sp.

<u>Six Phases</u>:

qtz.-micr.-bio.-horn.-epi.-sp.
" -micr.-musc.-bio.-epi.-cal.
" -musc.-bio.-gar.-horn.-epi.
" -musc.-and.-chl.-bio.-gar.
" -plag.-bio.-horn.-epi.-sp.

<u>Seven Phases</u>:

qtz.-micr.-musc.-bio.-epi.-cal.-sp.

<u>Eight Phases</u>:

qtz.-micr.-plag.-bio.-horn.-epi.-cal.-sp.

<u>Explanation</u>

qtz. - quartz
musc. - muscovite
bio. - biotite
grun. - grunerite and/or cummingtonite
stilp. - stilpnomelane
Micr. - microline or orthoclase
plag. - plagioclase
epi. - epidote incl. zoisite
horn. - hornblende
gar. - garnet
and. - andalusite
sill. - sillimanite
chl. - chlorite
sp. - sphene
cal. - calcite
pyr. - pyroxene
tour. - tourmaline

* Negaunee iron formation excluded

NOTE: Minerals accounting for less than one per cent volume not included.
Al_2SiO_5 polymorphs treated as one phase.
Opaque minerals and apatite not considered.

Specific Mineral Occurrences and Inferred Metamorphic Reactions

The following discussion is concerned primarily with specific mineral occurrences and possible sources for their formation. Only those minerals that exhibit characteristics that may reflect upon the metamorphic history of the area are included. Various metamorphic reactions and their applicability to mineral occurrences are considered. These reactions, for the most part, are taken from the literature. Special emphasis is placed on more recent phase investigations in an attempt to correlate these data with field occurrences.

The Negaunee iron-formation is not considered as this is treated elsewhere as a separate entity.

Sillimanite.--The establishment of sillimanite schists and gneisses within indisputable bedrock merits particular note, even though it was found only to a limited areal extent. Significance of the $Al_2 SiO_5$ polymorphs relative to metamorphic zoning has been the subject of numerous studies. Classic isograds are generally delineated by the appearance of sillimanite and kyanite.

Several reactions have been proposed for the appearance of sillimanite throughout progressive metamorphism. One which is frequently considered involves the breakdown of muscovite (Turner and Verhoogen, 1960; Yoder, 1956).

Muscovite + quartz =
potash feldspar + sillimanite + vapor.

This potash feldspar-sillimanite producing reaction is normally correlated with conditions of the second (higher) sillimanite or orthoclase isograd. The requisite appearance of potash feldspar in conjunction with sillimanite was not observed within specimens from the Ajibik. Furthermore, muscovite is present in most assemblages as a coexisting phase. Therefore, conditions for this reaction were apparently never attained.

Another sillimanite producing reaction has been proposed which involves staurolite as a reactant (Turner and Verhoogen, 1951; Wykcoff, 1952).

Staurolite + quartz =
almandine + sillimanite + vapor.

This reaction is favored by James (1955) for the appearance of sillimanite in the Peavy dam rocks of southeastern Iron County, Michigan. In those rocks staurolite appears with sillimanite which would indicate a sluggish reaction or some other circumstance impeding equilibrium conditions. Although staurolite was not identified in the sillimanitic rocks of the Republic Trough, it appears to be a reasonable reactant. Staurolite schists represent an abundant phase of the Michigamme formation immediately north of the trough area. The major oxide constituents of the Ajibik schists are certainly adequate to form staurolite under proper conditions.

A second reaction involving staurolite is also believed to merit consideration.

Staurolite + muscovite =
sillimanite + biotite.

This reaction has generally been employed in reverse to account for staurolite as a retrograde product (Billings, 1937). If equilibrium conditions were attained, and the reaction proceeded from left to right during progressive metamorphism, muscovite would be consumed. However, after the depletion of staurolite, muscovite could coexist with sillimanite as a stable phase. For the most part, there is little direct evidence in thin sections as to the parentage of sillimanite. A few samples reflect an intergrowth of sillimanite blades and biotite. This relationships is illustrated in Figure 57.

In several areas pyrophyllite was observed replacing sillimanite. The replacement is frequently pseudomorphic (see Figure 58) and, therefore, considered secondary. It is interesting to note that adjacent andalusite crystals exhibit little or no alteration. The sensitivity of sillimanite to alteration suggests that andalusite was the more stable polymorph formed under the conditions that prevailed.

Andalusite.--Assemblages containing andalusite were found throughout the entire extent of the Republic Trough area. It occurs predominantly within the Ajibik and Michigamme formations. Andalusite is also found as a major constituent in the belt of Michigamme metasediments extending north of the trough area and in the Animikie series near the Humboldt Mine. This widespread occurrence certainly suggests a considerable range of stability. Therefore, it is unlikely that any specific indications relative to differential metamorphic conditions would be reflected through its occurrence within the trough area.

The aforementioned observations suggest that andalusite could initiate development during early periods of metamorphism. Growth must have continued throughout increasing thermal conditions as indicated in thin sections where andalusite porphyroblasts truncate all coexisting phases except garnet (see Figure 59).

Variations in the development of andalusite were noted. In assemblages containing chlorite it frequently appears clouded with numerous inclusions. The crystals are noticeably clearer in rocks without chlorite. This latter generalization does not preclude the presence of chlorite as an alteration product of ferromagnesium silicates.

The initial formation of andalusite presumably involved a dehydration reaction of one or more members of the montmorillonite group, diaspore or pyrophyllite. A logical reaction could proceed as follows:

Pyrophyllite =
andalusite + quartz + vapor.

Chlorite.--Varying quantities of chlorite were observed throughout most of the metasediments. A great majority of this chlorite, which is commonly penninite, can be clearly attributed to retrograde or later alterations. In many cases host minerals such as garnet, biotite, and amphibole can be readily distinguished. However, in two localities, metacrysts of chlorite were found that appear to be stable products of progressive metamorphism. One such area is within the Ajibik formation of the south sector along the northeast limb. In this instance, chlorite is in coexistence with muscovite, quartz, and garnet. The garnet is essentially free of any chloritization. Chlorite is present as distinctive metacrysts with no indications of any replacement features. Iron oxides are the only inclusions. The chlorite commonly exhibits abnormal brown interference colors and is optically positive. This is in contrast to the abnormal blue and violet colors exhibited by the chlorites elsewhere. According to Albee (1962) this would be an indication of a magnesium rich variety with a composition in the range of $Sp_{40}\ At_{60}$ where:

$$Sp = Fe_4\ Al_2 \cdot Al_2\ Si_2\ O_{10}\ (OH)_1 \text{ and}$$
$$At = Mg_4\ Al_2 \cdot Al_2\ Si_2\ O_{10}\ (OH)_8.$$

Chlorites have generally been considered an indicator of low temperature metamorphism. However, recent laboratory studies have indicated a greater range of stability for certain chlorites (Nelson and Roy, 1958; Turnock, 1960). A reaction that explains the prevalence of chlorite during more intense metamorphism has been suggested by Atherton (1964).

$$\text{Chlorite}_{(a)} + \text{quartz} = \text{garnet} + \text{chlorite}_{(b)}.$$

$\text{Chlorite}_{(b)}$ would have a higher MgO/FeO ratio than $\text{chlorite}_{(a)}$. This applies very well to the Ajibik rocks which also contain garnet.

A second occurrence of porphyroblastic chlorite was observed within the Michigamme formation of the north sector. It was found coexisting with quartz, andalusite, biotite, garnet, and muscovite. The chlorite again appears as a stable metacryst. It commonly truncates surrounding biotite but is cut by andalusite and garnet (see Figure 60). In this case the interference colors are in part abnormally blue and the optic sign is negative. Thus, according to Albee (1962) this would represent a chlorite of approximate $Sp_{60}\ At_{40}$ composition. Therefore, the aforementioned reaction would not apply and one must appeal to a chamosite type mineral for initial chlorite development. However, this does not preclude the possibility of continuing transitions and extended stabilities throughout increasing temperatures. For example, Nelson and Roy (1958) have demonstrated in the laboratory that normal chlorite structure in the presence of high water pressures is stable up to approximately 700° C. and 1000 atmospheres pressure. Extreme conditions such as this are not postulated but merely noted to emphasize the greater possible range of stability for chlorites during progressive metamorphism.

Biotite.--Various members occur throughout many of the rocks within the trough area. As in the case of chlorite there is little direct evidence as to their parentage prior to initial stages of transformation. However, certain petrographic observations provide clues relative to logical reactants involved in their formation.

There are numerous examples of an intimate association between biotite and muscovite. This suggests, in part, a similar mechanism for the formation of both minrals. Halferdahl (1961) has proposed such a reaction:

Glauconite + daphnite =
muscovite + biotite + vapor.

The above reaction would mark the incipent growth of biotite. In light of the variable bulk chemistry of the rock types it is unlikely that any single reaction could account for all biotite. For example, in rocks with a relatively high lime content there appears to be an interrelationship between biotite and epidote as well (see Figure 61). The writer found no precedent for a reaction producing a biotite-epidote assemblage during progressive metamorphism. However, a feasible choice of reactants and products might be:

Glauconite + calcite $\pm$ (chlorite) =
biotite + epidote + carbon dioxide + vapor $\pm$ (muscovite).

There are strong indications that a third reaction was also active locally. In several thin sections of Ajibik schist, where biotite and garnet coexist, there is a noticeable variation in the color of biotite. The biotite of these rocks is normally greenish brown but it becomes noticeably browner in the vicinity of garnet. This color variation is apparent within a surrounding area of approximately 5 millimeters. One way to explain such a color variation would be through a reaction proposed by Atherton (1964):

$$\text{Chlorite} + \text{biotite}_{(a)} + \text{quartz} = \text{garnet} + \text{biotite}_{(b)} + \text{vapor.}$$

In the event that the garnet is almanditic, $\text{biotite}_{(b)}$ would have a higher magnesia content than $\text{biotite}_{(a)}$. This, in turn, should reflect in a more brownish coloration (Hall, 1941).

Several writers have attempted to utilize variations in the color of biotite as an indicator of metamorphic grade (Tilley, 1925; Harker, 1932; Engle and Engle, 1960). Most have agreed that transitions are from greenish black or greenish brown to brown to reddish brown with increasing grade of metamorphism. These color changes are directly related to variations in the molecular proportions of FeO, MgO, and TiO_2. Within the trough area minor color changes were noted. However, these are limited to the range of greenish black to greenish brown to brown. Attempts to delineate a "colorgrad" (Engle and Engle, 1960) on the basis of characteristic colors prcvded fruitless.

Garnet.--Poikiloblastic garnet is a rather common constituent of the rock types within this region. Chemical data on these garnets is not available although they are believed to be almanditic. Heavy liquid separations on several local occurrences resulted in a garnet "sink" at 4.15 gravity. Furthermore, the refractive index is known to exceed 1.80. However, it should be emphasized that the aforementioned determinations were made on limited samples and may not be representative of all the garnets.

A number of garnet producing reactions have been considered in previous discussions. These include:

Staurolite + quartz =
almandine + sillimanite + vapor

$\text{Chlorite}_{(a)}$ + quartz =
garnet + $\text{chlorite}_{(b)}$

Chlorite + $\text{biotite}_{(a)}$ + quartz =
garnet + $\text{biotite}_{(b)}$ + water.

These reactions could account for the majority of garnet on the basis of coexisting products. In assemblages devoid of sillimanite, chlorite or biotite, garnet is generally found with combinations of plagioclase, amphibole, and muscovite.

Halferdahl (1961) has proposed reactions, based on his experimental work, which seem very appropriate for the rocks of the Michigamme formation where garnet is found with grunerite.

Ferrostilpnomelane + iron chlorite =
grunerite + almandine + vapor

Ferrostilpnomelane =
grunerite + almandine + quartz + vapor.

Occurrences of stilpnomelane were established within the Michigamme formation in the north sector. The rocks also contain grunerite but in what appears to be early stages of development. These features are discussed further with relation to the overall metamorphic zoning of the area.

Garnet may also form at the expense of muscovite and biotite according to a reaction given by Ramberg (1952).

Biotite + muscovite + quartz =
potash feldspar + almandine + water.

However, with one exception the coexistence of garent and potash feldspar was not observed. Plagioclase is normally the only feldspar found with garnet. In the one exception, a minor cluster of garnet was observed in a rock containing microcline. The garnet accounted for only one per cent of the rock volume and was not observed in contact with microcline. Because of the extreme localized nature of this assemblage, it is not considered as evidence for the above reaction. It is, therefore, doubtful if this reaction ever attained significant magnitude to be considered as a source of garnet within the trough area.

In rocks of a simple chlorite-quartz parentage, almandine may also form directly from chlorite according to the classic reaction

Iron chlorite + quartz =
almandine + vapor.

Evidence for this reaction (left to right) is lacking. However, there are numerous examples of the reverse (right to left) which can be correlated with retrograde or later alterations.

Epidote.--A number of lithologic types from the Goodrich formation contain substantial quantities of the epidote minerals. They are also found locally within the Ajibik formation and the various amphibolites. However, in these later examples their occurrence might be associated with retrograde metamorphism. Pseudomorphic and peripheral replacement of amphibole are common sources. The epidote minerals thus formed are frequently associated with calcite and sphene. This is a feature common to many regions and is generally attributed to the release of calcium ions during retrograde metamorphism which are then fixed in mienrals such as epidote, sphene and calcite (see Figure 62).

The preponderance of epidote within the Goodrich formation is considered a direct product of progressive metamorphism. Alteration is ruled out by the presence of other minerals such as hornblende that exhibit no secondary replacement features.

Two major associations were observed for the epidote minerals of the Goodrich. One of these is with biotite which has been discussed previously in conjunction with the formation of that mineral. The second invovles muscovite and in some instances calcite. In these assemblages epidote appears to be developing at the expense of muscovite. Potash feldspar is also a common associate (see Figure 63). A reaction proposed by Yoder and Eugster (1955) fits these occurrences very well.

Muscovite + calcite + quartz =
epidote + potash feldspar + vapor + carbon dioxide.

In the event that the CO_2 pressures become high, this reaction would be retarded and calcite in part stablized. This would account for local prevalence of muscovite-calcite-potash feldspar-epidote assemblages.

Hornblende.--The major occurrence of hornblende is within the sill-like amphibolites. It is also found to a lesser extent in various lithologic types of the Ajibik, Goodrich and Michigamme formations.

Hornblendes are known to be stable over wide ranges of temperature and pressure. This span of stability often obscures any evidence as to their parentage within limited areas. They are known to form at the expense of calcic plagioclase and pyroxene in basic rocks or from the original constituents of calcareous shales. Although these are plausible sources, there is no evidence for relating the hornblendes of the trough area to constituents of this type.

The color and chemical changes within hornblendes have been utilized by several writers as an indication of metamorphic grade (Eskola, 1952; Ward, 1958; Engle and Engle, 1962). In general the lower metamorphic grades are characterized by an actinolite variety. Compton (1958) observed an abrupt change from actinolite to hornblende within the metabasaltic rocks of northern Sierra Nevada. He suggests the following reaction:

Actinolite + clorite + epidote =
hornblende + magnetite + vapor + Mg.

The rocks of the trough area locally contain actinolitic hornblende. This is found most commonly in altered phases. However, it does occur within relatively fresh samples of the quartz amphibolites from the north sector.

Engle and Engle (1962) noted a systematic change in the color of hornblende from bluish green to greenish brown to brown with increasing grade of metamorphism in the northwest Adirondacks. Color changes within the "normal" hornblendes of the trough are not marked. Within the amphibolites they are generally green to bluish green. A slightly more brownish hue was noted for the fresh hornblendes of south sector amphibolites.

There is an interesting occurrence of bluish green hornblende within the Michigamme formation (south sector). The hornblende appears intergrown with grunerite. Intergrowths such as this between the cummingtonite-grunerite and hornblende-tremolite series have been observed elsewhere (Eskola, 1950; Tilley, 1957; Asklund, et al. 1962). Speculation on these occurrences has centered mainly on proposing a miscibility gap between the two series. The aforementioned observation cannot detract or substantiate such speculation. However, a field observation is considered worthy of note. The bluish green hornblende-grunerite intergrowths were noted only in assemblages without biotite. In fact, biotite appears to restrict the occurrence of hornblende in these rocks. This does not preclude the aforementioned miscibility gap but does suggest the feasibility of relating such occurrences directly to pressure, temperature and compositional environments during metamorphism.

Stilpnomelane.--The appearance of stilpnomelane in rocks of the Michigamme formation (north sector) may well mark a critical assemblage. In these rocks it coexists with grunerite which is in an initial stage of growth as compared to the grunerites of the south sector. In thin section the stil pnomelane can be seen actually truncating the grunerite (see Figure 48). This indicates a period of formation which was comparable to, or later than, the initial development of grunerite.

Breakdown reactions of stilpnomelane have been discussed in conjunction with the development of garnet. Reactants involved in the actual growth of stilpnomelane were not defined in the field. However, the experimental work of Halferdahl (1961) provides some pertinent data relative to potential sources as reactants. The following reaction is considered especially applicable:

Minnesotaite + iron chlorite =
grunerite + ferrostilpnomelane + vapor.

Minnesotaite, as well as iron chlorites, are known to occur in outlying areas. In the absence of minnesotaite, stilpnomelane could form at the expense of chamosite and quartz in the original sediments. The latter reaction would probably initiate at a lower temperature and, therefore, be of less significance in narrowing the range of metamorphic conditions within the trough area.

Other minerals.--Previous discussions have incorproated the majority of critical minerals within the trough area. The occurrence of quartz has not been considered at any length. It is not thought to be a reliable indicator of metamorphic conditions within the area being considered. The feasibility of employing grain size distributions appears remote in light of the extreme variations noted within limited areas.

Potash and plagioclase feldspars are common constituents within many of the rock types. Systematic transitions within these minerals were not detected. However, in several assemblages their presence provides an indication as to possible limiting metamorphic conditions. This is also true in

THIN SECTION SKETCHES OF VARIOUS MINERAL OCCURRENCES

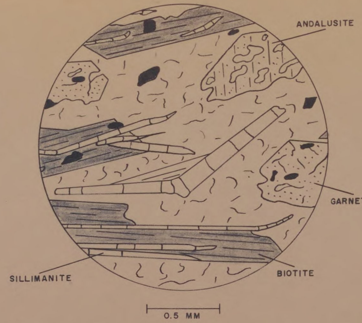


FIG. 57 QUARTZOSE SILLIMANITE SCHIST
WITH BIOTITE, GARNET, AND ANDALUSITE
NOTE CLOSE ASSOCIATION BETWEEN
BIOTITE AND SILLIMANITE

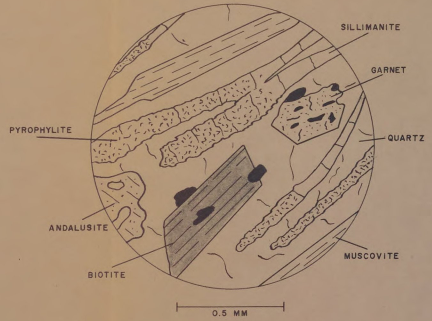


FIG. 58 PSEUDOMORPHIC ALTERATION OF
SILLIMANITE TO PYROPHYLLITE
NOTE UNALTERED ANDALUSITE
BIOTITE AND GARNET

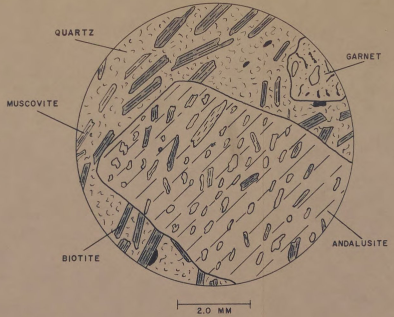


FIG. 59 POIKILOBLASTIC ANDALUSITE
WITH GARNET, BIOTITE AND MUSCOVITE
NOTE TRUNCATION OF MICAS AND QUARTZ
BY ANDALUSITE

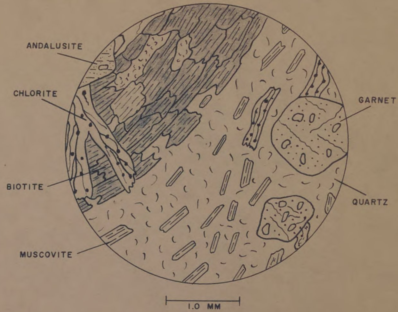


FIG. 60 CHLORITE PORPHYROBLASTS
WITH BIOTITE, GARNET, MUSCOVITE
AND ANDALUSITE
NOTE CHLORITE TRUNCATES BIOTITE
BUT IS CUT BY ANDALUSITE AND GARNET

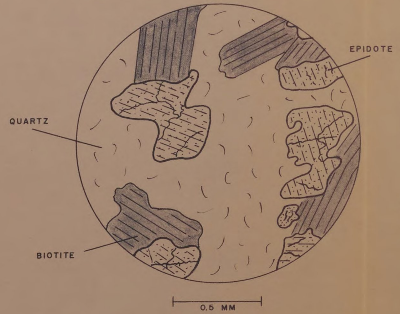


FIG. 61 FREQUENT ASSOCIATION OF BIOTITE
AND EPIDOTE INDICATING MUTUAL
MODE OF DEVELOPMENT

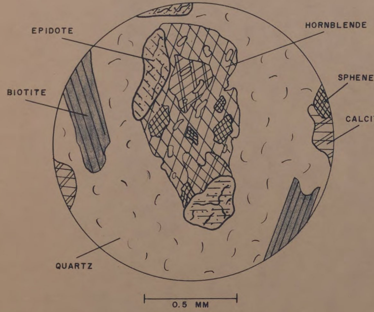


FIG. 62 POIKILOBLASTIC HORNBLENDE
BEING REPLACED BY EPIDOTE,
SPHENE AND CALCITE

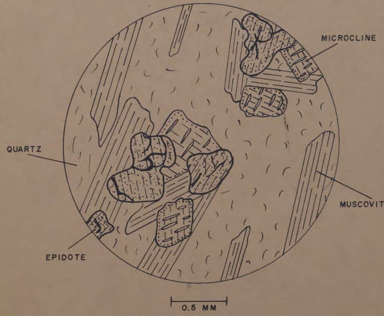


FIG. 63 QUARTZOSE SCHIST SHOWING CLOSE
ASSOCIATION OF MUSCOVITE, EPIDOTE
AND MICROCLINE
EPIDOTE AND MICROCLINE APPEAR TO
DEVELOP AT EXPENSE OF MUSCOVITE
AND CALCITE (NOT SHOWN)

the case of calcite. These circumstances will be discussed in a forthcoming section.

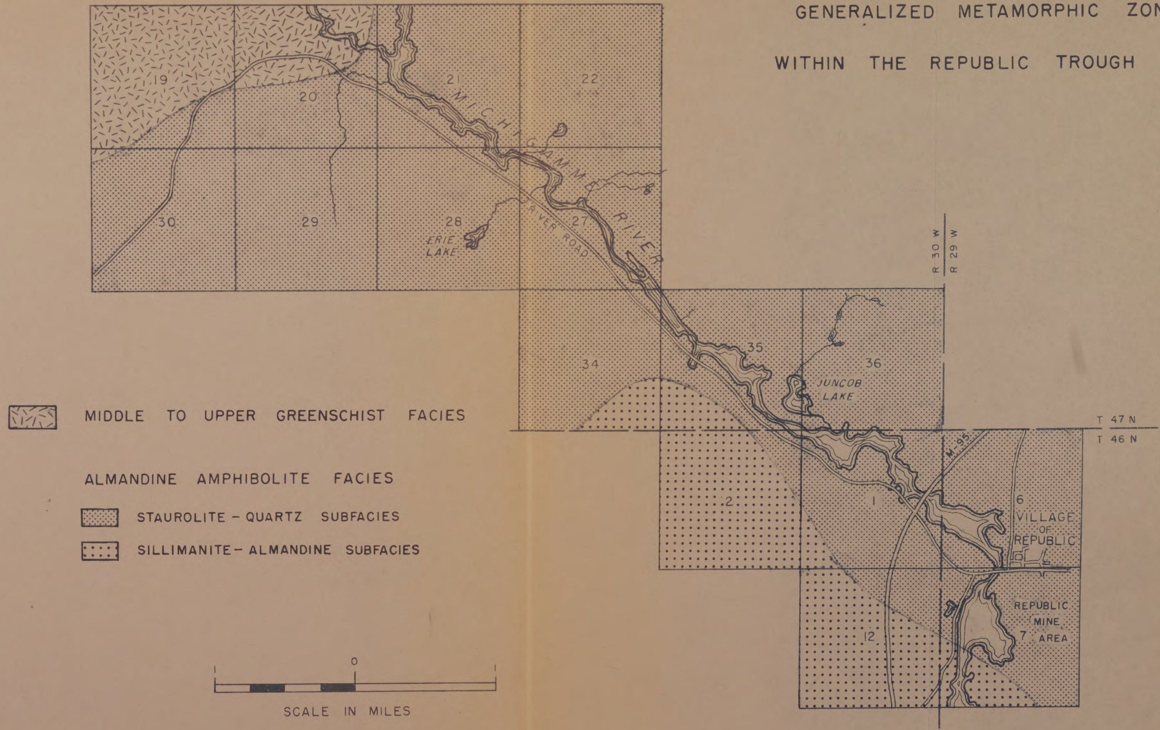
Metamorphic Zoning

The rocks of the Republic Trough do not lend themselves readily to systematic classification with respect to established metamorphic facies or isograds. Correlation is in part impeded by wide variations in the bulk chemistry of the different lithologic types. It is further complicated by retrograde and later alterations which have locally obliterated representative mineral assemblages. However, there are several "key" assemblages which appear indicative of the overall prograde metamorphic environments. These coupled with low and high temperature-pressure restrictions, as suggested by the stability of certain phases, provide a means for broad classification. At best, a framework can be constructed within which there are exceptions to established assemblages representing classic metamorphic facies. Figure 64 illustrated the proposed zones.

It should be emphasized that due to limited outcrops it is not possible to continuously trace a rock unit through a facies transition or across an inferred isograd. There transitions are based primarily on the appearance or disappearance of a critical mineral or assemblage throughout scattered outcrops.

FIGURE 64

GENERALIZED METAMORPHIC ZONING WITHIN THE REPUBLIC TROUGH AREA



Metamorphism of the Ajibik, Goodrich, and Michigamme Formations

Mineral assemblages reflecting conditions of both the greenschist and almandine amphibolite facies are present within the metasediments of the trough area. The following discussion is concerned primarily with rocks of the Ajibik, Goodrich, and Michigamme formations. Assemblages within amphibolite and the Negaunee iron-fromation are considered in detail elsewhere. However, occastional reference is made to these rock types for the sake of continuity.

Greenschist facies.--Prograde mineral assemblages of the greenschist facies were observed in limited quantity. These occurrences are restricted to the northern portion of the north sector (see Figure 64). The principal indicator is stilpnomelane which is present in rocks of the lower Michigamme formation. Adjacent metasediments are composed of minerals such as quartz, muscovite and iron rich biotite, all of which have a considerable stability range and, therefore, relate very little with respect to metamorphic grade.

The occurrence of stilpnomelane is generally considered as evidence of low grade regional metamorphism (James, 1955; Deer, 1962). Fyfe, et al. (1958) consider it only within assemblages of the lower greenschist facies; namely the quartz-albite-muscovite-chlorite subfacies. However, in light of its proximity to higher grade zones and the coexistence of grunerite, a somewhat elevated position is proposed.

This seems entirely plausible if minnesotaite were involved in the production of stilpnomelane as suggested by the experimental work of Halferdahl (1961). The appearance of stilpnomelane with grunerite is, therefore, considered equivalent to the middle (quartz-albite-epidote-biotite subfacies) or upper (quartz-albite-epidote-almandine subfacies) greenschist facies. This is based on the breakdown of minnesotaite which is a common constituent in adjacent areas representing low grade metamorphism. The assumed transition is illustrated in Figure 65. This diagram also predicts the incompatability of almandine garnet in quartzose schists containing both grunerite and stilpnomelane. Field observations are in accord with this prediction.

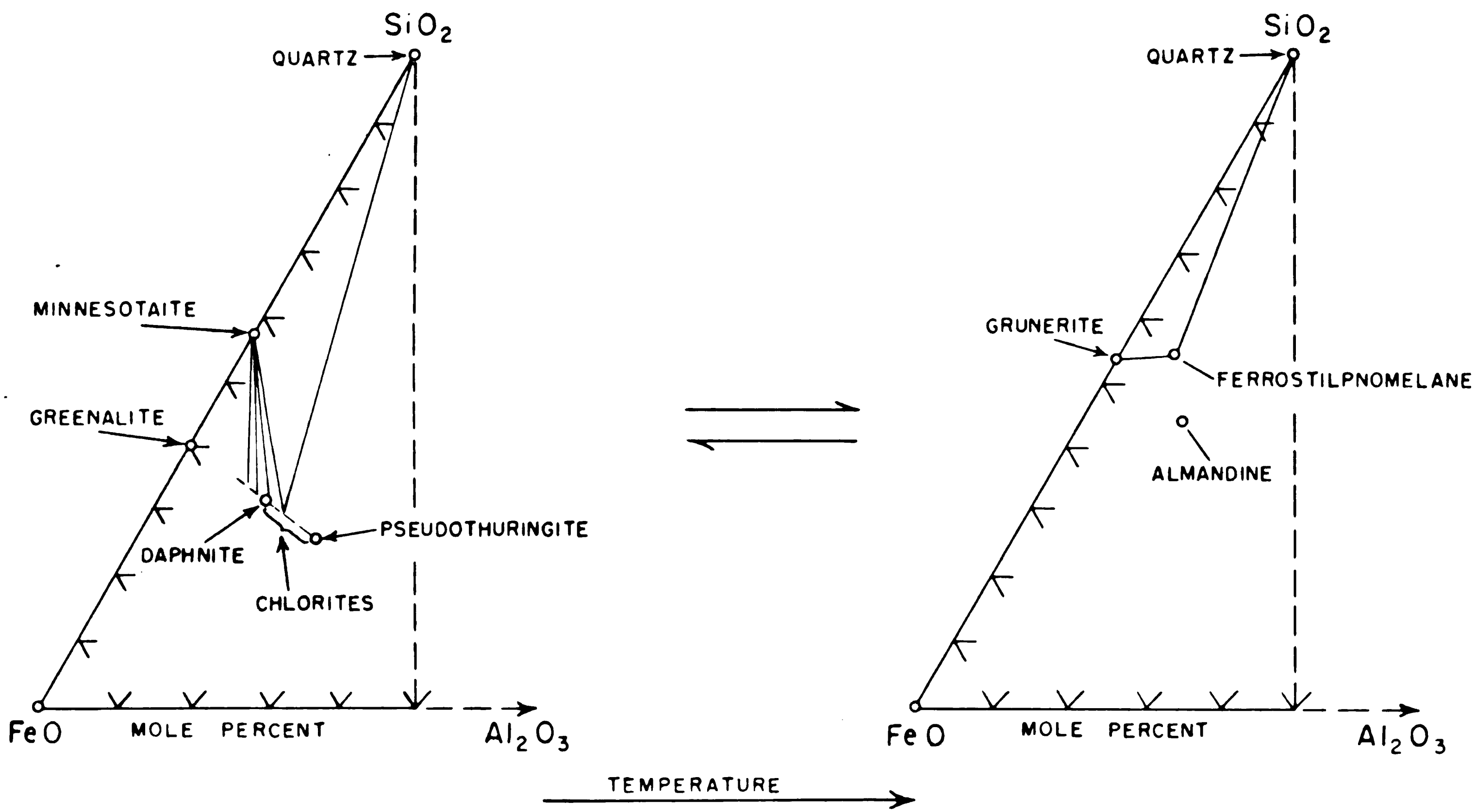
The appearance of actinolitic hornblende in adjacent amphibolites further suggests temperatures more nearly in the range of the upper greenschist facies. Supporting data based on the metamorphism of amphibolite are discussed in more detail in a forthcoming section.

Quartzose schists with abundant iron biotite and muscovite were previously referred to as being a common lithologic type within this area. Although muscovite (high silica sericites) may form very early during regional metamorphism, biotite is generally associated with conditions somewhat above the lower greenschist facies.

The aforementioned transitions generally involve chlorite as a reactant. This does not preclude the presence

FIGURE 65

MINERALS PROJECTED ONTO A PORTION OF THE $FeO-Al_2O_3-SiO_2$ PLANE SHOWING INFERRED TRANSITION FROM LOWER TO MIDDLE OR UPPER GREENSCHIST FACIES



of chlorite in rocks of appropriate bulk chemistry. It does, however, restrict the coexistence of iron rich chlorite with ferruginous biotite or stilpnomelane if equilibrium conditions were attained.

Almandine amphibolite facies.--Transition from the greenschist to the almandine amphibolite facies is not clearly defined. However, certain assemblages have been noted which characterize the lower almandine amphibolite facies. This is especially true of the area immediately north of the trough. The presence of staurolite as a major constituent of the Michigamme schists is a characteristic feature. Portions of the Michigamme formation of comparable bulk chemistry are not exposed within the trough area. However, conditions equivalent to the staurolite-quartz subfacies are believed to have prevailed over much of the area within the Republic Trough.

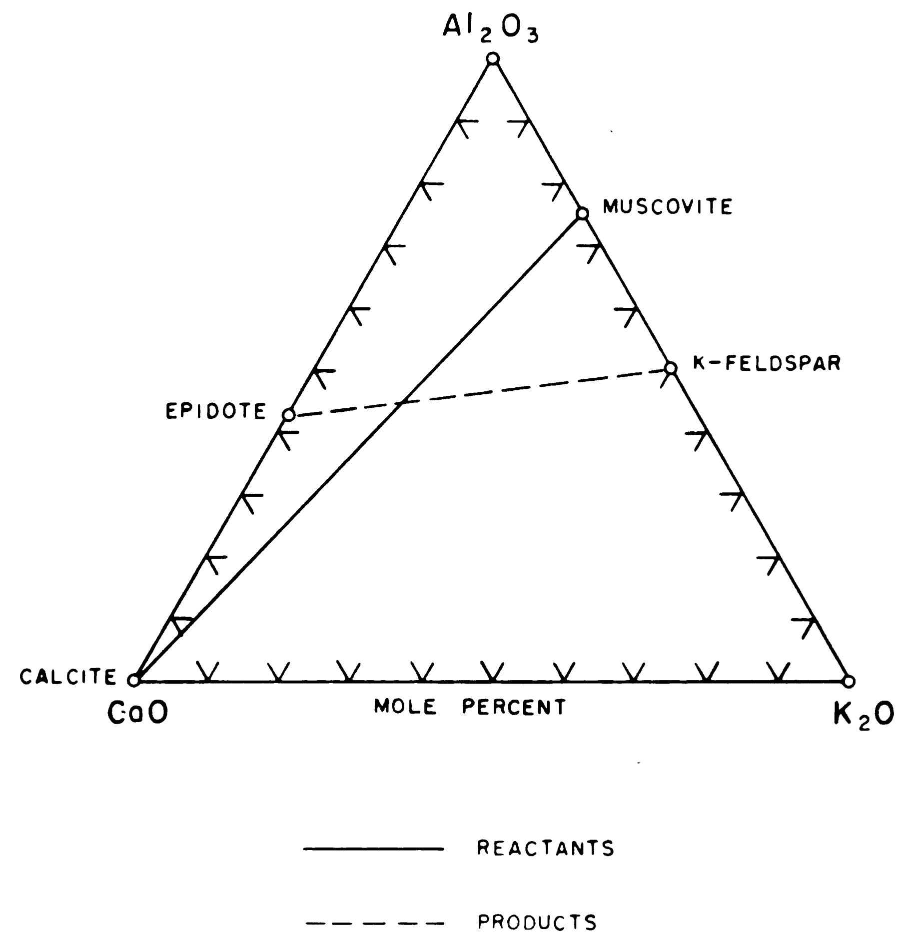
This is exemplified in the Goodrich formation which normally contains numerous epidote bearing assemblages. Epidote with intermediate plagioclase (oligoclase-andesine) is generally considered as characteristic of the staurolite-quartz subfacies (Fyfe, et al., 1958). The epidotes of the greenschist facies are normally associated with albite and in higher metamorphic grades such as the sillimanite-almandine subfacies with andesine or a more calcic plagioclase. Many of the assemblages recorded in the Goodrich formation do not contain plagioclase. However, when plagioclase was found with epidote it normally contained in the neighborhood of 20 per cent anorthite. This would suggest conditions at the lower end of the staurolite-quartz subfacies. Sphene, which is frequently present in these assemblages, has also been recorded as a typical accessory mineral of this subfacies (Turner and Verhoogen, 1960). At more elevated temperatures and pressures it tends to become unstable.

Calcite appears to have a limited stability within the lower portion of this subfacies. It is believed to react with muscovite to form epidote and potash feldspar in rocks of appropriate composition (see Figure 66). The initiation of this reaction may well mark the threshold of this subfacies. However, the extent of it would depend largely on the availability of muscovite and calcite and the partial pressure of Co_2 within the system during the prevailing thermal conditions.

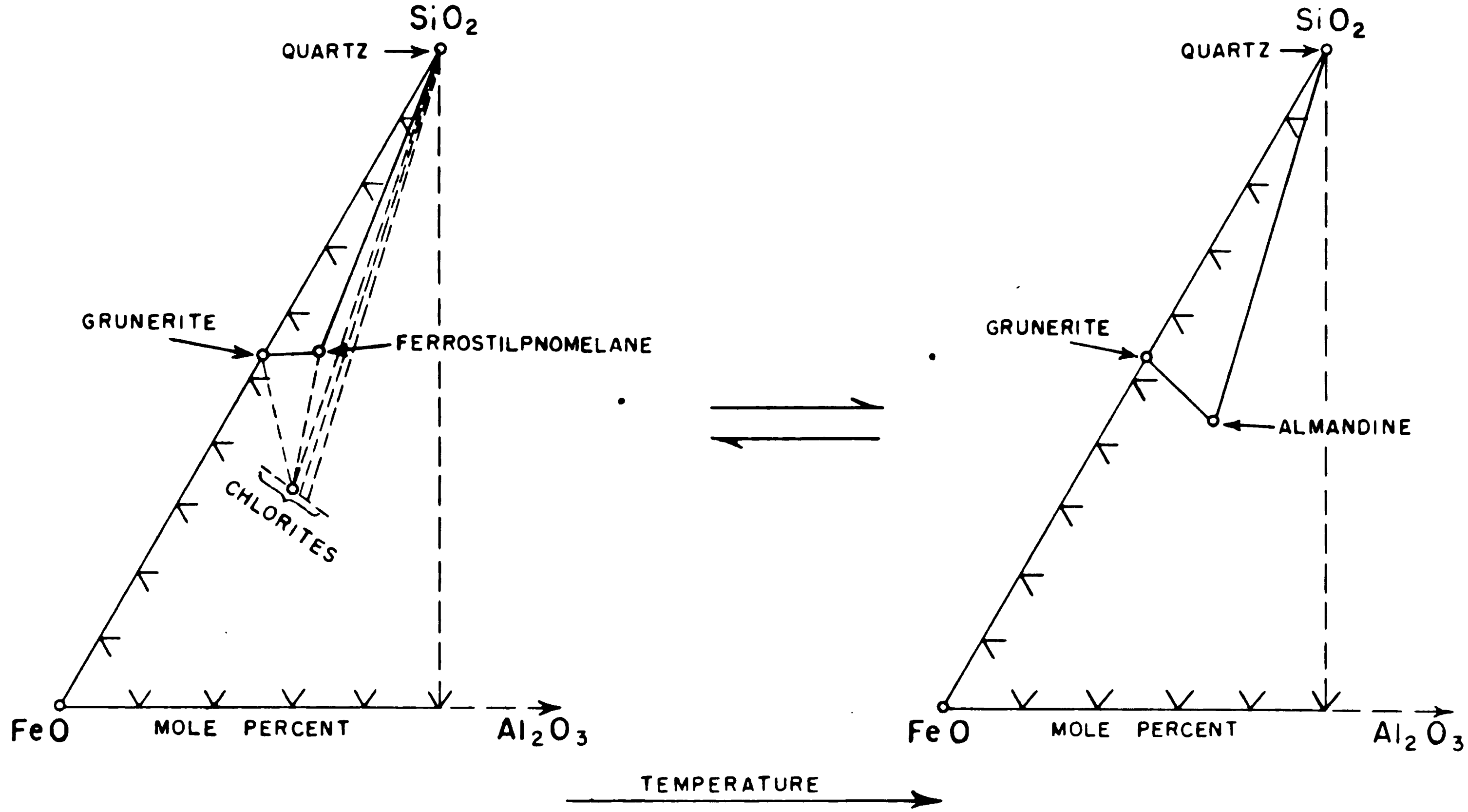
The breakdown of stilpnomelane is considered prima facie evidence for transition from the greenschist facies. It is, therefore, unfortunate that stilpnomelane was recognized within only a limited portion of the Michigamme formation. However, rocks of comparable composition occurring in a similar stratigraphic position were observed within areas that are believed to reflect more intense metamorphic conditions. The inferred transition based on the breakdown of stilpnomelane is illustrated in Figure 67.

FIGURE 66

SIMPLE POINT PROJECTION ONTO $Al_2O_3 - CaO - K_2O$ PLANE INDICATING CALCITE - MUSCOVITE REACTION DURING TRANSITION FROM GREENSCHIST TO LOWER ALMANDINE AMPHIBOLITE FACIES (RESTRICTED TO ROCKS WITHOUT ALMANDINE)



MINERALS PROJECTED ONTO A PORTION OF THE $FeO - Al_2O_3 - SiO_2$ PLANE SHOWING TRANSITION FROM GREENSCHIST TO ALMANDINE AMPHIBOLITE FACIES



NOTE: DASHED JOIN VALID ONLY IN ROCKS WHERE CHLORITE WAS NOT CONSUMED IN REACTION PRODUCING FERROSTILPNOMELANE

This diagram shows that the assemblage quartz-grunerite-almandine may originate by either a simple breakdown of stilpnomelane or by a reaction between iron chlorite and stilpnomelane. The latter case would be restricted to those rocks in which the chlorite was not consumed during an earlier reaction producing stilpnomelane. The diagram also illustrates that the assemblage grunerite-stilpnomelane-iron chlorite is highly unlikely in that it would be limited to quartz deficient rocks which were not observed in the Republic Trough area.

The common appearance of almandine in many lithologic types is a further indication that the metamorphic grade had progressed beyond the greenschist facies. The abundance of chlorite minerals also decreases markedly; however, their appearance is not precluded. It is felt that the magnesium or aluminous varieties may exist as a stable phase throughout even higher temperatures. Examples were previously presented of magneisum chlorites coexisting with essentially unaltered garnet in apparent equilibrium.

There is evidence within the trough area to indicate that metamorphic grades exceeding the staurolite-quartz subfacies were locally attained. The major indicator for transition from the staurolite-quartz subfacies is the appearance of sillimanite within the Ajibik formation. These rocks are believed to reflect metamorphic conditions equivalent to the lower part of the sillimanite-almandine subfacies.

The breakdown of staurolite is inferred for this transition. In the simplest case it is believed to react with quartz to produce sillimanite plus almandine. The transition is illustrated in Figure 68. Almandine is a ubiquitous phase in these rocks and, therefore, a logical product. However, it should be noted that in the lower temperature assemblage (staurolite-quartz subfacies) the join staurolite-quartz would theoretically prevent the appearance of almandine plus andalusite. This is not in agreement with field observations and, therefore, some stabilizing elements such as Mg, Ca, Mn, etc. must constitute a portion of the garnet composition.

In one area sillimanite was found without msucovite. This is considered unusual in that muscovite is present in nearly all the pelitic type rocks of the trough. It disappearance would, therefore, suggest consumption during a reaction producing sillimanite. The classic example of muscovite breakdown to produce sillimanite involves the appearance of potash feldspar. This is not the case within these rocks. Another potential reaction, which was previously discussed, involves staurolite to produce both sillimanite and biotite. This is the condition that is favored for the trough area. The close association observed between biotite and sillimanite in thin sections from this area further substantiates the aforementioned reaction. Figure 69 illustrates the proposed transition. If muscovite were

FIGURE 68

STAUROLITE – QUARTZ REACTION PROJECTED
ONTO A PORTION OF THE $FeO - Al_2O_3 - SiO_2$ PLANE
INDICATING TRANSITION WITHIN ALMANDINE AMPHIBOLITE FACIES

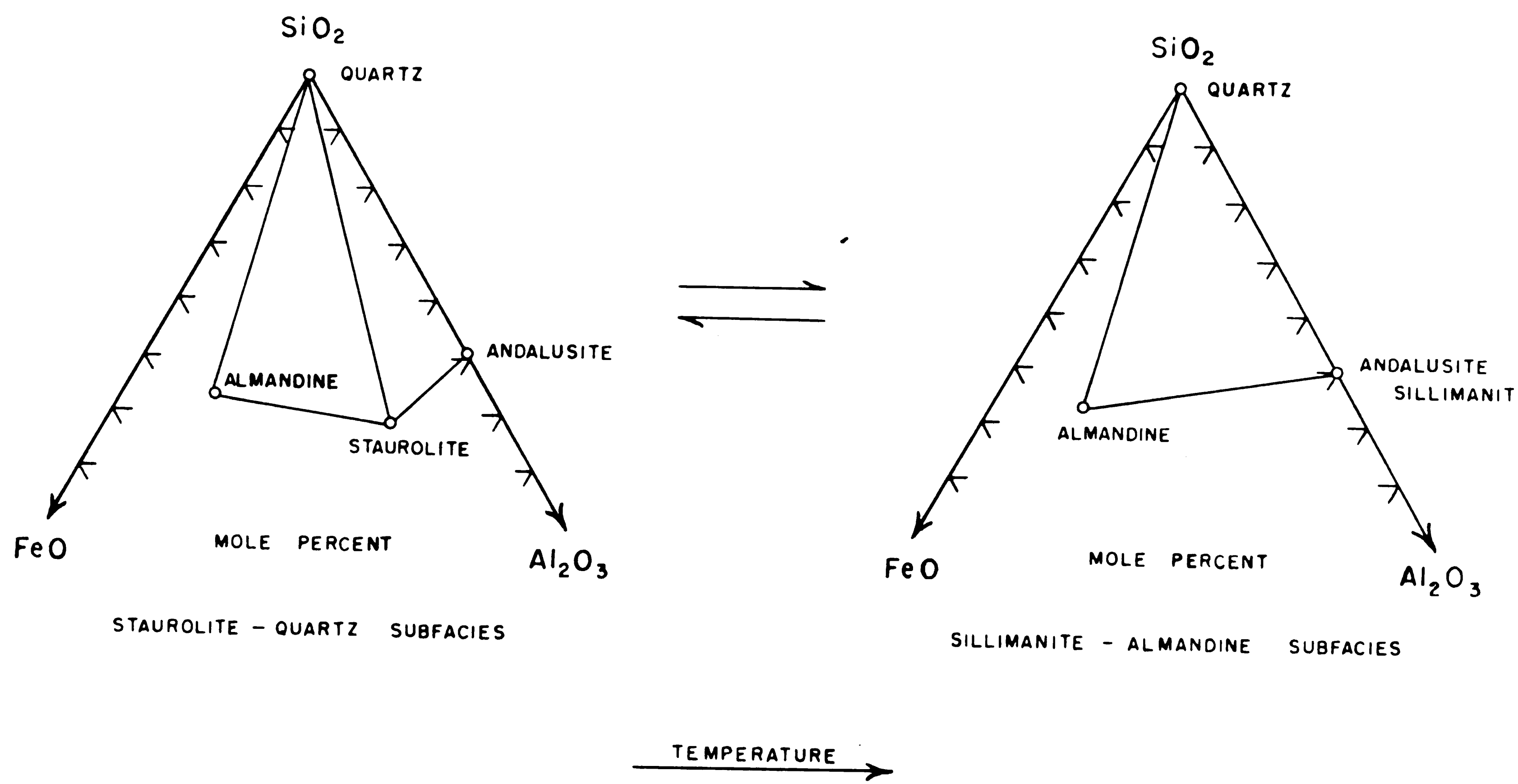
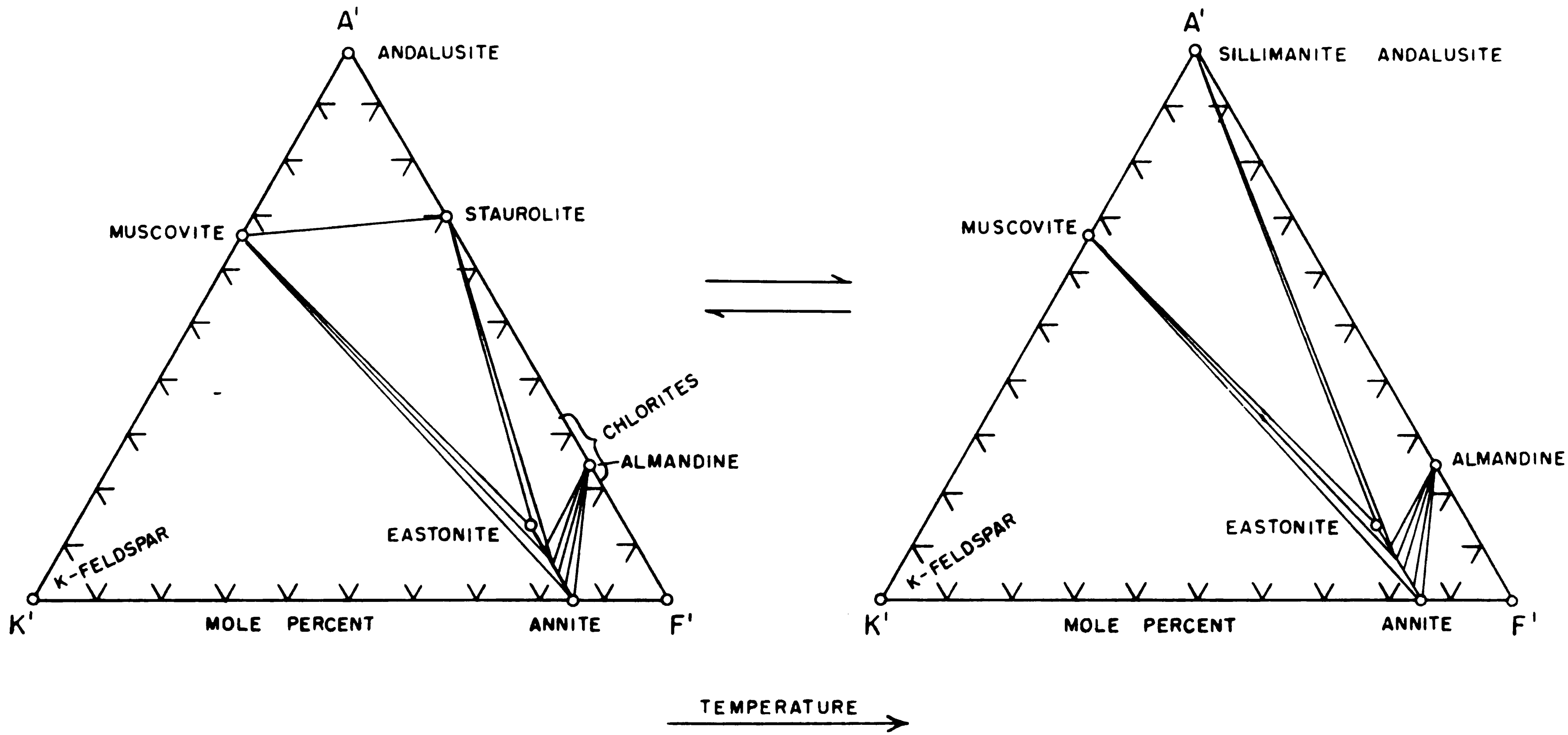


FIGURE 69

STAUROLITE – MUSCOVITE REACTION MARKING TRANSITION FROM STAUROLITE-QUARTZ TO SILLIMANITE ALMANDINE SUBFACIES



$A' = Al_2O_3 + Fe_2O_3$

$K' = K_2O \cdot Al_2O_3 + Na_2O \cdot Al_2O_3$

$F' = FeO + MgO + TiO_2$

in stoichiometric excess of staurolite within the lower temperature assemblage it could appear as an additional phase. This would, however, require that biotite and/or almandine contain stabilizing elements.

The preponderance of data points to conditions of the so-called "first sillimanite isograd." There is no evidence of potash feldspar appearance at the expense of muscovite. Furthermore, the common association of sillimanite with combinations of muscovite, almandine and biotite requires tie lines which would reduce the feasibility of coexisting potash feldspar under the metamorphic conditions that prevailed.

The disappearance of biotite and the appearance of hornblende within portions of grunerite schist from the Michigamme formation in the south sector merits note. Although the writer was unable to delineate any specific zone across which biotite was or was not present, it is believed to represent conditions approaching the sillimanite-almandine subfacies.

Amphibolite Metamorphism

Chemical data on the Republic Trough amphibolites are wanting. Only two occurrences were analyzed. These represent a composite sample from Section 7, T. 46 N., R. 29 W. and one from Section 20, T. 47 N., R. 30 W. The two sample sites are separated by approximately seven miles but occur in a relatively similar stratigraphic horizon.

Results of these analyses have been presented in Tables 27 and 28. Although sample coverage is insufficient to formulate any specific conclusions; it is believed that generalized trends are indicated relative to thermal gradient.

Engle and Engle (1962) have recorded systematic mineralogical and chemical transitions in amphibolites of the northwest Adirondacks. These variations were correlated with metamorphic grades ranging from the upper almandine amphibolite through the lower granulite facies. Several goethermometers from surrounding rocks indicated a thermal gradient of 525°C. to 625°C. In light of their findings a cursory comparison was made in an effort to detect analogous trends within the Republic Trough amphibolites.

Comparative data on major oxide variations as a function of increasing metamorphic grade are presented in Table 34 and Figure 70. The thermal gradient indicated for the trough area (Section 20 $\xrightarrow{T}$ Section 7) is based on mineral assemblages in adjacent metasediments. There appears to be a definite parallelism in the depletion or increase of these oxides as higher metamorphic grades are encountered. The oxides that are compared in Table 34 and Figure 70 are those indicated by Engle and Engle (1962) as revealing the most systematic variations. One exception to the general parallelism can be noted. This is in the case of alumina which

Engle and Engle have listed as merely a "probable" increase with increasing temperature.

There is considerable variation in the absolute magnitude of change within the respective areas. However, this would be expected in light of overall environmental differences between the two regions.

Mineralogical variations were also noted by Engle and Engle as being significant indicators of metamorphic grade within the Adriondack amphibolites. The transitions with increasing temperature that were reported by them include a decrease in hornblende and quartz with a corresponding increase in pyroxene and more calcic plagioclase. These changes were not fully relaized within the trough amphibolites. In part the amount of quartz appears to decrease in conjunction with increasing quantities of plagioclase. On the other hand there seems to be no correlation with respect to hornblende quantities and metamorphic grade. Pyroxene appears in only one area which does correspond to an inferred thermal high on the basis of other rock types. However, a systematic increase in pyroxene was not observed.

The aforementioned divergency in correlating mineralogical changes as a function of metamorphic grade may well be attributed to the degree of metamorphism realized in the respective areas. Data from adjacent metasediments in the trough area strongly suggest lower overall temperatures. Conditions comparable to the granulite facies were certainly never attained. The only possible overlap would be in the almandine amphibolite facies which is the lowest grade reported by Engle and Engle. They noted that for temperatures in excess of the almandine amphibolite facies there was a marked decrease in the quantity of sphene. The prevalence of sphene within the amphibolites of the south sector suggests temperature conditions below its progressive breakdown revealed in the Adirondacks. This would restrict the trough amphibolites to a metamorphic grade equal to or below the almandine amphibolite facies. The pyroxene amphibolites observed in Section 2, T. 46 N., R. 30 W., may represent a local exception. However, data from rocks immediately adjacent these occurrences suggest conditions within the almandine amphibolite facies.

Although there are local exceptions, several mineralogical transitions in the Republic Trough amphibolites are suggested. The following general changes were noted with increasing metamorphic intensity:

(1) actinolitic hornblende ⟶ blue green hornblende ⟶ green hornblende ⟶ brownish green hornblende. ⟶

(2) slight increase in anorthite molecule of plagioclase.

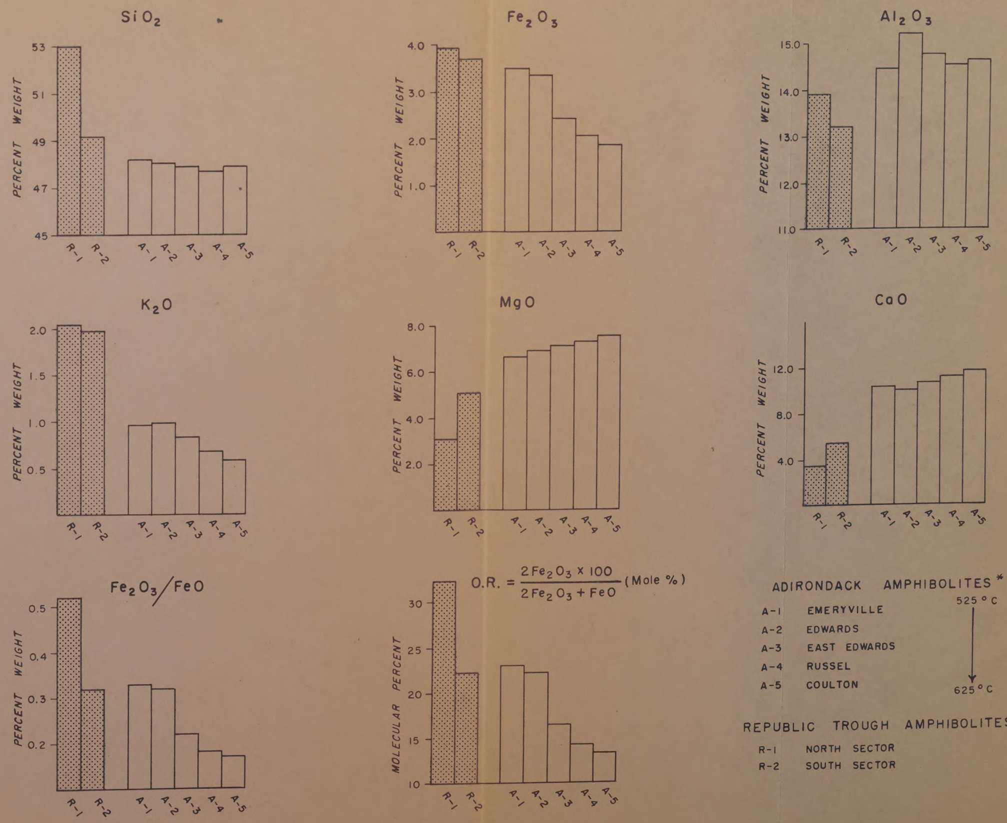
(3) decreasing quantities of quartz and biotite.

(4) pyroxene appearance.

The above generalizations are meant to include only prograde assemblages with no reference to retrograde alterations.

FIGURE 70

INFLUENCE OF THERMAL GRADIENT ON MAJOR OXIDE COMPOSITION OF AMPHIBOLITES



[*CHEMICAL DATA ON ADIRONDACK AMPHIBOLITES FROM ENGLE & ENGLE (1962)]

Table 34.--Major Oxide Variation of Republic Trough and Adirondack* Amphibolites with Increasing Metamorphic Grade.

	Republic Trough Amphibolites	Adirondack Amphibolites
	Sec. 20 Composite $\xrightarrow{T}$ Sec. 7 Composite	Emeryville Area (525°C) $\xrightarrow{T}$ Coulton Area (625°C)
Oxide	Per Cent Weight Difference	Per Cent Weight Difference
SiO_2	- 3.76	- 0.31
Fe2O3/FeO	- 0.20	- 0.16
Al_2O_3	- 0.70	+ 0.18
CaO	+ 2.04	+ 1.29
MgO	+ 2.00	+ 0.79
K_2O	- 0.06	- 0.38
	Molecular Per Cent Difference	Molecular Per Cent Difference
O. R.	-10.0	- 9.7

$$\text{O. R.} = \frac{2\ Fe_2O_3}{2\ Fe_2O_3 + FeO}\ (\text{Molecular Per Cent}) \times 100$$

* Chemical data on Adirondack Amphibolites from Engle and Engle (1962).

Temperature of Metamorphism

James and Clayton (1962) investigated the degree of oxygen isotops fractionation in samples of iron formation from the Lake Superior region. Their studies included several samples from the Republic Trough area.

In principle the O^{18} to O^{16} ratios in coexisting iron oxides and quartz should reflect the thermal history of the rock units. If equilibrium conditions were realized during metamorphism and the isotopic compositions were not altered during subsequent processes, these ratios should be an absolute measurement of the peak temperature to which the mienrals were subjected.

The data obtained by James and Clayton (1962) on the samples from the trough area are tabulated in Table 35.

TABLE 35.--Isotopic Temperature Determinations of Iron Formation Samples from the Republic Trough Area.

Sample No.	O^{16}/O^{18} Values Quartz	Magnetite	Hematite	Isotopic Qtz-Mag	Temperatures Qtz-Hem
16	10.4	-0.1		280°C.	
17	12.4		2.7		305°C.
18	8.7	-0.5		320°C.	

(after James and Clayton, 1962)

The first two samples (16 and 17) were collected from the iron formation near Republic. They apparently represent smaples of the middle or lower magnetite (#16) and upper specular hematite (#17) lithologic types. The third sample (#18) is described as originating from the Magnetic Mine area

(Section 20, T. 47 N., R. 30 W.). These are all considered by James as being within the sillimanite zone. He attributes the low temperature measurements to retrograde environments and concludes that the isotopic composition of rocks formed at high temperatures is not frozen until temperatures decline to approximately 300°C.

A sample of vein material from the Republic Mine consisting of specular hematite, calcite and quartz was also analyzed by James and Clayton (1962). This sample related somewhat higher temperatures (see Table 36) than the host rocks.

TABLE 36.--Isotopic Temperature Determinations of Vein Material from the Republic Mine.

O^{16}/O^{18} Values			Isotopic Temperatures	
Quartz	Calcite	Hematite	Qtz-Hem	Cal-Hem
10.7	7.6	2.2	355°C.	385°C.

(after James and Clayton, 1962)

These veins appear to be a product of metamorphic differentiation and, therefore, should reflect the termal conditions during metamorphism. This would then indicate that temperatures of at least 385°C. were realized throughout the south sector. Furthermore, based on the previous discussion where mienral assemblages were compared within amphibolites of the trough area and the northwest Adirondacks, it would appear that the prevailing temperatures of metamorphism were somewhat less than 500°C. This would bracket the termal peak.

between 385°C. and 500°C. in the south sector. The temperatures within the north sector were probably somewhat lower with an established minimum possibility of 320°C.

Age of Metamorphism

The writer submitted samples of muscovite schist to S. S. Goldrich, then at the University of Minnesota, for radioactivity age determination by the potassium-argon method. The samples were collected from the upper part of the Nagunee iron formation near the Goodrich contact at the Republic Mine. Goldrich (personal communication) dated the samples at 1.61 billion years on the basis of a K^{40}/A^{40} determination. These data are given in Table 37.

TABLE 37.--Potassium-Argon Age Determination of Muscovite Schist from Republic Mine Area.

K_2O %	K^{40} ppm	A^{40} ppm	A^{40}/K^{40}	K-A Age 10^9 Years
6.68	6.69	1.00	0.150	1.61

(after S. S. Goldrich, personal communication)

Goldrich considered this age as representing the time of major regional metamorphism. This was later correlated with post-kinematic thermal conditions of the Penokean orogeny (1.7 b.y.) which corresponds to the time boundary between Middle and Late Precambrian (Goldrich, et al., 1961).

A sample of garnetiferous schist which was reported as originating from the footwall portion of the "oxidized" iron formation at Republic was also dated by Goldrich, et al. (1961). This probably refers to a zone between the specular hematite and iron silicate type formations. In this case the K^{40}/A^{40} age determination was conducted on biotite and a date of 1.89 billion years was assigned. It was interpreted by Goldrich as reflecting a survival value of an earlier orogeny which was later altered by the Penokean. The writer believes that this second sample may be suspect due to the extensive alteration which characterizes the biotite in the area where the sample was probably collected. To what extent chloritization may influence K-A age determination on biotite is still unknown.

CHAPTER IX

SUGGESTIONS FOR FURTHER STUDY

Throughout this study a number of areas that seem worthy of detailed investigation become apparent. Several of those that are considered most pertinent to a better geologic understanding of the area are summarized below.

Magnetic-Specular Hematite Relationships

A detailed study of the relationships between specular hematite and magnetite throughout the iron formation may provide a significant insight on the paragenesis of the iron oxides. Consideration of the magnetite remnants within specular hematite plates affords a clue as to the possible sequencial development. Such a study should encompass several occurrences such as the Republic Trough, Humboldt area, North Michigamme district, and Champion. All these areas have transition zones from quartz-specular hematite to quartz-magnetite members. Detailed microscopic study and chemical analyses correlated with stratigraphic relationships would be an initial approach.

Iron Rich Conglomerate

The mineralogical details of the pebbles and matrix materials that constitute the iron rich conglomerate at the base of the Goodrich formation have not been studied to any great extent. Recent mining activity at Republic and Humboldt has opened up a considerable area that was previously covered. This affords an excellent opportunity to collect samples and conduct detailed mapping. Cursory examination by the writer indicates an interesting distribution between magnetite and hematite rich pebbles. In areas of intense folding such as the nose of the Republic Trough the pebbles are predominantly hematite in constrast to magnetite bearing pebbles along the less distorted limbs. This may be the result of either differences in primary sedimentation or subsequent variations in deformational and metamorphic environments.

Quartz Diameters and Metamorphic Gradients

In several areas the diameters of quartz grains resulting from the recrystallization of chert have been taken as an indicator of metamorphic grade (James, 1955). A relationship of this type was not apparent throughout the trough area. However, there appears to be a relationship between the size of quartz grains and their degree of clarity. Impurities within the quartz seems to have impeded growth. A systematic study of this possible relationships subjected to statistical scrutiny would provide data as to the validity of utilizing measurements of this nature.

Compositional Variations Within Individual Iron-Formation Minerals

Preliminary data indicates a considerable range in the composition of individual minerals throughout the iron-formation. This is particularly true of grunerite and garnet. With considerable effort it may be possible to obtain samples of sufficient purity to determine compositional variations as a function of the hose rock chemistry or stratigraphic occurrences. For example, the chemistry of the various garnets occurring in different mineral assemblages throughout the iron-formation would be extremely relevant to evaluating equilibrium conditions.

Isograds Based on Silicate Mineral Assembalges Within the Iron-Formation

The establishment of metamorphic grades based on iron-formation mineral assemblages poses an especially challenging problem. If reactions could be determined for the more common silicates under differing conditions this may well resolve the ambiguities that are commonly encountered. A sequence such as minnesotaite to stilpnomelane to grunerite to pyroxene may be applicable only under very specialized conditions. For example, there is evidence in the trough area for both stilpnomelane and grunerite appearing at low grades of metamorphism. There is also evidence of at least two reactions producing grunerite which represent entirely different thermal conditions.

Chemical and Mineralogical Variations in Amphibolites as a Function of Metamorphic gradient

The rocks of the Marquette Range offer an excellent opportunity to extend the work of Engle and Engle (1962) relative to systematic variations in the chemistry and mineralogy of amphibolites as a function of metamorphic gradients. Their work included only the higher metamorphic grades. Metamorphism on the Marquette Range extends throughout the lower grades. Furthermore, there are abundant outcrops of amphibolite and it may be possible to trace individual occurrences throughout several metamorphic grades.

Undifferentiated Basement Complex

The pre-Animikie rocks of the Republic Trough and surrounding area were not studied in any detail. However, cursory field examination of the so-called "undifferentiated basement complex" led the writer to believe that considerable study is warranted. The frequent observation of rocks that appear to be of sedimentary origin and the failure to establish contacts between granitic and metasedimentary units sheds considerable doubt on the concept of an entirely igneous origin. Furthermore, there appears to be a systematic distribution of lithologic types within the complex. Detailed mapping supplemented by chemical and petrographic studies may differentiate members reflecting either or both igneous and sedimentary parents.

Petrofabric Studies

The Republic Trough is somewhat of a structural rarity representing thin metasedimentary strata tightly folded over a considerable distance. The quartzitic and schistose rocks of the Animikie series provide an excellent opportunity to correlate fabric analyses to structural features. Orientation analyses of quartz axes developed through the recrystallization of chert in the iron-formation would also be of considerable interest.

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APPENDICES

PLATE I

PRECAMBRIAN GEOLOGY OF THE REPUBLIC TROUGH AREA
MARQUETTE COUNTY, MICHIGAN
(NORTH SECTOR)

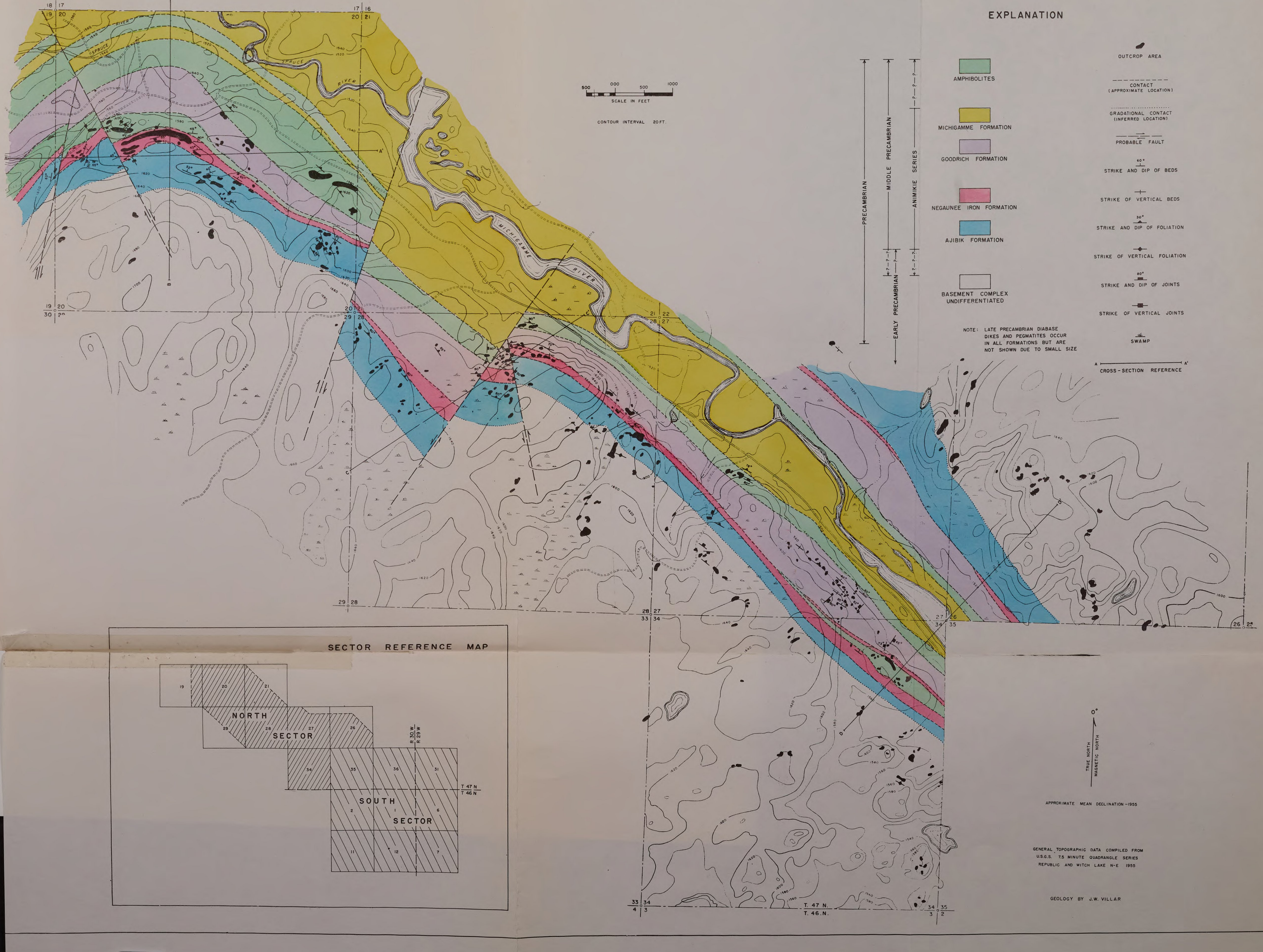
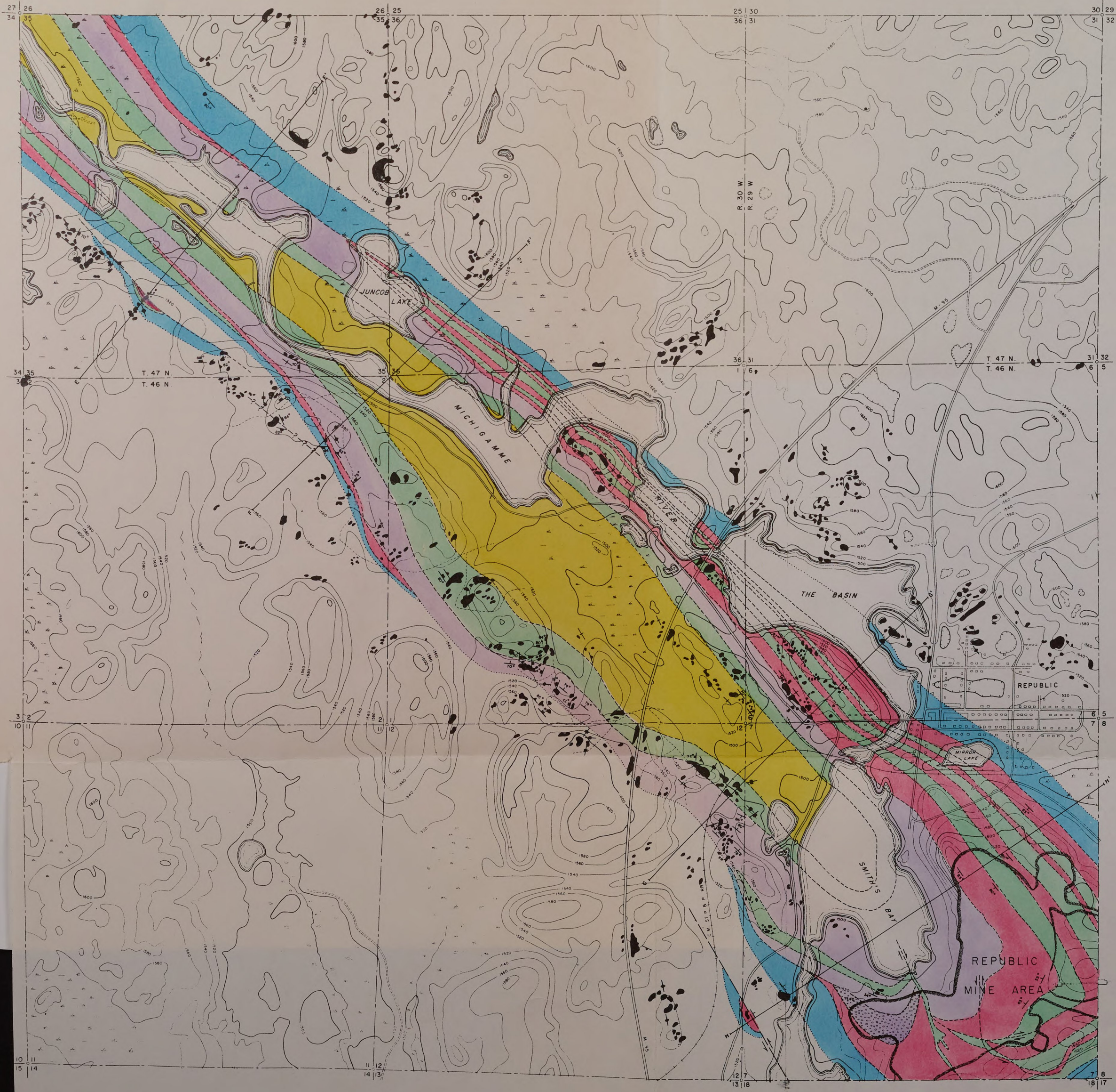


PLATE 2

PRECAMBRIAN GEOLOGY OF THE REPUBLIC TROUGH AREA
MARQUETTE COUNTY, MICHIGAN
(SOUTH SECTOR)



EXPLANATION

PRECAMBRIAN

MIDDLE PRECAMBRIAN — ANIMIKIE SERIES

- AMPHIBOLITES
- MICHIGAMME FORMATION
- GOODRICH FORMATION
- NEGAUNEE IRON FORMATION
- AJIBIK FORMATION

EARLY PRECAMBRIAN

- BASEMENT COMPLEX UNDIFFERENTIATED

NOTE: LATE PRECAMBRIAN DIABASE DIKES AND PEGMATITES OCCUR IN ALL FORMATIONS BUT ARE NOT SHOWN DUE TO SMALL SIZE

- OUTCROP AREA
- CONTACT (APPROXIMATE LOCATION)
- GRADATIONAL CONTACT (INFERRED LOCATION)
- PROBABLE FAULT
- STRIKE AND DIP OF BEDS
- STRIKE OF VERTICAL BEDS
- STRIKE AND DIP OF FOLIATION
- STRIKE OF VERTICAL FOLIATION
- STRIKE AND DIP OF JOINTS
- STRIKE OF VERTICAL JOINTS
- SWAMP
- A — A' CROSS-SECTION REFERENCE

SCALE IN FEET

CONTOUR INTERVAL 20 FT.

TRUE NORTH
MAGNETIC NORTH

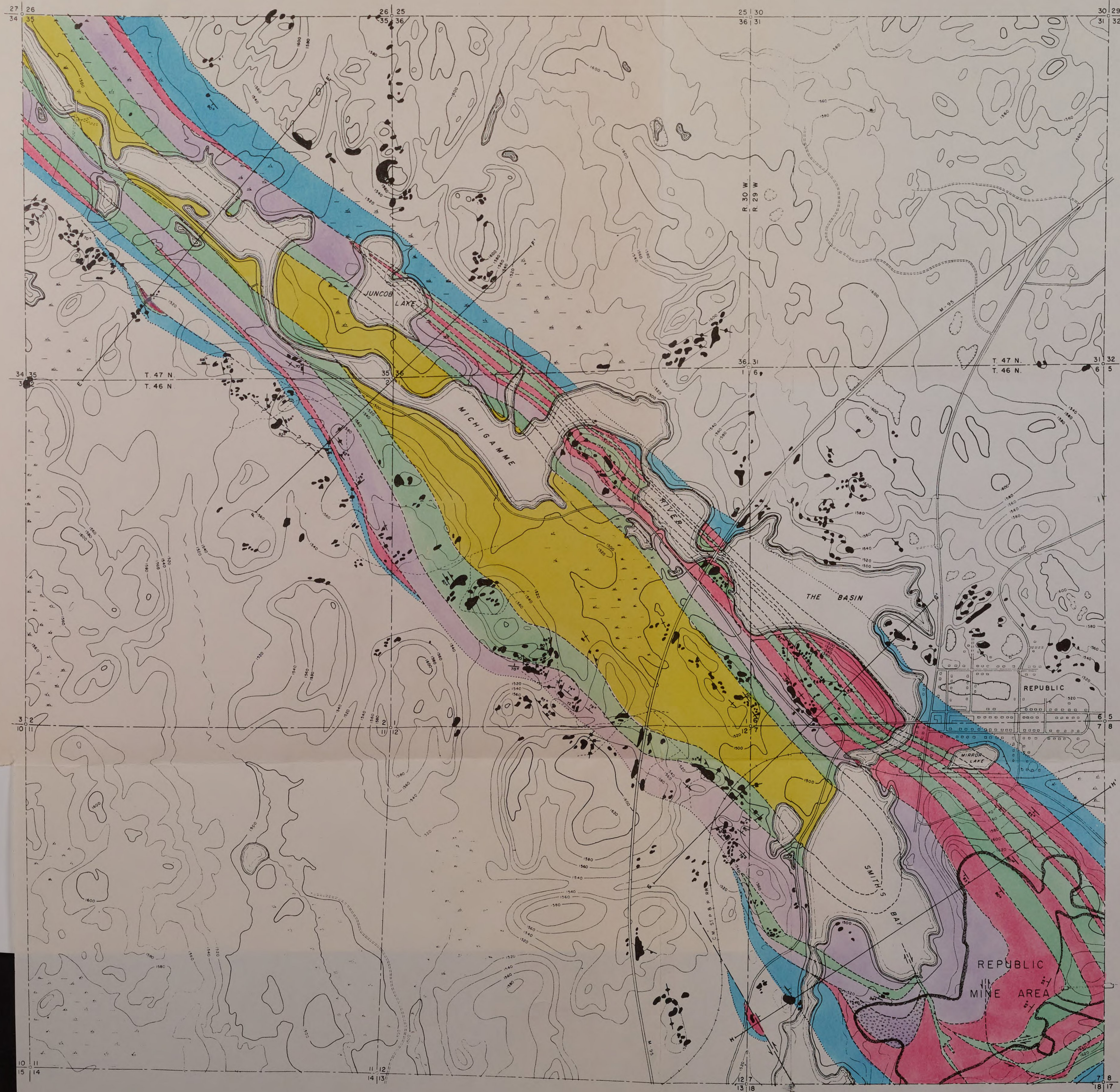
APPROXIMATE MEAN DECLINATION - 1955

GENERAL TOPOGRAPHIC DATA COMPILED FROM U.S.G.S. 7.5 MINUTE QUADRANGLE SERIES REPUBLIC AND WITCH LAKE N-E 1955

GEOLOGY BY J.W. VILLAR

FOR AREA REFERENCE SEE PLATE 1

PRECAMBRIAN GEOLOGY OF THE REPUBLIC TROUGH AREA
MARQUETTE COUNTY, MICHIGAN
(SOUTH SECTOR)



EXPLANATION

PRECAMBRIAN
MIDDLE PRECAMBRIAN
EARLY PRECAMBRIAN
ANIMIKIE SERIES

AMPHIBOLITES

MICHIGAMME FORMATION

GOODRICH FORMATION

NEGAUNEE IRON FORMATION

AJIBIK FORMATION

BASEMENT COMPLEX UNDIFFERENTIATED

NOTE: LATE PRECAMBRIAN DIABASE DIKES AND PEGMATITES OCCUR IN ALL FORMATIONS BUT ARE NOT SHOWN DUE TO SMALL SIZE

OUTCROP AREA

CONTACT (APPROXIMATE LOCATION)

GRADATIONAL CONTACT (INFERRED LOCATION)

PROBABLE FAULT

60°
STRIKE AND DIP OF BEDS

STRIKE OF VERTICAL BEDS

30°
STRIKE AND DIP OF FOLIATION

STRIKE OF VERTICAL FOLIATION

80°
STRIKE AND DIP OF JOINTS

STRIKE OF VERTICAL JOINTS

SWAMP

A A'
CROSS-SECTION REFERENCE

500 000 500 1000
SCALE IN FEET

CONTOUR INTERVAL 20 FT.

0°
TRUE NORTH
MAGNETIC NORTH

APPROXIMATE MEAN DECLINATION - 1955

GENERAL TOPOGRAPHIC DATA COMPILED FROM U.S.G.S. 7.5 MINUTE QUADRANGLE SERIES REPUBLIC AND WITCH LAKE N-E 1955

GEOLOGY BY J.W. VILLAR

FOR AREA REFERENCE SEE PLATE I

PLATE 2

PRECAMBRIAN GEOLOGY OF THE REPUBLIC TROUGH AREA
MARQUETTE COUNTY, MICHIGAN
(SOUTH SECTOR)

EXPLANATION

PRECAMBRIAN
MIDDLE PRECAMBRIAN
EARLY PRECAMBRIAN
ANIMIKIE SERIES

AMPHIBOLITES

MICHIGAMME FORMATION

GOODRICH FORMATION

NEGAUNEE IRON FORMATION

AJIBIK FORMATION

BASEMENT COMPLEX UNDIFFERENTIATED

NOTE: LATE PRECAMBRIAN DIABASE DIKES AND PEGMATITES OCCUR IN ALL FORMATIONS BUT ARE NOT SHOWN DUE TO SMALL SIZE

OUTCROP AREA

CONTACT (APPROXIMATE LOCATION)

GRADATIONAL CONTACT (INFERRED LOCATION)

PROBABLE FAULT

60° STRIKE AND DIP OF BEDS

STRIKE OF VERTICAL BEDS

30° STRIKE AND DIP OF FOLIATION

STRIKE OF VERTICAL FOLIATION

80° STRIKE AND DIP OF JOINTS

STRIKE OF VERTICAL JOINTS

SWAMP

A — A' CROSS-SECTION REFERENCE

500 000 500 1000
SCALE IN FEET

CONTOUR INTERVAL 20 FT.

0°
TRUE NORTH
MAGNETIC NORTH

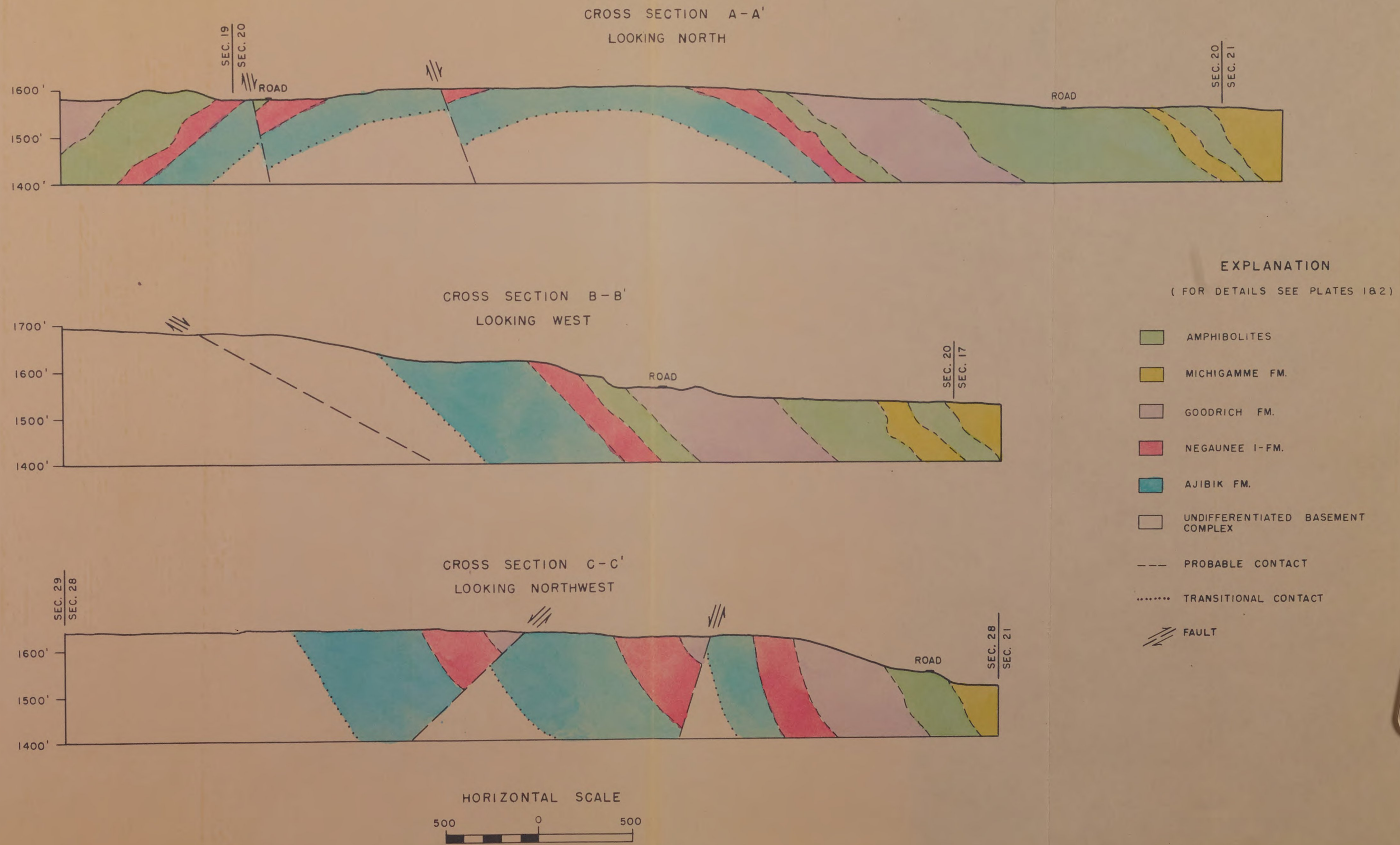
APPROXIMATE MEAN DECLINATION-1955

GENERAL TOPOGRAPHIC DATA COMPILED FROM U.S.G.S. 7.5 MINUTE QUADRANGLE SERIES REPUBLIC AND WITCH LAKE N-E 1955

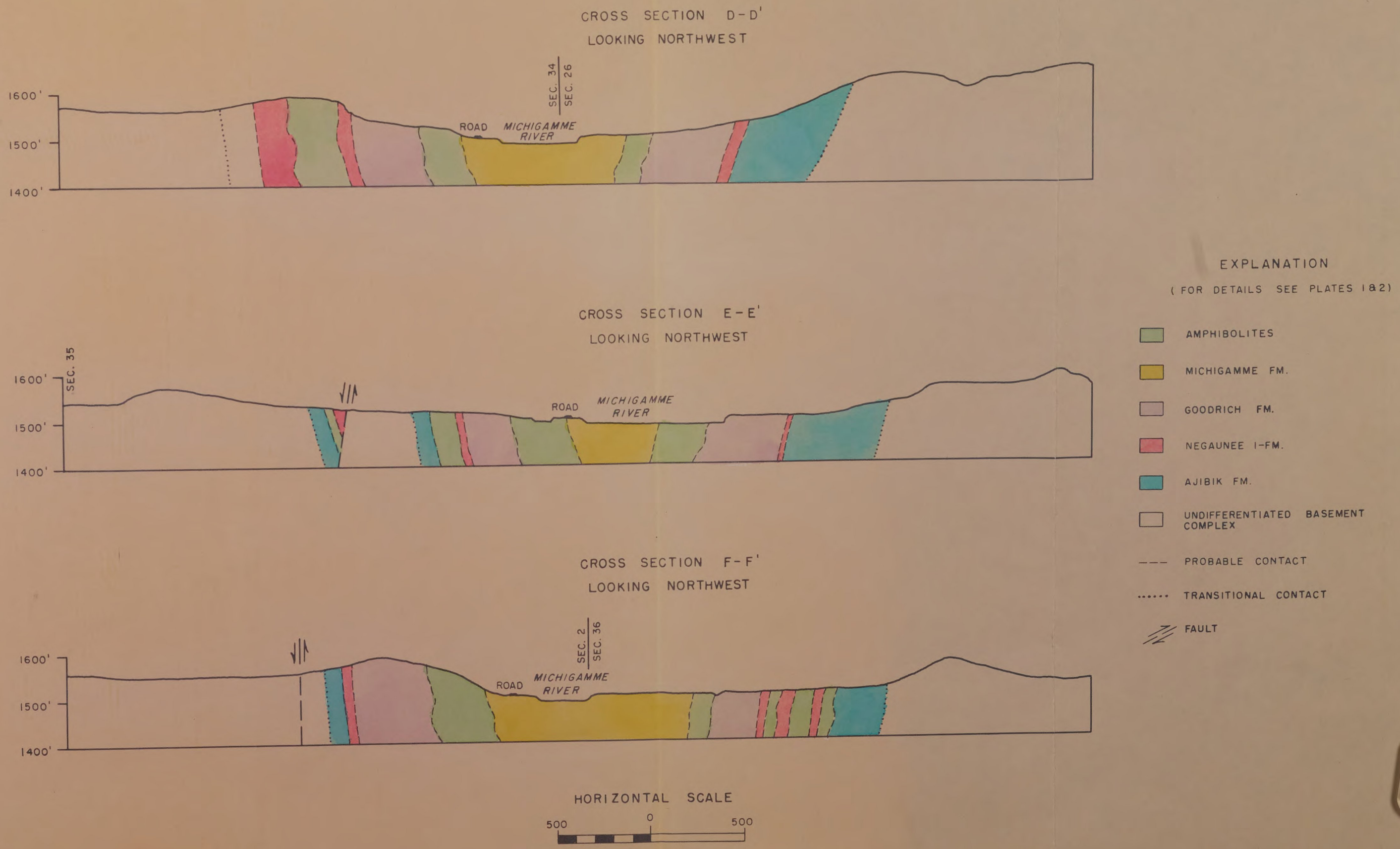
GEOLOGY BY J.W. VILLAR

FOR AREA REFERENCE SEE PLATE I

GENERALIZED GEOLOGIC CROSS SECTIONS

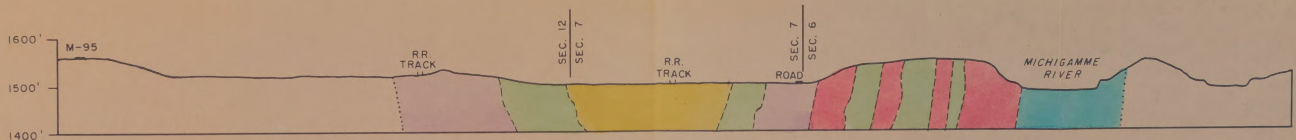


GENERALIZED GEOLOGIC CROSS SECTIONS

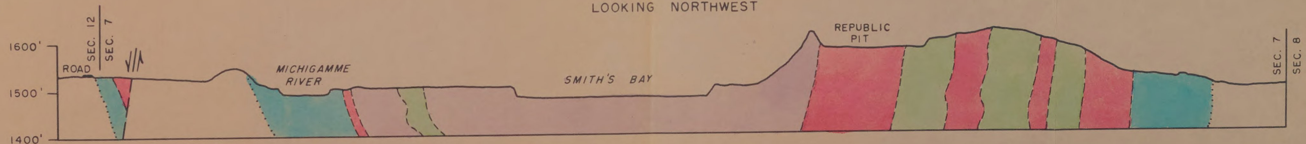


GENERALIZED GEOLOGIC CROSS SECTIONS

CROSS SECTION G-G'
LOOKING NORTHWEST



CROSS SECTION H-H'
LOOKING NORTHWEST



EXPLANATION

(FOR DETAILS SEE PLATES 1&2)

AMPHIBOLITES

MICHIGAMME FM.

GOODRICH FM.

NEGAUNEE I-FM.

AJIBIK FM.

UNDIFFERENTIATED BASEMENT COMPLEX

--- PROBABLE CONTACT

..... TRANSITIONAL CONTACT

FAULT

HORIZONTAL SCALE

500 0 500