

A STUDY OF THE RELATIONSHIP BETWEEN
THE METAMORPHICALLY RECRYSTALLIZED
CHERTS OF THE NEGAUNEE IRON FORMATION
AND METAMORPHIC GRADE

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ABSTRACT

A STUDY OF THE RELATIONSHIP BETWEEN THE METAMORPHICALLY RECRYSTALLIZED CHERTS OF THE NEGAUNEE IRON FORMATION AND METAMORPHIC GRADE

by Arthur Lifshin

The possibility of the use of metamorphically recrystallized chert in the iron formations to determine metamorphic grade provided the basis for this study. It is known that the grain size of a mineral will increase with increase in metamorphic grade provided that the mineral is stable and that there is enough material for growth to proceed. If a regular and consistent relationship between the grain size of metamorphically recrystallized chert and metamorphic grade could be found, it would then be possible to use this tool in the field of metamorphic petrology. The Negaunee Iron Formation was considered to be ideal for this study in that it is composed of beds of iron minerals and beds of quartz. The quartz was originally chert. Since the chert is cryptocrystalline, the problem of original grain size does not appear. In a study such as this the metamorphic grade must be known with a fairly high degree of accuracy.

Henrickson (1956) determined the metamorphic zones for the Marquette District. On the basis of his isograds, samples were collected from the iron formation for the determination of grain size and from the metabasites for the determination of the metamorphic grade. Samples for the determination of the metamorphic grade were used as a check on Henrickson's work. The results of the study of the metamorphic samples

showed that of those that had an assemblage distinctive enough to be placed in a metamorphic zone, the majority of them agreed with Henrickson. The major difference occurred in the samples from Republic. Of the four samples from the Republic area, two had assemblages indicative of the staurolite zone, and two were characteristic of the sillimanite zone. The sillimanite isograd drawn by Henrickson does not go through the Republic area. The author does not consider the redrawing of the sillimanite isograd to be warranted on the basis of these four samples. Henrickson's isograds were, therefore, retained with the change in the position of the sillimanite isograd being considered.

The samples of the Iron Formation which were used to determine grain size were grouped by geographic location. The grain size distributions were treated statistically with the Analysis of Variance test. The statistical results showed that although the grain size of the metamorphically recrystallized cherts increased with increase in metamorphic grade, it is not possible to use the grain size of the recrystallized cherts to determine the metamorphic grade due to the range of grain sizes present in any one metamorphic zone and the large amount of overlap of grain size between zones.

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TABLE OF CONTENTS

CHAPTER	Page
I. INTRODUCTION	1
Statement and Object of Thesis	1
Location	2
Previous Work	2
II. GENERAL GEOLOGY	5
Stratigraphy of the Marquette District	5
Lithologic Descriptions of Formations	7
Chocolay Group	7
Mesnard Formation	7
Kona Formation	7
Wewe Formation	7
Menominee Group	8
Ajibik Formation	8
Siamo Formation	8
Negaunee Formation	9
Baraga Group	11
Goodrich Formation	11
Michigamme Formation	12
Greenwood Iron Formation	12
Clarksburg Volcanics	12
Lower Argillite	13
Bijiki Iron Formation	13
Upper Argillite	13
Meta-Igneous (basic)	13
Late Basic Intrusives	14
Tectonic History	14
III. DESCRIPTION OF SAMPLES	17
Methods and Techniques	17
Bedding	17
Description of Samples	18

TABLE OF CONTENTS - Continued

CHAPTER	Page
Iron Formation	18
Negaunee Group	18
Clarksburg Group	18
Champion Group	19
Michigamme Group	20
Republic Group	21
Pelitic Schists	22
Metabasites	23
Republic Area	23
Michigamme Area	25
IV. METAMORPHISM	26
Metamorphism	26
Metamorphic Facies in Iron Formation	27
Metamorphic Facies in Metabasites	31
Metamorphic Facies in Pelites.	32
Conclusions on the Metamorphism of the Marquette District	33
V. EXPERIMENTAL RESULTS.	35
Statistical Methods	35
Presentation and Discussion of Data	37
Effects of Quartz Grain Orientation.	61
Errors in Measurement	64
Further Discussion	65
VI. SUMMARY AND CONCLUSIONS.	68
BIBLIOGRAPHY	70
APPENDIX	73

LIST OF TABLES

TABLE	Page
1. Chart Showing Tentative Conclusions Regarding Metamorphism of Principal Types of Iron Formations (From James)	28
2. Metamorphic Mineral Associations in the Marquette District Iron Formations (From Henrickson).	29
3. Metamorphic Mineral Assemblages for Mt. Wright Area Iron Formation (From Mueller).	30
4. Metamorphic Mineral Assemblages for the Mt. Reed Area Iron Formation (From Kranck)	30
5. Mineral Assemblages of the Marquette Metabasites . .	31
6. Sample Sizes, Means, Modes and Standard Deviations of the Iron Formation Samples	38
7. Results of the Analysis of Variance Between Areas . .	39
8. Results of the Analysis of Variance for the Republic Group	41
9. Results of the Analysis of Variance for the Champion Group	42
10. Metamorphic Grade of the Iron Formation Samples . .	42
11. Table Showing Consistency of Individual Peaks and Troughs of the Frequency Distribution Curves Across Metamorphic Grade	58

LIST OF FIGURES

FIGURE	Page
1. Map of a part of the Marquette District.	Pocket
2. Map of a part of the Upper Peninsula of Michigan showing the location of the Marquette District	3
3. Simplified geologic column for the Marquette District	6
4. Photomicrograph showing moasic texture	11
5. Sketch of the location of the Republic Iron Formation samples	43
6. Plot of distance from the dike against the means and modes of the grain size distribution for the Republic samples	44
7. Grain size distribution curve for slide number 2. . .	44
8. Grain size distribution curve for slide number 3. . .	45
9. Grain size distribution curve for slide number 3a-I. .	45
10. Grain size distribution curve for slide number 3a-II. .	46
11. Grain size distribution curve for slide number 4-I. .	46
12. Grain size distribution curve for slide number 4-II. .	47
13. Comparison of grain size distribution curves for composite curves of slides 3, 3a-I, 3a-II and slides 4-I, 4-II.	47
14. Grain size distribution curve for slide number 5.	48
15. Grain size distribution curve for slide number 6. . .	48

LIST OF FIGURES - Continued

FIGURE	Page
16. Grain size distribution curve for slide number 7-I. . .	49
17. Grain size distribution curve for slide number 7-II . .	49
18. Grain size distribution curve for slide number 7-III. .	50
19. Grain size distribution curve for slide number 7-IV . .	50
20. Grain size distribution curve for slide number 7-V . .	51
21. Composite grain size distribution curve for slides 7-I, 7-II, 7-III, 7-IV and 7-V.	51
22. Grain size distribution curve for slide number 8.....	52
23. Grain size distribution curve for slide number 9. . . .	52
24. Grain size distribution curve for slide number 10 . . .	53
25. Grain size distribution curve for slide number 11 . . .	53
26. Plot of grain size distribution means against meta- morphic grade	54
27. Plot of grain size distribution modes against meta- morphic grade	55
28. Approximation of the grain size distribution curves by a succession of modified normal curves	57
29. Intersections between a right circular cylinder and a cutting plane for various orientations of the cutting plane.	62
30. Frequency distribution of diameter ratios of slide 7-I reduced to 0° C axis inclination	63

CHAPTER I

INTRODUCTION

Statement and Object of Thesis

The writer became interested in the problem of correlation of metamorphically recrystallized chert with metamorphic grade after it was suggested by Dr. Justin Zinn of the Department of Geology at Michigan State University as a possible thesis project. The problem and the possibility of testing it appeared to offer a way to explore certain facets of metamorphism that have not yet gone beyond the theoretical stage. It also presented the possibility of developing a new tool for metamorphic petrology.

The primary objective of this study was to determine whether or not a correlation could be found between the grain size of metamorphically recrystallized cherts and metamorphic intensity. If such a correlation could be found, it was felt that it would be a valuable tool in delineating metamorphic zones in areas that were known or thought to have contained sedimentary chert which has now been metamorphically recrystallized to quartz. In areas such as the Lake Superior District, where outcrops are scarce due to glacial cover, the ability to use the Iron Formations in determining metamorphic grade would enable one to map the metamorphic zones with a greater degree of assurance than has been done previously.

The use of the grain size of metamorphically recrystallized chert to delineate metamorphic zones is based on the theory that the grain size of a given mineral will increase with increase in metamorphic

intensity provided that there is sufficient material available, and the mineral remains stable throughout the range of metamorphism. With this in mind, it was felt that a study of this type would provide added insight into the metamorphic recrystallization of minerals and grain growth during metamorphism, and that possibly some information concerning any other factors which might affect grain size might be obtained.

Location

The area in which this investigation was conducted is in the Marquette District of the Upper Peninsula of Michigan (Figure 2). The specific area which was studied is in the western part of the district and includes parts of Marquette and Baraga Counties (Figure 1).¹

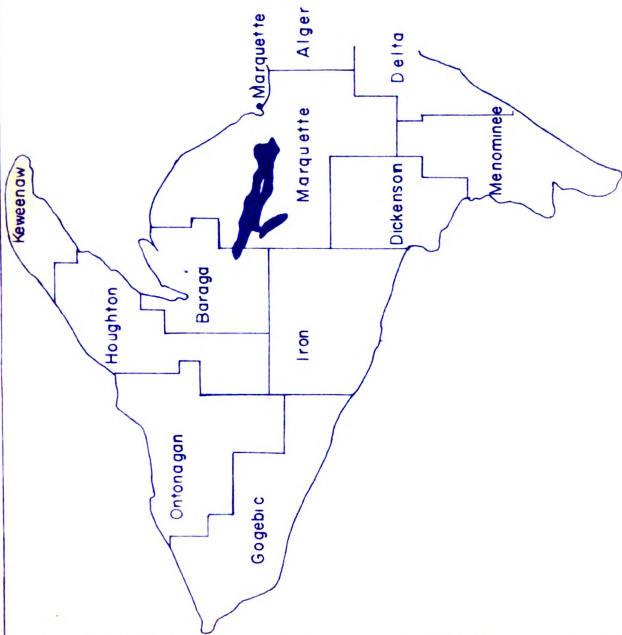
Previous Work

While much work has been done in the Marquette District, only one person appears to have dealt with this subject in more than a cursory manner. Most workers in the district have noted that the grain size in the chert bands of the Iron Formation varies in different parts of the district. As early as 1897, Van Hise stated that the quartz grains in some specimens appear to have a preferred orientation and that the quartz grains in Jaspilite from the Michigamme and Spurr Mine areas have diameters of 0.10 to 0.15 mm. Differences in chert grain size were also noted by Leith in his study of the Mesabi District in 1903. In Monograph 52, Van Hise and Leith also noted the differences in chert grain size and gave values of 0.15 mm. in the extreme western

¹This map will be found in the pocket of this book.

MAP
of a
part of the
Upper Peninsula
Michigan
SHOWING
the
location of the
Marquette District

Figure 2



end of the district and 0.20 to 0.40 mm. with high values of 1.00 mm. in the Republic Trough. Other than this, no further work was done on this problem until 1955. James (1955) gives a range of grain sizes for metamorphically recrystallized cherts for the various metamorphic zones. He does not give any evidence that these values are valid nor does he state how he obtained them. As will be seen later, a cursory examination of a specimen may easily produce erroneous values.

The only other work done on metamorphically recrystallized cherts was to note that the resulting material was a chert that had been metamorphosed. Such mention has been made in the Grenville by Tarr and Keller (1940) and by Blackwelder (1935) in the Medicine Bow Range of Wyoming and by various workers in the Franciscan rocks in California. In most of these cases the chert had reacted with other components of the rock to form silicates and thus could not be used for this type of study. However, where the chert had not reacted to form silicates it was noted that it had been recrystallized to quartz with a mosaic texture.

The only comprehensive work on the metamorphism of the entire Marquette District appears to be that of James (1955) and of Henrickson (1956). James (1955) drew a series of metamorphic isograds for the entire Upper Peninsula based on a large number of thin sections on which he and others before him had worked. Henrickson (1956) delineated the metamorphic zones of the Marquette District. This study was based on both field and thin section work.

In this study, the writer has relied heavily on both James' and Henrickson's publications for information regarding the metamorphic zones in the Marquette District. Samples to test the metamorphic grade were taken wherever possible but only as a check on the work of James and Henrickson, and if possible, to break down the isograd intervals still further.

CHAPTER II

GENERAL GEOLOGY

Stratigraphy of the Marquette District

With the exception of recent glacial debris and some Cambrian sandstones, the rocks in the Marquette District are all Precambrian. As may be seen from the stratigraphic column (Figure 3), the Precambrian rocks have been divided into three "periods," Upper, Middle and Lower. The Lower Precambrian is not involved in this investigation and shall not be discussed. Only those formations that are important to this study will be described in any detail.

The following is a general description of the lithologies and thickness and extent of the various formations in the Upper and Middle Precambrian in the Marquette District. Due to poor outcrops, glacial cover, and tightly folded structures the data for the thickness of the formations should be considered to be a maximum and may be less than the value given by hundreds of feet. The areal extent of the various formations is also subject to error for the same reasons, and while the surface expressions of these formations have been accurately mapped, the actual extent is in doubt. Therefore, data on both the thickness and areal extent will be of a general nature.

The descriptions of the various formations are taken from Monographs 28 and 52, and Zinn (Personal Communication, 1963). For more detailed lithologic descriptions, the reader is referred to these references.

Figure 3. Simplified Geologic Column for the Marquette District*

	Quaternary				recent glacial deposits
Paleozoic	Cambrian		Lake Superior		sandstones and conglomerates
Pre- cambrian	Upper	Keweenawan			basic dikes sandstones
	Middle				granites basic meta-igneous
		Animikie or Huronian	Baraga Group	Michigamme	Upper Member
					Bijiki Iron Fm
					Lower Member
					Clarksburg Volcanics
					Greenwood Iron Fm
				Goodrich	quartzite slate
			Menominee Group	Negaunee	iron formation
				Siamo	argillite
				Ajibik	quartzite
			Chocolay Group	Wewe	argillite
				Kona	dolomite argillite
				Mesnard	quartzite
	Lower				granites gneisses
				Kitchi	meta- sediments
				Mona	meta- igneous

*From Cleveland Cliffs map of Marquette District 1962.

Lithologic Description of Formations

Chocolay Group

The Chocolay Group is the oldest of the Middle Precambrian and is part of the Huronian. It comprises the Mesnard, Kona, and Wewe formations. The name is taken from the Chocolay Quarry Area.

Mesnard Formation. The Mesnard Formation is composed of conglomerates, graywackes, graywacke-slates, and quartzites. All gradations of the various rock types are found but the quartzite is predominant. The quartzite is a vitreous, fairly massive rock, although bedding may be seen in outcrop. Ripple marks may be found in some areas. The quartzite passes into a shaly phase in places.

The Mesnard is confined to the eastern part of the district and is found bordering the outside of the syncline. The thickness varies from about 150 to 1200 feet. The maximum thickness is probably less than 1200 feet but exact data is lacking.

Kona Formation. The Kona is composed primarily of a cherty dolomite with minor phases of graywacke-slate and quartzite. The dolomite is fragmental and brecciated at numerous horizons and contains much secondary chert and many algal structures. The dolomite varies in color from a white to a dark brown with pinks, purples, and reds depending on its purity. The texture varies from aphanitic to coarsely crystalline.

The Kona, like the Mesnard, is confined to the eastern part of the district and borders the Mesnard on the inside of the trough. The thickness of the Kona ranges from a few hundred feet to about 1000 feet. The accuracy of this data is the same as for the Mesnard.

Wewe Formation. The Wewe has a fairly variable lithology. In the extreme east it is composed of slates and graywackes while in the

rest of the district the basal member is a conglomeratic quartzite and quartzite. The Wewe then grades upwards into slates and graywackes with some novaculites. The predominant lithology is the slate.

The Wewe, like the two previous formations, is confined to the eastern part of the district and has the approximate areal extent as the Mesnard and the Kona. The thickness of the Wewe ranges from about 600 feet to over 1000 feet.

Menominee Group

Ajibik Formation. The basal member of the Ajibik has two distinct lithologies. In the western part of the district the basal member is a conglomerate derived from the underlying crystallines. In the eastern part it is slaty. The basal member grades upward into a "normal" quartzite and contains conglomeratic and fractured zones. The fractured zones have been filled with various cements. The upper part of the Ajibik is a fairly clean quartzite. At various levels throughout the Ajibik may be found thin, discontinuous beds of shale or graywacke.

The Ajibik is fairly extensive and is found throughout the entire district. In the east it overlays the Wewe and appears to be fairly thick. In the west the Ajibik is found bordering the trough; it is fairly discontinuous and extends down into the Republic Trough. The Ajibik has a thickness of about 20 feet to 600 feet.

Siamo Formation. The Siamo varies from a fine grained slaty rock, to a massive graywacke, to a coarse grained feldspathic graywacke which approaches a quartzite. The upper and lower horizons both contain much iron oxide, but the middle part of the Siamo contains very little. There are occasional interlaminated beds of chert and ferruginous chert, and grunerite schist. Some of the coarser phases of the Siamo have been brecciated but this is not common. The character of this

formation, along with the others, changes as the metamorphic grade increases (westward). These changes will not be discussed here. These are the "normal" changes associated with metamorphism and will be discussed in the chapter on metamorphism.

The Siamo is found in the eastern part of the district and along the northern border. It is not found along the southern part of the district. The Siamo has an approximate maximum thickness of about 1200 feet.

Negaunee Formation. The lithology of the Negaunee Formation is very variable. Some of the variations are due to secondary concentration of the iron prior to metamorphism, secondary concentration of iron after metamorphism, and metamorphism. These three factors along with the original rock composition acted (both individually and in combination) to produce the varied lithologies now seen. A detailed description of the various lithologies is beyond the scope of this paper, therefore only some of the more important ones will be described.

The Negaunee is primarily an iron formation with an original mineralogy of primary chert and an iron mineral; oxide, carbonate, or silicate; in distinct laminae or beds (James, 1954). Brecciated zones are common and the resulting rock, where oxidized before folding and metamorphism is known as a jaspilite. Secondary concentration of the iron formation was accomplished by the removal, by solutions, of much of the chert and the transformation of the iron mineral into an oxide. The ore bodies while numerous do not make up the bulk of the formation. The rocks that were not heavily affected by the secondary concentration retained their original texture and mineralogy until they were changed by the subsequent weathering and metamorphism. In the eastern part of the district, where the metamorphic intensity was low, the rock retains much of its original characteristics, the bedding is

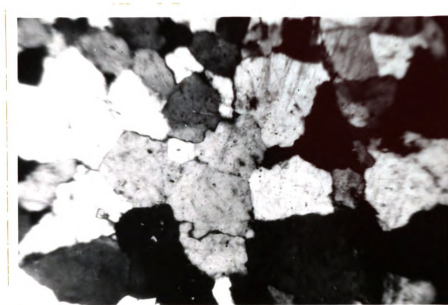
distinct and the individual beds have a maximum thickness of an inch or so. Both the chert and the iron minerals are extremely fine grained. With increasing metamorphism the individual laminae become smaller and the chert increases in grain size. The mineralogy of the iron minerals changes and increasing amounts of both magnetite and grunerite are found. In some cases there is very little chert left and the rock becomes a grunerite-magnetite schist. Chlorite is evident in some samples and others appear to have been intruded by small quartz veins and veinlets although these may be chert that has been mobilized by solutions. Secondary iron minerals are fairly common; among these are magnetite, hematite, grunerite, stilpnomelane, and pyrite.

The Negaunee Iron Formation is quite extensive throughout the entire district. It is found in a large area around Negaunee and Ishpeming and south. It extends along both the north and south borders of the trough and into the Republic Trough. It has been extensively mined throughout most of the district but only where it has been previously concentrated to form an economic ore deposit.

The thickness of the Negaunee Iron Formation is very variable and is in part due to the subsequent erosion of it before deposition of the overlying formations. The original thickness of the Negaunee has been estimated to be as great as 3000 feet and measured thicknesses range from several feet to more than 2000 feet.

The presence of chert in the Negaunee has been inferred from existing evidence since none of it is cryptocrystalline at the present time. The evidence for the chert is mainly twofold. The mosaic texture of the quartz bands has been interpreted to be the result of chert that has been recrystallized. This mosaic (Figure 4) is composed of interlocking grains of quartz with apparently the same general size. Further evidence comes from the appearance of the quartz bands in the

Figure 4



Photomicrograph of a quartz bed in an Iron Formation slide showing the mosaic texture of the quartz (360x).

formation. They are quite thin and continuous, the alternation of laminae is fairly continuous over a large stratigraphic distance, and the bands have the appearance of chert bands. These and other reasons are the main ones for calling the quartz bands recrystallized chert.

Baraga Group

Goodrich Formation. The Goodrich Formation is characterized by a basal conglomerate which was derived from the earlier underlying rock. In most places this is the Negaunee Iron Formation but in others the earlier crystallines form the detritus for the Goodrich. The basal conglomerate grades up into a quartzite which contains many

minute fragments of chert and jasper. The upper horizons of the formation are feldspathic. The metamorphism has caused schistose textures in many places.

The Goodrich Formation occurs in a small area in the southeastern part of the district and is also found in the rest of the district above the Negaunee Iron Formation. The average thickness of the Goodrich Formation is about 300 feet but both larger and smaller thicknesses have been measured.

Michigamme Formation. The Michigamme Formation has been subdivided into a number of members which are described below. In some places there are slates at the top of the Goodrich but these are not extensive.

Greenwood Iron Formation. The Greenwood is an Iron Formation which is lithologically similar to the Negaunee Iron Formation although it is not as variable as the Negaunee. It has a thickness of about 50 feet.

Clarksburg Volcanics. The Clarksburg is composed mainly of volcanics along with some water-laid material derived from the volcanics. The rocks have been affected by the subsequent metamorphism enough to change their mineralogy. The result is a crystalline rock with a basic appearance. Schists are most common although more basic igneous appearing rocks such as hornblendites are also found. Tuffs, breccias, and conglomerates derived from the volcanics are found interfingering with "normal" sediments near the edge of the volcanic zone.

The thickness of the Clarksburg Volcanics varies from 0 feet at the edge of the volcanic zone to about 1500 feet in the thicker parts toward the middle.

Lower Argillite. The Lower Argillite is composed primarily of slates, the upper horizons of which are graphitic. Much of it is metamorphosed, and slaty and schistose textures and metamorphic minerals are common.

Bijiki Iron Formation. The Bijiki Iron Formation is similar in composition to the Negaunee Iron Formation. The lower and upper horizons of it grade into the Lower and Upper Argillite respectively. The middle part of it is primarily a banded grunerite-magnetite schist where it has been sufficiently metamorphosed.

Upper Argillite. The Upper Argillite is composed of slates and graywackes. The slates are graphitic at the base of the member. Schistose structures are developed in this as in other members of the Michigamme Formation.

The Michigamme Formation is found extensively throughout the entire district. It occupies a major part of the trough from the area of Ishpeming west and into the Republic Trough. The Clarksburg Volcanics occupy a restricted zone in the southern half of the central part of the district.

The thickness of the entire Michigamme Formation can only be estimated for much of it has been removed by erosion. Estimates as high as 3000 feet have been made, but more likely the actual thickness may be as much as 10,000 feet.

Meta-Igneous (basic)

These rocks are upper Middle Precambrian and were probably intruded partly during the deposition of the Negaunee Iron Formation and partly during the Clarksburg Volcanic interval. They are all metamorphosed and originally basic in nature. They are dikes and sills varying in thickness from a few feet to several hundred feet.

Their appearance is that of a gabbro or diorite, but evidences of metamorphism are easily seen both in thin sections and in the field by the presence of metamorphic minerals such as garnets, urallite, and chlorite, and in some cases by a schistose texture where the rocks have been sheared.

Late Basic Intrusives

These basic intrusives are distinguished from the others by the fact that they are not metamorphosed. They are post-metamorphic and post-orogenic. They are considered to be Precambrian and are probably middle Keewenawan. They are mainly gabbros and diabases and contain olivines and orthopyroxenes. They can be differentiated from the earlier meta-gabbros by their fresher appearance in the field and their lack of metamorphic minerals.

Tectonic History

The tectonic history of the Marquette District is complex and only imperfectly known. For the purposes of this study only that portion of the tectonic history which occurred during or after the deposition of the Negaunee Iron Formation will be considered.

There are two events prior to the introduction of the intrusives into the area that are of importance; these are the erosion of the Negaunee Iron Formation with the subsequent secondary concentration to form the hard ore bodies, and the deposition of the volcanics to form the Clarksburg member. The meta-igneous basic intrusives were introduced at this time but they will be discussed later.

The effect of the secondary concentration of the Negaunee is one of importance for this is probably the prime factor in forming the hard ore bodies, but it probably had little or no effect on the recrystallization of the chert.

The Clarksburg Volcanics are a group of basic extrusives which appear to be restricted in area. Since they are separated from the Negaunee by hundreds of feet, it is improbable that they had any effect on the recrystallization of the chert.

Both the metamorphosed intrusives which are associated by age with the Clarksburg and the late basic intrusives may have affected the chert to a small degree. The effect of the intrusives on the chert in the Negaunee may be inferred from the contact phenomena along larger basic intrusives that have been studied. Along large basic intrusive bodies such as the Palisades diabase in New Jersey and the Duluth Gabbro in Minnesota the contact aureole is very narrow and amounts to no more than a few feet. In the small intrusive bodies in the Marquette District, the contact aureole is probably extremely narrow. Some contamination of the wall rock and some recrystallization of the chert probably occurred. This effect, which was presumably limited to a foot or two on either side of the sills and dikes, can be considered to be a minor but common effect which could possibly be detected by comparing petrofabric diagrams and size analysis of the recrystallized chert near and away from the dikes. Since all of the early intrusives are pre-metamorphic, their effect, if any, has been modified by the subsequent metamorphism. When both the post and pre-metamorphic dikes are taken into account, it is doubtful if they had any major effect on this study and can be ignored by the simple method of taking samples far enough removed from the contacts so that these samples will have had no contamination or recrystallization due to the intrusive.

The only major event in this area was that of the post-Huronian orogeny. This included the folding, faulting, intrusion of granites, and the metamorphism; all of which is seen in the district. The effect of this orogeny on the Negaunee Iron Formation is fairly complex and

involves changes in gross structures, textures and mineralogy. Part of this effect, i. e., the metamorphic recrystallization of the chert in the Negaunee Iron Formation, is what the writer hopes to determine from this study. As these events just outlined are the only ones that could have affected the chert in the Negaunee and the effect of those events other than the orogeny are small enough to be discounted, it is assumed that the changes in texture and mineralogy that affected the entire Huronian series were developed during the orogeny. One of the assumptions on which this study has been based is that the recrystallization of the chert is due only locally to the basic intrusives and regionally to the orogeny affecting the whole area. It is considered to be valid.

CHAPTER III

DESCRIPTION OF SAMPLES

Methods and Techniques

Samples were collected from the Marquette District (Figure 1) during the month of June, 1962. Thin sections, which were made of a number of the collected samples, were studied and measured with a petrographic microscope. Standard methods for the identification of minerals in thin section were employed and Winchell's text (1956) was used as a reference.

Orientation of the quartz grains in recrystallized chert was plotted with the aid of a four axis universal stage. A micrometer ocular and integrating stage were used to measure quartz grain diameters. The ocular was calibrated against a 2 mm. Leitz stage micrometer.

The photomicrographs were taken with a Leitz microscope and Viscam camera equipment. Panatomic-X film and Hyfinol developer were used.

Bedding

All of the iron formation is bedded, and the bedding appears distinctly both in thin section and in hand specimen. It is difficult to give thicknesses for the beds due to extreme variation found. In a single hand specimen the bed thickness will vary from $\frac{1}{4}$ inch to less than $\frac{1}{64}$ inch. In thin section this variation is even more noticeable.

The thicknesses of the quartz beds are more uniform than the others, but even here variations occur in the same pattern as described. The iron mineral beds are different in that if the mineral is predominantly oxide, the bed is usually extremely thin; while if it is silicate, it is usually close to the quartz bed in width.

The color of the iron formation is fairly uniform. The weathered surface usually shows light and dark bands that have been stained by iron oxide. On a fresh surface the quartz beds are usually white, and the iron beds will be either black, reddish, or greenish depending on whether the iron mineral is magnetite, hematite, or iron silicate.

Description of Samples

Iron Formation

Negaunee Group. Sample 1 Iron Formation

Location - The sample is located S 31, T48N, R26W at the railroad cut west of the Bunker Hill mine at Negaunee.

Megascopic - The rock is a banded iron formation. The bedding is easily observed with bed width ranging from $\frac{1}{2}$ inch to $\frac{1}{64}$ inch. The beds are composed of alternate layers of quartz and an iron mineral.

Microscopic - The quartz beds are composed of very thin layers of quartz and mosaic quartz, and are in the order of one to two grains in width. The term mosaic quartz will refer to recrystallized chert, and the term quartz will denote all other types of this mineral present. The iron mineral layers are composed of a mixture of carbonate, quartz, chlorite and iron oxide.

Clarksburg Group. Sample 2 Iron Formation

Location - The outcrop is located in S7 T47N R28W approximately $\frac{1}{2}$ mile south of Route 41 on the dirt road leading south from Clarksburg.

Megascopic - The rock is a banded iron formation. Alternate layers of quartz and an iron mineral make up the beds.

Microscopic - The rock is composed of alternate layers of mosaic quartz and magnetite with biotite. The approximate proportions of the minerals present are; quartz - 80%, magnetite - 2%, biotite - 15%, hematite after magnetite - 2%, and "stilpnomelane" - 1%. The term "stilpnomelane" is used to denote a nearly colorless mineral having fairly high relief and low to moderate birefringence. The grains were too small to make any positive identification. The mineral may be either sericite, minnesotaite, or stilpnomelane. Minnesotaite and stilpnomelane are common in the iron formation. Sericite could be present in the shaly phases of the iron formation, or if there were clay impurities in the chert. The term "stilpnomelane" is used for convenience.

Champion Group. Sample 3, 3a Iron Formation

Location - The outcrop is found in S32 T48N R29W on the hill with the telephone relay tower at Champion.

Megascopic - Alternate layers of quartz and grunerite have produced distinct bedding. Garnet and iron oxides are also present.

Microscopic - The bedding is composed of alternate layers of mosaic quartz and grunerite. Garnet is present and magnetite occurs scattered throughout the section. The minerals are present in the following proportions; mosaic quartz - 70%, grunerite - 25%, magnetite - 2%, garnet - 3%. The type of garnet present in the iron formation is probably andradite. Due to the large number of inclusions in the garnets, it was felt that specific gravity measurements would not yield useful data. The inference of andradite is from the associations with which the garnet is found. A partial analysis of an iron formation garnet from the Mesabi (Wright, 1928) showed 90% andradite. This high andradite composition would probably hold for other iron formation garnets.

Sample 4 Iron Formation

Location - The sample was taken from S32 T48N R29W near Sample 3.

Megascopic - The rock is a banded iron formation. The banding is due to alternate layers of quartz and grunerite. Iron oxide minerals are also present.

Microscopic - The bedding shows distinctly as alternate layers of mosaic quartz and grunerite. The grunerite beds vary in thickness from very thin to that of the quartz beds. Mosaic quartz - 85%, grunerite - 8%, blue-green amphibole - 3%, magnetite and hematite - 3%, and garnet - 1% are the minerals present. The term blue-green amphibole is used to denote a mineral that appears to be the same material that was described by Richarz (1930). It has been noted by various others who studied the iron formations but no one has named it.

Michigamme Group. Sample 5 Iron Formation

Location - The outcrop is located in S20 T48N R30W on Route 41, 5 miles west of the Peshekee River.

Megascopic - The rock is composed of alternate layers of quartz and grunerite which gives it a banded appearance.

Microscopic - The beds are composed of alternate layers of mosaic quartz and grunerite. Within the grunerite beds are chlorite and blue-green amphibole. The approximate amounts of the minerals present are; mosaic quartz - 90%, grunerite and blue-green amphibole - 8%, magnetite and hematite after magnetite - 2%.

Sample 6 Iron Formation

Location - The sample was taken from S19 T48N R30W about 1 mile east of Sample 5 on Route 41.

Megascopic - The rock is a banded iron formation composed of alternate layers of quartz and grunerite with an iron oxide.

Microscopic - The bedding is shown by alternate layers of mosaic quartz and magnetite with grunerite and brown hornblende. Pyrite is also found. Amounts of the minerals present are; mosaic quartz - 95%, magnetite, grunerite, and hornblende - 5%, pyrite - negligible.

Republic Group. Sample 7, 7a Iron Formation

Location - This and the following samples of the iron formation from the Republic group were taken from S31, T47N R29W from the outcrop just south of the bridge over the Michigamme River on Route 95 near Republic (Figure 5).

Megascopic - Quartz and grunerite in alternating layers of variable thickness show the bedding in the rock.

Microscopic - The beds are composed of alternate layers of mosaic quartz and grunerite with magnetite, biotite, and blue-green amphibole. The mosaic quartz comprises 92% of the section with the biotite and amphiboles at 7% and magnetite and hematite about 1%.

Sample 8 Iron Formation

Megascopic - Thin alternate layers of quartz and grunerite with iron oxide minerals compose the bedding.

Microscopic - Mosaic quartz and grunerite with magnetite compose the beds. Mosaic quartz comprises 99% of the section, other minerals, about 1%. Some of the mosaic quartz appears to have a cataclastic texture. The grains have been fractured and show wavy extinction.

Sample 9 Iron Formation

Megascopic - The rock is a banded iron formation composed of quartz and an iron mineral in alternating sequence.

Microscopic - The beds consist of alternate layers of mosaic quartz - 99% and magnetite with hematite - 1%. Some grains of carbonate, too small to be identified, are seen.

Sample 10 Iron Formation

Megascopic - The bedding is distinct and is composed of bands of quartz and an iron mineral. The rock has a slaty appearance due to ease of fracture along the bedding planes.

Microscopic - Layers of mosaic quartz and grunerite with magnetite alternate. There are pods that have the appearance of garnet that has been completely altered. The inference of garnet is from the shape of the pods. The pods are filled with magnetite, quartz, and chlorite. Approximate percentages of the minerals present are; mosaic quartz - 80%, grunerite - 10%, magnetite - 8%, "pods" - 2%.

Sample 11 Iron Formation

Megascopic - The bedding is distinct and shown by the alternation of bands of quartz and grunerite with an iron mineral.

Microscopic - The layering is composed of alternate bands of mosaic quartz and grunerite with blue-green hornblende. The minerals present and their respective amounts are; mosaic quartz - 45%, grunerite and hornblende - 53%, magnetite and hematite after magnetite - 2%.

Pelitic Schists

Sample 12 Mica Schist

Location - The rock was taken from an outcrop located in S32 T48N R29W on the eastern part of the hill with the telephone relay tower near Champion.

Megascopic - The rock is a light colored mica schist. The mica is light colored and appears to be partly chloritized. Garnet and quartz are common.

Microscopic - The mica, which is biotite partly altered to chlorite, is segregated into beds and shows the foliation very well. The minerals present and their proportions are; biotite - 15%, quartz - 50%, chlorite

after biotite - 30%, garnet - 3%, magnetite - 2%. Zircon is present as inclusions in the biotite.

Sample 13 Mica Schist

Location - The rock is from S12 T46N R30W about $\frac{1}{2}$ mile south of the bridge over the Michigamme River at Republic on Route 95.

Megascopic - The rock is a light colored mica schist with the lineation and bedding both distinct and parallel. Biotite, quartz, and garnet are seen.

Microscopic - The section shows lineation with the biotite being well oriented. Minerals present are; biotite - 50%, quartz - 47%, garnet - 1%, magnetite - 1%, chlorite after the biotite - 1%. Zircon is present within the biotite.

Metabasites

The term metabasite is used to denote the basic meta-igneous rocks that were studied. The term was taken from the Glossary of Geology and Related Sciences and was originated by Hackman in 1907.

Republic Area. Sample 14 Metabasite

Location - The sample was taken from a dike intrusive into the iron formation from the outcrop at the bridge over the Michigamme River on Route 95 at Republic.

Megascopic - The rock is dark colored and massive. No foliation is observable. Garnets, quartz, light colored feldspar, biotite, chlorite and an iron oxide can be identified. The feldspar is present both as large phenocrysts and smaller, but still observable, grains.

Microscopic - There is a slight lineation of the biotite in the section which can be attributed to the affects of shearing. The minerals present are; quartz - 2%, albite-oligoclase - 80%, biotite 10%; garnet - 2%,

staurolite - 2%, magnetite - 2%, chlorite after biotite - 2%. Zircon is present as inclusions within the biotite.

Sample 15 Metabasite

Location - The rock was taken from S12 T46N R30W about $\frac{1}{2}$ mile south of the bridge on Route 95 at Republic.

Megascopeic - The rock is dark colored and shows some foliation.

The visible minerals are garnet, biotite, quartz and chlorite.

Microscopic - The section shows some degree of parallelism of the biotite. Minerals present are; biotite - 35%, garnet - 25%, quartz - 5%, oligoclase-andesine - 30%, orthoclase - less than 1%, chlorite - 4%, zircon (in the biotite) - less than 1%.

Sample 16 Metabasite

Location - The rock was taken from S1 T46N R30W just south of the road into Republic at the bridge over the Michigamme River on Route 95.

Megascopeic - The rock is dark colored with a schistose texture.

Visible minerals are; garnet, staurolite, biotite, quartz and chlorite.

Microscopic - Distinct foliation is shown by the biotite. Minerals present are; quartz - 15%, garnet - 15%, staurolite - 10%, biotite - 40%, chlorite after biotite - 18%, magnetite - 2%.

Sample 17 Metabasite

Location - The sample was taken from S19 T46N R29W on the old Route 95 about 1 mile south of the mine at Republic.

Megascopeic - The rock is dark colored and shows slight lineation.

Visible minerals are; quartz, biotite, and light colored feldspar.

Microscopic - The biotite shows a small amount of lineation. Minerals present are; quartz - 2%, andesine-labradorite - 68%, hornblende - 10%, biotite - 15%, apatite - 3%, magnetite - 2%.

Michigamme Area. Sample 18 Metabasite

Location - The sample was taken from S22 T48N R31 W about two miles east of Three Lakes on Route 41.

Megascopic - The rock is fine grained, dark colored and massive.

Hornblende, quartz and pyrite are visible.

Microscopic - No lineation is seen. Minerals present are; green hornblende - 65%, quartz - 2%, albite-oligoclase - 15%, biotite - 10%, chlorite after biotite and hornblende - 6%, apatite, calcite and magnetite - 2%. The rock approaches a hornblendite.

CHAPTER IV

METAMORPHISM

Metamorphism

"Metamorphism is the mineralogical and structural adjustment of solid rocks to physical or chemical conditions which have been imposed at depths below the surface zones of weathering and cementation and differ from the conditions under which the rocks in question originated." (Turner and Verhoogen, 1960, p. 450)

A number of theories and concepts have been devised to explain various metamorphic intensities. The most recent concept, metamorphic facies, appears to yield the best answers in the light of field and experimental studies. All concepts in this area suffer from a major lack of knowledge about the actual processes and conditions involved in metamorphism, but the concept of metamorphic facies appears flexible enough to include new facts as they are discovered. Turner and Verhoogen (1960, p. 503) define metamorphic facies as: "a series of metamorphic mineral assemblages conforming to the following specifications:

- 1 - Some or all of the assemblages are associated in space or time. The whole association tends to recur in other regions and in rocks of different ages.
- 2 - The mineral composition of each assemblage is strictly a function of the bulk chemical composition as it now exists regardless of the effects of metasomatism.

3 - The total number of essential mineral phases in common rocks of the facies as a whole is relatively small. Each assemblage consists of a limited number . . . of these phases.

4 - There is no textural or other evidence of mutual replacement by minerals of the same facies. "

For a discussion of the above, the reader is referred to Turner and Verhoogen (1960).

Metamorphic Facies in Iron Formation

The metamorphic mineral assemblages of iron formations have only recently been investigated, and little has been done in correlating these assemblages to pelitic ones. This lack of comparison of iron formation assemblages to products of the same metamorphic intensity in pelitic rocks prevents the use of metamorphosed iron formations in determining metamorphic grade.

James (1955) and Henrickson (1956) studied the metamorphism of the Marquette District including the iron formations. Kranck (1961) studied the metamorphosed iron formation in the Mt. Reed area in Quebec, and Mueller (1960) examined that of the Mt. Wright, Quebec area. The metamorphosed formations mapped in the Quebec areas were studied from a thermodynamic and thermochemical standpoint. Correlation with pelitic assemblages was not done. The iron formations of the Marquette District were examined in order to correlate with pelitic assemblages, but neither James nor Henrickson specified the metamorphic mineral assemblages. Both of these authors determined the minerals in the iron formations for specific grades but without describing the whole assemblages in which each occurred. As can be seen from both James' and Henrickson's results (Tables 1 and 2) none of the minerals found are confined to only one zone. It is possible that

Table 1. Chart Showing Tentative Conclusions Regarding Metamorphism of Principal Types of Iron Formations *

Sedimentary Facies	Metamorphic		
	Chlorite and Biotite Zones	Garnet and Staurolite	Sillimanite Zone
Sulfide	Pyrite Carbon Quartz Sericite	Pyrite Graphite Quartz Micas Garnet (rare)	Pyrite Graphite Pyrrhotite? Micas Garnet
Carbonate	Carbonate Quartz Stilpnomelane Minnesotaite	Grunerite Quartz Magnetite Carbonate	Grunerite Quartz Magnetite Pyroxene
Silicate (nonclastic)	Minnesotaite Stilpnomelane Quartz Carbonate Magnetite	Grunerite Quartz Magnetite	Grunerite Quartz Magnetite Pyroxene
Silicate (part-clastic)	Chlorite Stilpnomelane Quartz Carbonate Magnetite Biotite	Grunerite Quartz Magnetite Epidote Garnet Carbonate Mica	Grunerite Quartz Magnetite Garnet Hornblende Pyroxene
Oxide (Magnetite Banded)	Magnetite Quartz Stilpnomelane Minnesotaite Carbonate	Magnetite Grunerite Quartz Garnet	Magnetite Grunerite Quartz Pyroxene Garnet
Oxide (Hematite Banded)	Hematite Quartz Magnetite Calcite	Specular Hematite Quartz Magnetite Calcite	Specular Hematite Quartz Magnetite Calcite

* (After James, 1955)

Table 2. Metamorphic Mineral Associations in the Marquette District Iron Formations*

Chlorite Zone		Not fully determined.
Biotite Zone		Minnesotaite Stilpnomelane
Garnet Zone	Grunerite Quartz Biotite Muscovite Magnetite	Grunerite Quartz Hornblende Biotite Garnet Magnetite
Staurolite Zone	Quartz Grunerite Biotite Muscovite Magnetite Blue-green amphibole	Grunerite Quartz Hornblende Biotite Garnet Magnetite Blue-green amphibole
Sillimanite Zone	Same as staurolite zone, but grunerite, quartz, magnetite, and blue-green amphibole predominate.	

*(From Henrickson, 1956)

the assemblages for each zone might be distinctive enough to enable one to differentiate between metamorphic zones in the iron formation itself but further work needs to be done before this is definitive. The assemblages of the Quebec iron formations (Tables 3 and 4) contain minerals that are not found in iron formation in the Marquette District, and the use of these assemblages for the Marquette District does not appear to be valid. Some of the minerals in the assemblages that Kranck found may be comparable to those of the Marquette iron formations (e.g., cummingtonite-grunerite, calcite and ferrodolomite-carbonate) but more evidence is needed (either laboratory or field) before one can make these substitutions.

Table 3. Metamorphic Mineral Assemblages for Mt. Wright Area Iron Formation*

Assemblage A	Assemblage B		
	1	2	3
Cummingtonite	Actinolite	Cummingtonite	Ca-pyroxene
Ca-pyroxene	Talc	Actinolite	Actinolite
Actinolite	Magnetite	Talc	Magnetite
Magnetite	Hematite	Magnetite	Hematite
Calcite	Calcite	Quartz	Calcite
Quartz	Dolomite		Quartz
	Quartz		

*(From Mueller, 1960)

Table 4. Metamorphic Mineral Assemblages for the Mt. Reed Area Iron Formation*

The assemblages are listed in order of increasing metamorphic grade.

- a - siderite - ferrodolomite - greenalite - quartz
calcite - ferrodolomite - greenalite - quartz
- b - calcite - ferrodolomite - greenalite - quartz
ferrodolomite - greenalite - minnesotaite - quartz
ferrodolomite - minnesotaite - siderite - quartz
- c - calcite - ferrodolomite - minnesotaite - quartz
siderite - ferrodolomite - cummingtonite - quartz
- d - calcite - ferrodolomite - cummingtonite - quartz
siderite - ferrodolomite - cummingtonite - quartz
- e - calcite - ferrodolomite - cummingtonite - quartz
ferrodolomite - cummingtonite - ferrohypersthene - quartz
- f - calcite - ferroaugite - cummingtonite - quartz
ferroaugite - cummingtonite - ferrohypersthene - quartz
- g - calcite - ferroaugite - ferrohypersthene - cummingtonite - quartz
- h - wollastonite - ferroaugite - quartz
ferroaugite - ferrohypersthene - quartz

*(From Kranck, 1961)

Metamorphic Facies in Metabasites

The mineral assemblages of the metamorphosed basic dikes have been well studied and described. The metabasites of the Marquette District can easily be placed within the proper facies provided that the assemblages are fairly complete. A lack of plagioclase feldspar in the assemblage, in most cases, makes it extremely difficult to place the rock within the metamorphic grade to which it belongs if other distinctive minerals are not present. This is due to the fact that most of the other minerals found in these rocks do not form a distinctive enough assemblage to enable it to be distinguished from the assemblages of other facies.

The metabasites of the Marquette District that were studied, along with the critical assemblages of each rock, are presented below in Table 5.

Table 5. Mineral Assemblages of the Marquette Metabasites

Sample No.	Mineral Assemblage
14	Biotite - garnet - staurolite - albite oligoclase - quartz Almandite-amphibolite Facies Staurolite-almandite subfacies
15	Garnet - orthoclase - quartz - oligoclase andesine - biotite Almandite-amphibolite Facies Sillimanite subfacies
16	Garnet - staurolite - biotite - quartz Almandite-amphibolite Facies Staurolite-almandite subfacies
17	Quartz - hornblende - biotite - andesine Almandite-amphibolite Facies Sillimanite Facies
18	Quartz - biotite - hornblende - albite oligoclase Almandite-amphibolite Facies Staurolite-almandite subfacies

The facies classification of the various assemblages shown depends on the presence of plagioclase and/or staurolite. Plagioclase is fairly sensitive to changes in metamorphic intensity and is therefore valuable in the determination of facies. According to Turner and Verhoogen, the pair staurolite-almandite, becomes stable at the staurolite isograd and unstable at the kyanite isograd, and forms the pair kyanite-almandite, or at the sillimanite isograd (in the absence of the kyanite-almandite facies), the pair sillimanite-almandite. James (1955) found an occurrence of staurolite-sillimanite at the Peavy Dam in Iron County. He suggests the possibility of the staurolite remaining in the rock as a metastable phase. Since this reaction has been postulated for pelitic schists only, its effects on a basic assemblage may be questionable. The possibility of the staurolite being in a metastable condition is possible for sample 16 only. This is due to the fact that the plagioclase in sample 14 definitely indicates a lower grade than sillimanite, but the assemblage of sample 16 lacks any plagioclase as an indicator, and the assignment of the rock to staurolite-almandite subfacies is based on the almandite-staurolite pair only. It is more probable, however, that both staurolite containing assemblages belong in the staurolite-almandite subfacies.

Metamorphic Facies in Pelites

The metamorphic mineral assemblages of pelitic rocks are usually fairly distinctive for facies determination and have been well described. A desirable condition for the determination of the facies is a distinctive enough assemblage. The assemblages of the two pelitic schists described are deficient in this respect, in that the only minerals found in them are; quartz-biotite-garnet. The rocks are fairly coarse grained and were taken from Henrickson's Garnet zone. They are

placed in the Almandite-amphibolite zone on the bases of the coarseness of grain and the prior work of Henrickson.

Conclusions on the Metamorphism of the Marquette District

The primary purpose of this study is to determine whether or not a relationship can be found between the grain size of metamorphically recrystallized cherts in the Negaunee Iron Formation and the metamorphic grade. It is therefore necessary to know the metamorphic grade at each of the locations of the iron formation samples.

The study of the metamorphic rocks of the Marquette District (other than the Iron Formations) by this author, was done with the intent to check Henrickson's isograds. Henrickson (1956) drew a series of isograds for the Marquette District based upon both field and thin section study. On the basis of the 7 thin sections which are described by the author (samples 12 through 18) little can be stated beyond possibilities as the rocks represented are too few and too widely scattered. Samples 14 through 17 are from the Republic area and fall into Henrickson's sillimanite zone. Of these four, only two show assemblages that are characteristic of the sillimanite zone. The two samples with staurolite assemblages were taken about one mile from the two sillimanite zone assemblages. There are two possibilities present; the first, and most probable, is that the staurolite-sillimanite isograd lies between the two groups, the second is that the staurolite assemblages are either metastable or products of retrograde metamorphism. The other samples (number 12, 13 and 18) are in agreement with Henrickson's isograds.

The results of this part of the study seem to indicate that some revision in the isograds drawn by Henrickson is necessary. Due to the

small number of samples studied, however, it is not possible for the writer to do this with any degree of certainty. In view of this, the isograds drawn by Henrickson will be used, with a correction in the position of the staurolite-sillimanite isograd in the Republic area considered.

CHAPTER V

EXPERIMENTAL RESULTS

Statistical Methods

A valid measure of the distribution of grain size in recrystallized chert necessitates the measurement of a large number of grains within a single slide. The Chi-square test was employed in order to obtain the optimum number of grains needed to be measured for a single determination. Approximately 85% to 95% of the quartz grains in a single bed in slide number 3 were measured. This yielded a sample size of approximately 1000 grains. With the aid of a table of random numbers, smaller numbers of grains were taken from the original sample. These several samples were then compared with the initial 1000 grain sample by means of the Chi-square test. A sample size of 250 grains was found to be valid at the 0.10 percentile. Actual sample sizes that were used were approximately 300 to 350 grains, which was valid at about the 0.05 percentile. Slide number 3a-II was determined with a sample size of only 173 grains due to the small size of the chert bed.

In order to determine the closeness of fit of the various groups to each other, a test was needed that would be able to cope with more than two groups at the same time. The term group is used to indicate a single determination, e.g., Group 1 is the determination of slide number 1. It was decided to use the Simple Analysis of Variance for the following reasons: 1 - it is a fairly simple test to use; 2 - it can be used with any number of groups; 3 - the sample sizes for the various groups do not need to be equal; and 4 - it is a more powerful test than

the others that were considered, that is, it is more sensitive to variations within and between the groups and yields more information than the other tests.

Complex Analysis of Variance was not used due to the extremely large number of calculations which would probably demand the use of a computer.

The assumptions in the use of Simple Analysis of Variance are: that the variable under consideration, in this case the grain size of the metamorphically recrystallized chert, has a normal and continuous distribution in the population, or the sampling distribution of the means has a normal distribution; and that the variances within the population are homogeneous.

If these assumptions are not valid, a non-parametric test should be used. The reason for this is that the significance tables for the various parametric tests are based on the normality of the population sampled. The tests themselves are not invalidated when using data from a non-normal population (see Walker and Lev, p. 426). Often when the above assumptions are not met, the data can be transformed to meet them.

The data used in this study were tested for homogeneity of variance (assumption 2) and were found not to hold to this assumption in most cases; therefore, the use of any parametric statistical test becomes less useful due to the loss of the significance tables which are based upon the distribution of the statistic. Even in this situation, however, the Simple Analysis of Variance test is still more desirable than the others which are not as powerful and cannot cope with large numbers of groups with the same efficiency.

The results of the Simple Analysis of Variance test are given in Tables 7 to 9. The values with asterisks are those for which the assumption of homogeneity of variance is met and for which the

significance tables apply. For those sets in which the variances are not homogeneous, the most that can be said is that the groups differ. The degree of difference is not known other than from the values of F .

The statistic F , in the Simple Analysis of Variance, is the ratio of the estimate of variance between the groups to the estimate of variance within the groups, and may be considered to be the result of the test. A number of sets with values of F below 50 are grouped as if they were not significant (the validity of this is questionable) due to the closeness of the distribution curves. One reason for the extremely high values obtained on the Simple Analysis of Variance test is the large size of the samples. The test is sensitive to small variations in the distributions. At high sample sizes (greater than 100) the amount of allowable variation between the distributions is very small for non-significant F values. Inspection of the distribution curves obtained in this study shows that there is a great amount of variation between the curves on the coarse grained side of the distribution. In this study, variations on the coarse grained side of the curve affected the test to a greater degree than did the variations on the fine grained side.

For a fuller description of the statistical tests used, the reader is referred to Walker and Lev (1953) or to any other statistics text in which the material is discussed.

Presentation and Discussion of Data

The data on the grain size of the metamorphically recrystallized cherts are presented in Figures 6 to 27 and Tables 6 to 10. In a number of cases it was possible to sample independently a number of beds within a given slide. When this was done, the beds were differentiated by a Roman numeral (e.g., 7-I, 7-II, 7-III, and 7-IV).

Table 6. Sample Sizes, Means, Modes, and Standard Deviations of the Iron Formation Samples

Slide Number	Sample Size	Mean	Mode	Standard Deviation
1	---	-----	0.032 mm.	-----
2	312	0.094 mm.	0.080 mm.	0.028 mm.
3	312	0.148 mm.	0.112 mm. and/or 0.160 mm.	0.043 mm.
3a-I	373	0.148 mm.	0.112 mm. and/or 0.160 mm.	0.046 mm.
3a-II	351	0.140 mm.	0.112 mm. and/or 0.160 mm.	0.043 mm.
4-I	312	0.104 mm.	0.080 mm.	0.031 mm.
4-II	312	0.115 mm.	0.128 mm.	0.032 mm.
5	312	0.082 mm.	0.112 mm.	0.025 mm.
6	312	0.073 mm.	0.070 mm.	0.018 mm.
7-I	584	0.172 mm.	0.160 mm.	0.082 mm.
7-II	312	0.205 mm.	0.160 mm.	0.070 mm.
7-III	173	0.252 mm.	0.320 mm.	0.037 mm.
7-IV	383	0.210 mm.	0.160 mm.	0.029 mm.
7-V	432	0.178 mm.	0.160 mm.	0.058 mm.
8	312	0.250 mm.	0.200 mm.	0.081 mm.
9	312	0.090 mm.	0.100 mm.	0.023 mm.
10	312	0.111 mm.	0.100 mm.	0.040 mm.
11	312	0.202 mm.	0.160 mm.	0.076 mm.

Table 7. Results of the Analysis of Variance Between Areas

Areas	Slide Numbers	F*
Michigamme	5, 6	25.05
Republic- Champion	3, 3a-I, 3a-II, 7-II, 7-III, 7-IV, 7-V, 8, 11	96.88
Republic- Champion	3, 3a-I, 3a-II, 7-II, 7-III, 7-IV, 7-V	184.65
Republic- Champion	3, 3a-I, 3a-II, 8, 11	218.53
Republic- Champion	3, 3a-I, 3a-II, 9, 10	135.90
Champion- Republic	4-I, 4-II, 7-II, 7-III, 7-IV, 7-V, 8, 11	206.76
Champion- Republic	4-I, 4-II, 7-II, 7-III, 7-IV, 7-V	268.00
Champion- Republic	4-I, 4-II, 8, 11	328.83
Champion- Republic	4-I, 4-II, 9, 10	24.95
Michigamme- Republic	7-II, 7-III, 7-IV, 7-V, 5, 6, 8, 11	274.91
Michigamme- Republic	5, 6, 9, 10	140.31
Michigamme- Republic	5, 9	16.04
Michigamme- Republic	5, 10	112.30
Michigamme- Republic	6, 10	257.28
Michigamme- Republic	6, 9	97.32
Michigamme- Republic	5, 6, 8, 11	774.33

Continued

Table 7 - Continued

Areas	Slide Numbers	F*
Michigamme- Republic	5, 6, 7-III	477.77
Michigamme- Champion	5, 6, 4-I, 4-II	226.97
Michigamme- Champion	5, 4-I, 4-II	59.16
Michigamme- Champion	5, 4-I	72.16
Michigamme- Champion	5, 4-II	12.25
Michigamme- Champion	5, 6, 3, 3a-I, 3a-II	307.52
Republic- Clarksburg	2, 8, 11, 7-II 7-III, 7-IV, 7-V	266.61
Republic- Clarksburg	2, 9, 10	106.88
Republic- Clarksburg	2, 10	622.37
Republic- Clarksburg	2, 9	39.83
Republic- Clarksburg	2, 8, 11	682.50
Republic- Clarksburg	2, 7-II, 7-III, 7-IV, 7-V	332.39
Clarksburg- Michigamme	2, 5, 6	13.03
Clarksburg- Michigamme	2, 6	0.09
Clarksburg- Michigamme	2, 5	14.99
Clarksburg- Champion	2, 4-I, 4-II	1097.05
Clarksburg- Champion	2, 3, 3a-I, 3a-II	229.84

* F = 8.18 is significant at the .005 level for 2 and 120 degrees of freedom. The assumption of homogeneity of variance was not met in any of the above comparisons. The probabilities of the F values given in the above table, therefore, were not given.

Table 8. Results of the Analysis of Variance for the Republic Group

Slide Number	F	Probability of F for Those Comparisons in Which the Assumption of Homogeneity of Variance Was Met
7-I, 7-II	68.27	
7-I, 7-III	497.12	
7-I, 7-IV	66.35	
7-I, 7-V	104.72*	Less than .005
7-II, 7-III	26.47	
7-II, 7-IV	0.36	
7-II, 7-V	35.67	
7-III, 7-IV	18.64	
7-III, 7-V	101.74	
7-IV, 7-V	35.67	
7-I, 7-II, 7-III, 7-IV, 7-V	49.61	
7-II, 7-III, 7-IV, 7-V	33.55	
9, 10	73.35	
8, 10	760.58	
10, 11	360.93	
8, 9	1121.35	
10, 11	610.25	
8, 11	61.30*	Less than .005
7-II, 7-III, 7-IV, 7-V, 8, 11	30.13	
7-III, 8, 11	79.60	
7-III, 10, 9	196.86	
7-II, 7-III, 7-IV, 7-V, 9, 10	219.94	

* Indicates that the assumption of homogeneity of variance was met for the analysis of the slides so noted.

Table 9. Results of the Analysis of Variance for the Champion Group

Slide Number	F	Probability of F for Those Comparisons in Which the Assumption of Homogeneity of Variance Was Met
3, 3a-I, 3a-II, 4-I, 4-II	101.07	
4-I, 4-II	14.87	
3a-I, 3a-II	2.58*	Less than .005
3a-I, 4-I	209.34	
3a-I, 4-II	81.50*	Less than .005
3a-I, 3	0.07*	-----
3a-II, 4-I	147.07	
3a-II, 4-II	37.14*	Less than .005
3a-II, 3	1.28*	Greater than .250
3, 4-I	204.70	
3, 4-II	74.50*	Less than .005
3, 3a-I, 3a-II	3.75*	Less than .025

* Indicates that the assumption of homogeneity of variance was met for the analysis of the slides so noted.

Table 10. Metamorphic Grade of the Iron Formation Samples

Area	Slide Number	Metamorphic Grade
Negaunee Group	1	Chlorite
Clarksburg Group	2	Garnet
Champion Group	3, 3a-I, 3a-II, 4-I, 4-II	Staurolite
Michigamme Group	5, 6	Staurolite
Republic Group	7-I, 7-II, 7-III, 7-IV, 7-V, 8, 9, 10, 11	Sillimanite

Figure 5

Sketch of the location of
the Republic Iron Formation
Samples

all distances approximate

M
95

metabasite

55'

x sample 7

50'

x sample 11

Iron Formation

30'

x sample 9

25'

x sample 10

15'

x sample 8

to Republic

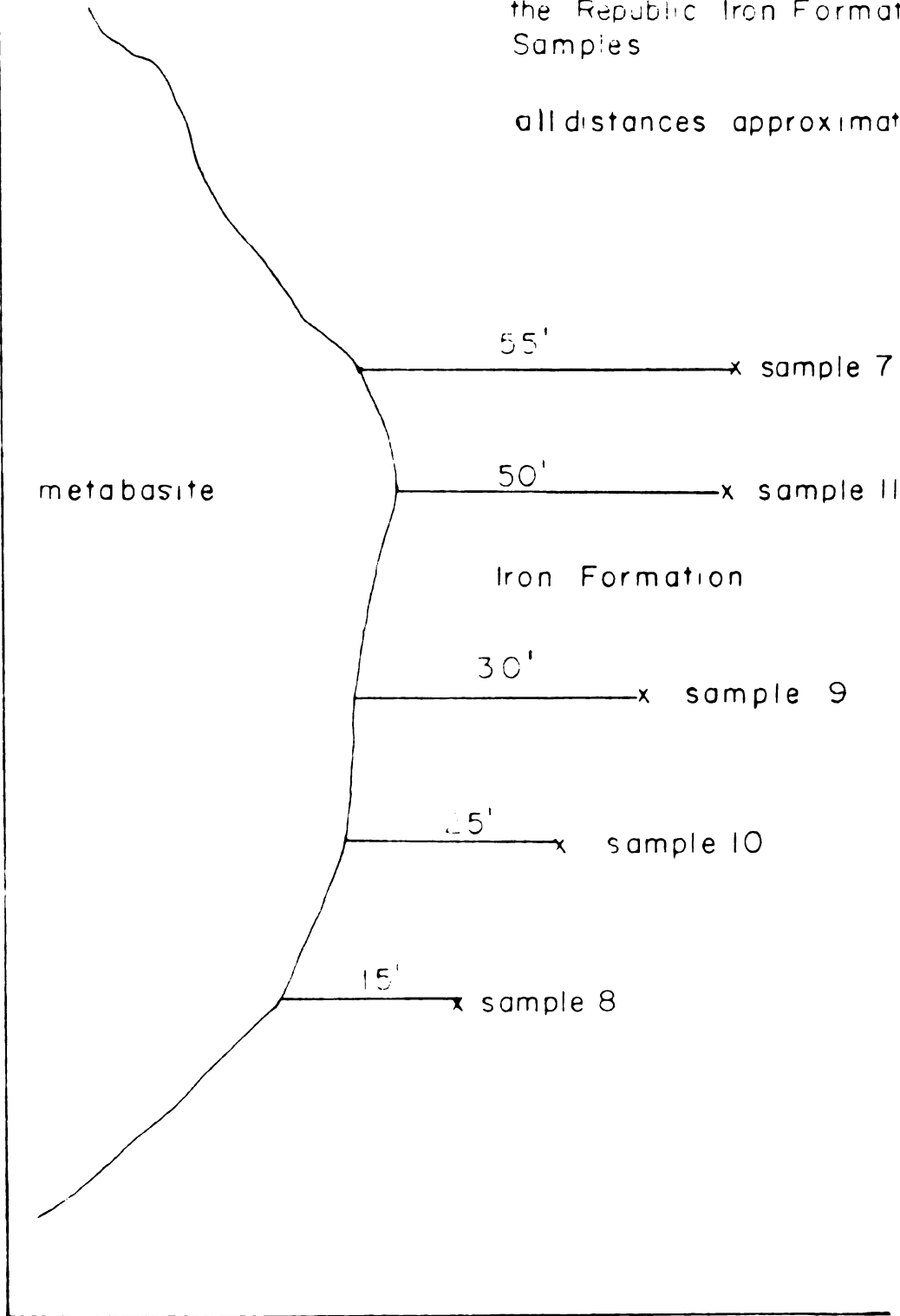
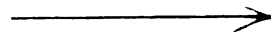


Figure 6 Plot of distance from the dike vs grain size means (x) and modes (o) for the Republic samples

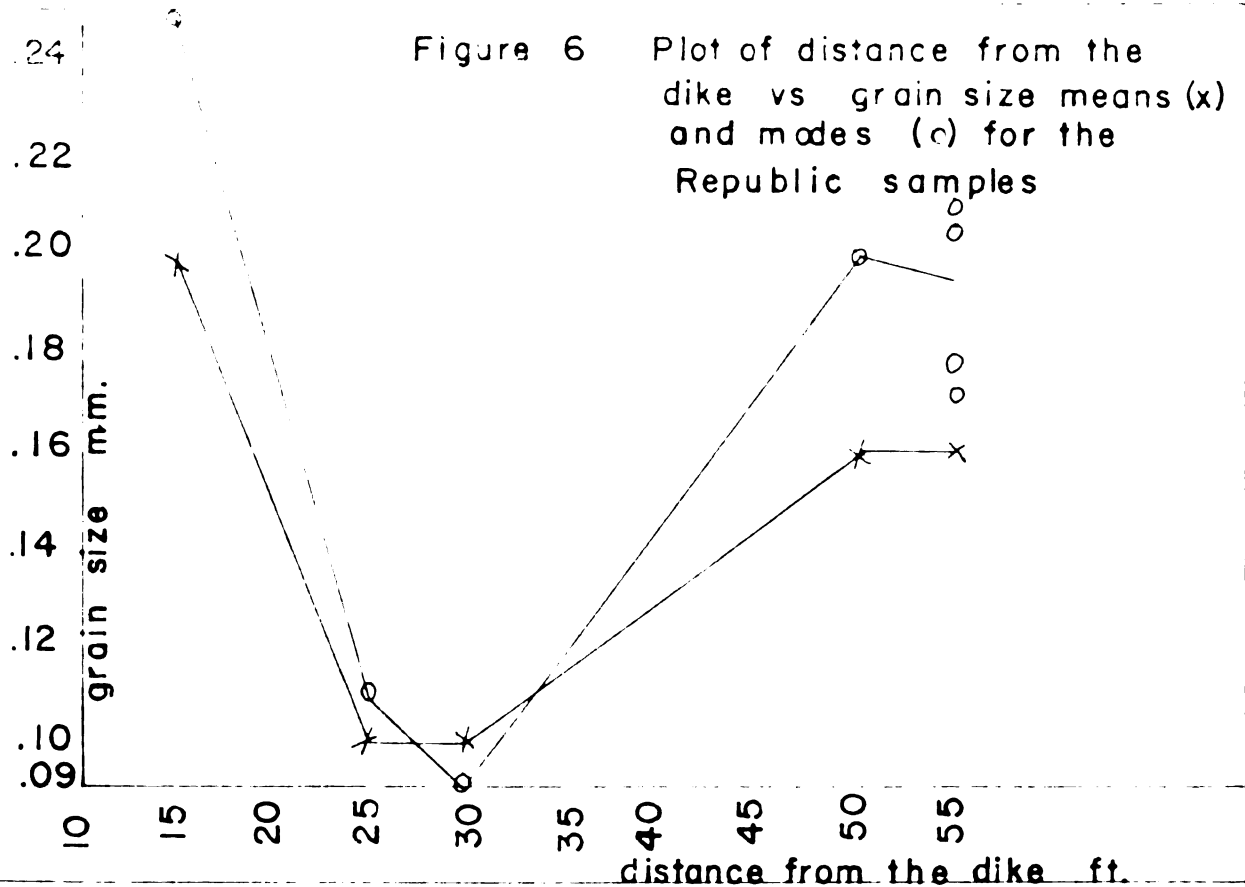


Figure 7 Grain size distribution curve for slide 2

mean - 0.094 mm.
mode - 0.080 mm.

N-312

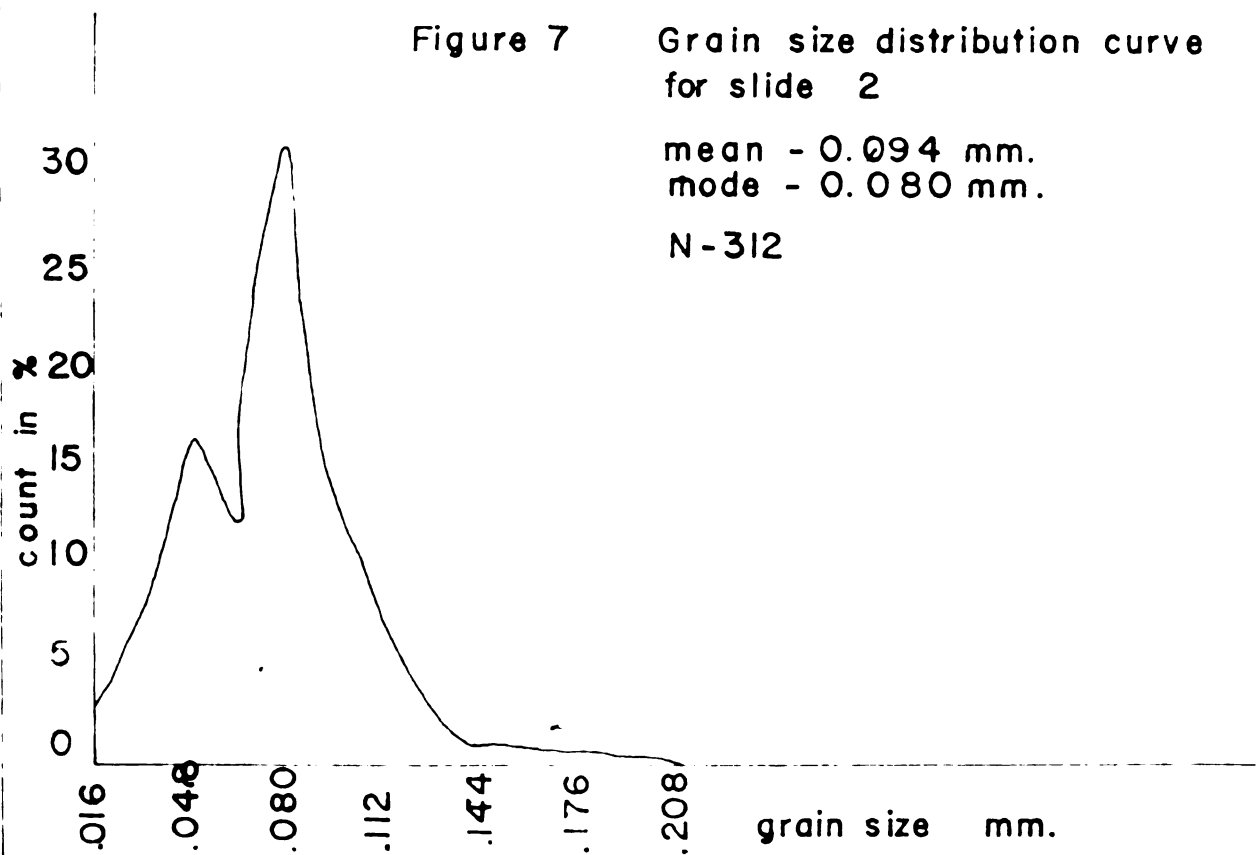


Figure 8

Grain size distribution
curve for slide 3

mean - 0.148 mm.

mode - 0.112 mm. &/or
0.160 mm.

N - 312

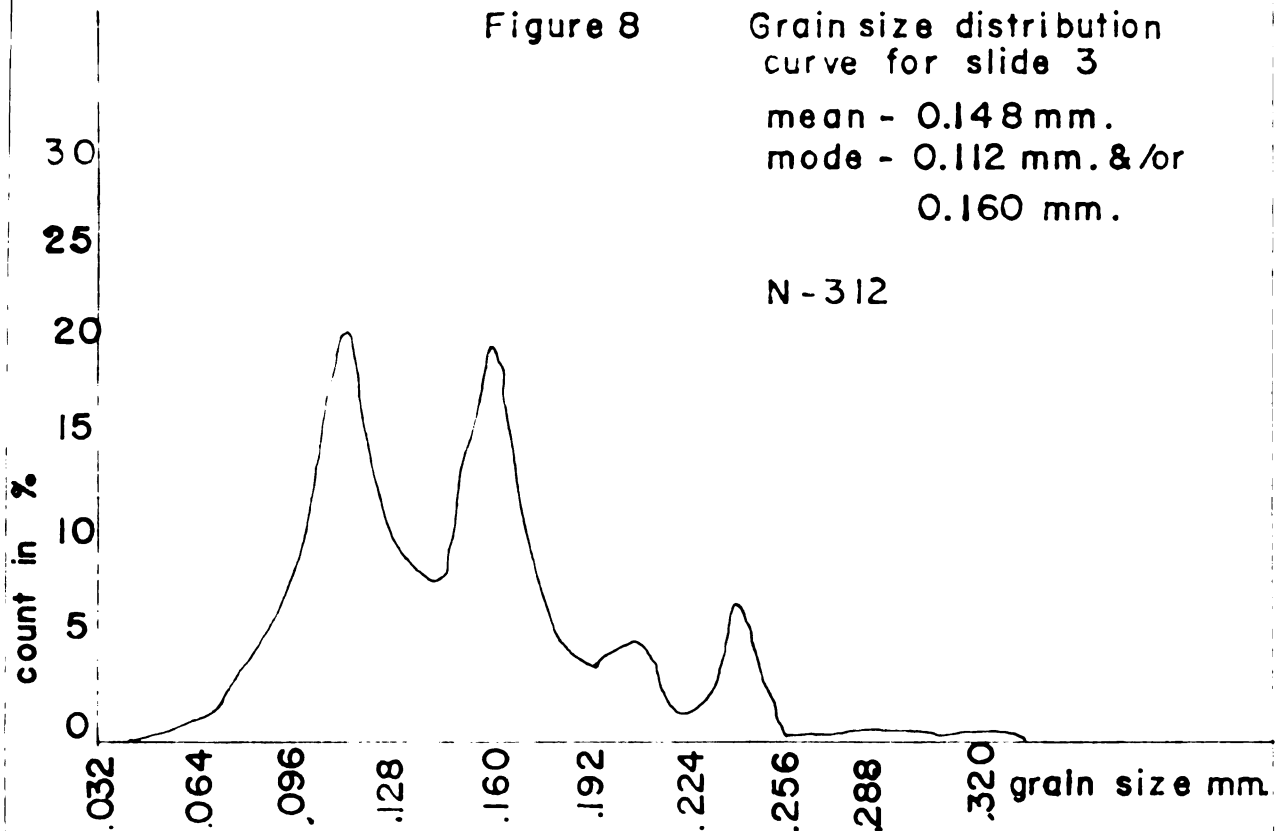


Figure 9

Grain size distribution
curve for slide 3a-I

mean - 0.148 mm.

mode - 0.112 mm.

N - 373

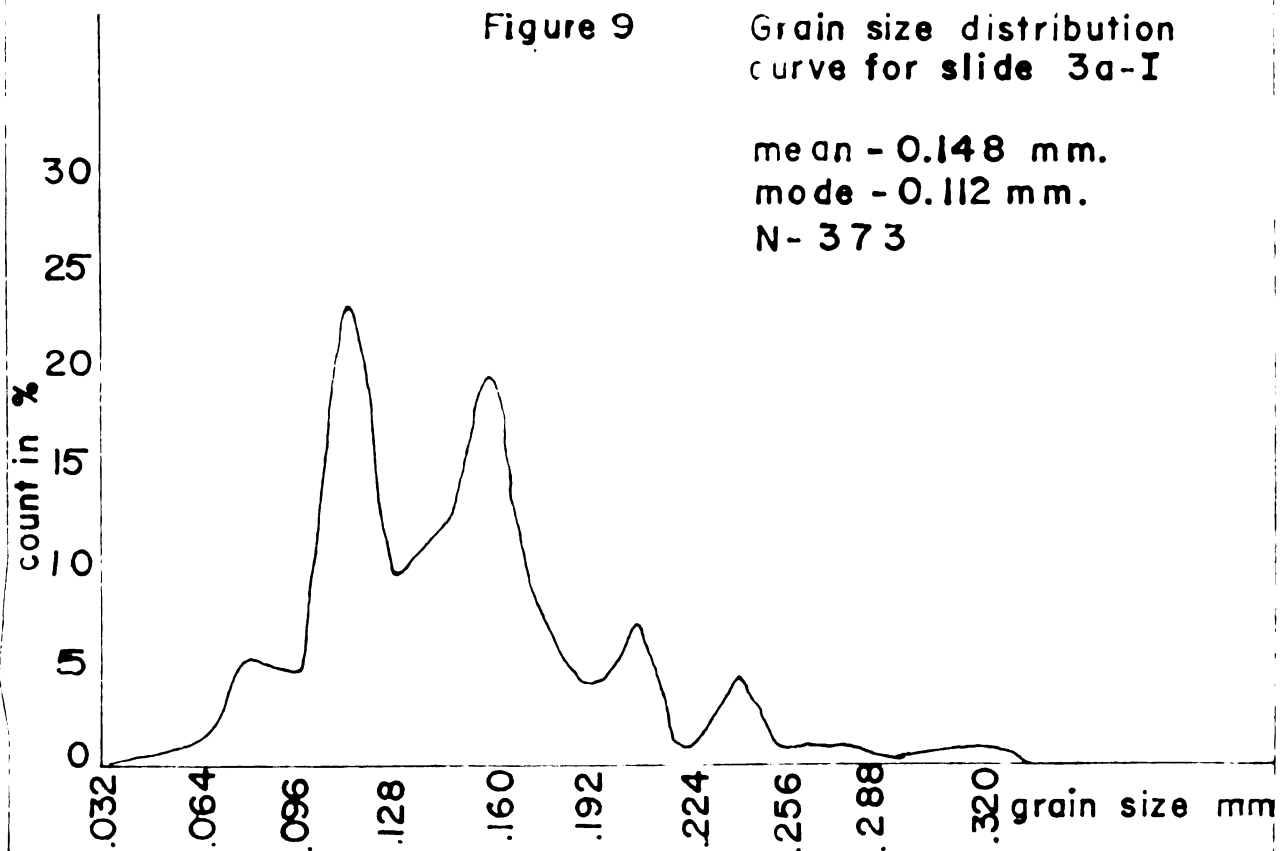


Figure 10

Grain size distribution
curve for slide 3a-II

mean - 0.140mm.

mode - 0.112 mm. &/or
0.160mm.

N - 351

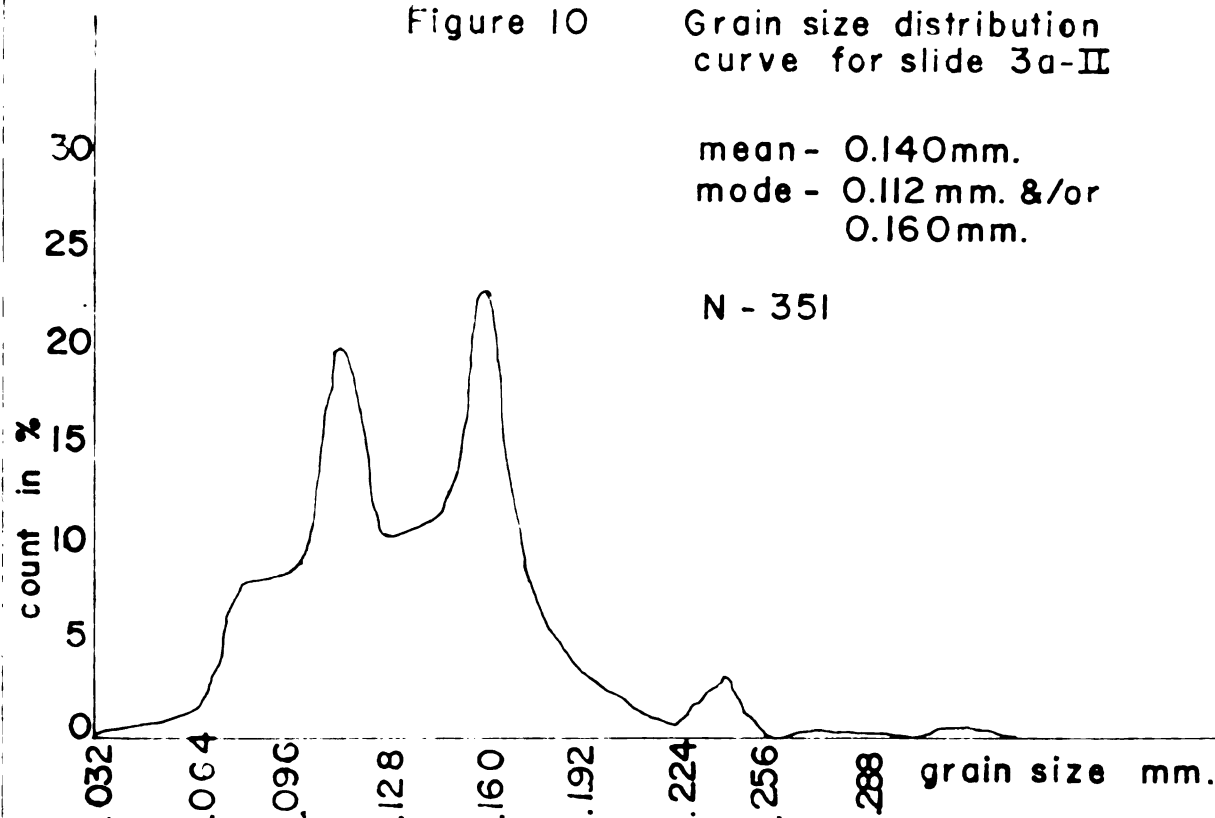


Figure 11

Grain size distribution
curve for slide 4-I

mean - 0.104 mm.

mode - 0.080 mm.

N - 312

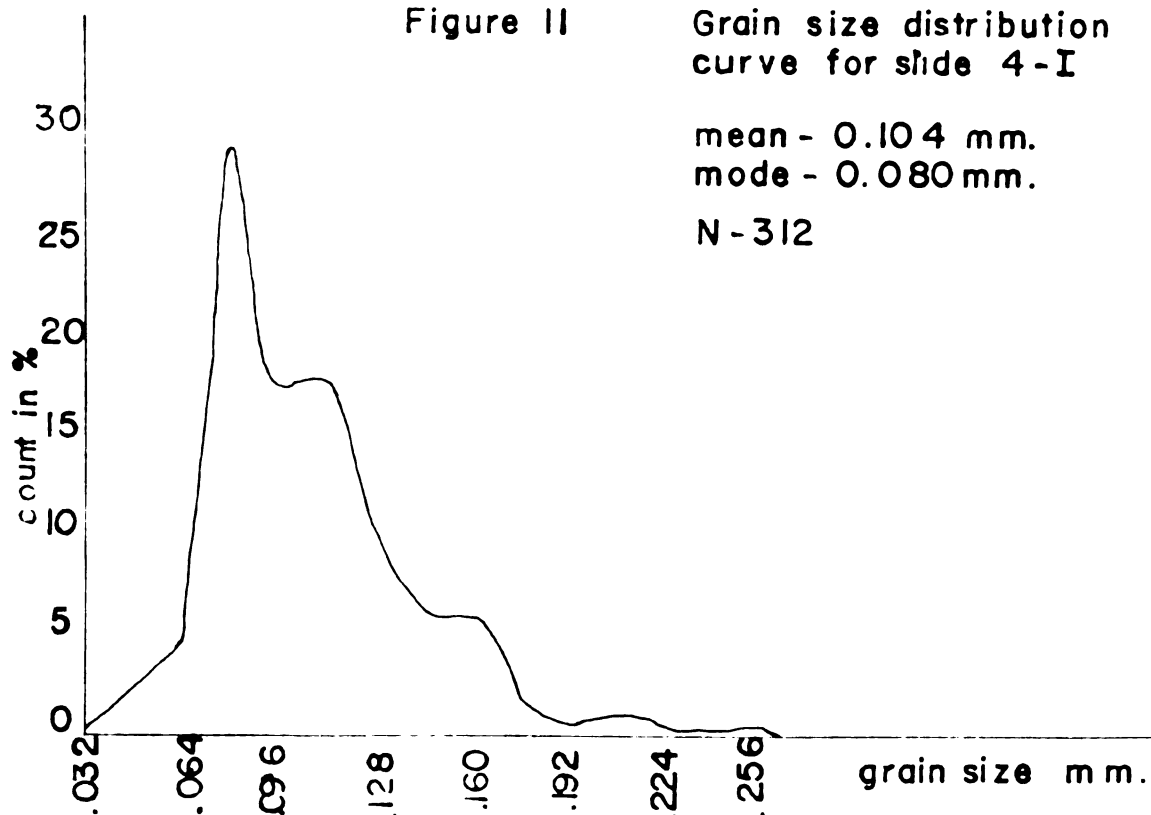


Figure 12

Grain size distribution curve
for slide 4-IImean - 0.115 mm.
mode - 0.080 mm.

N - 312

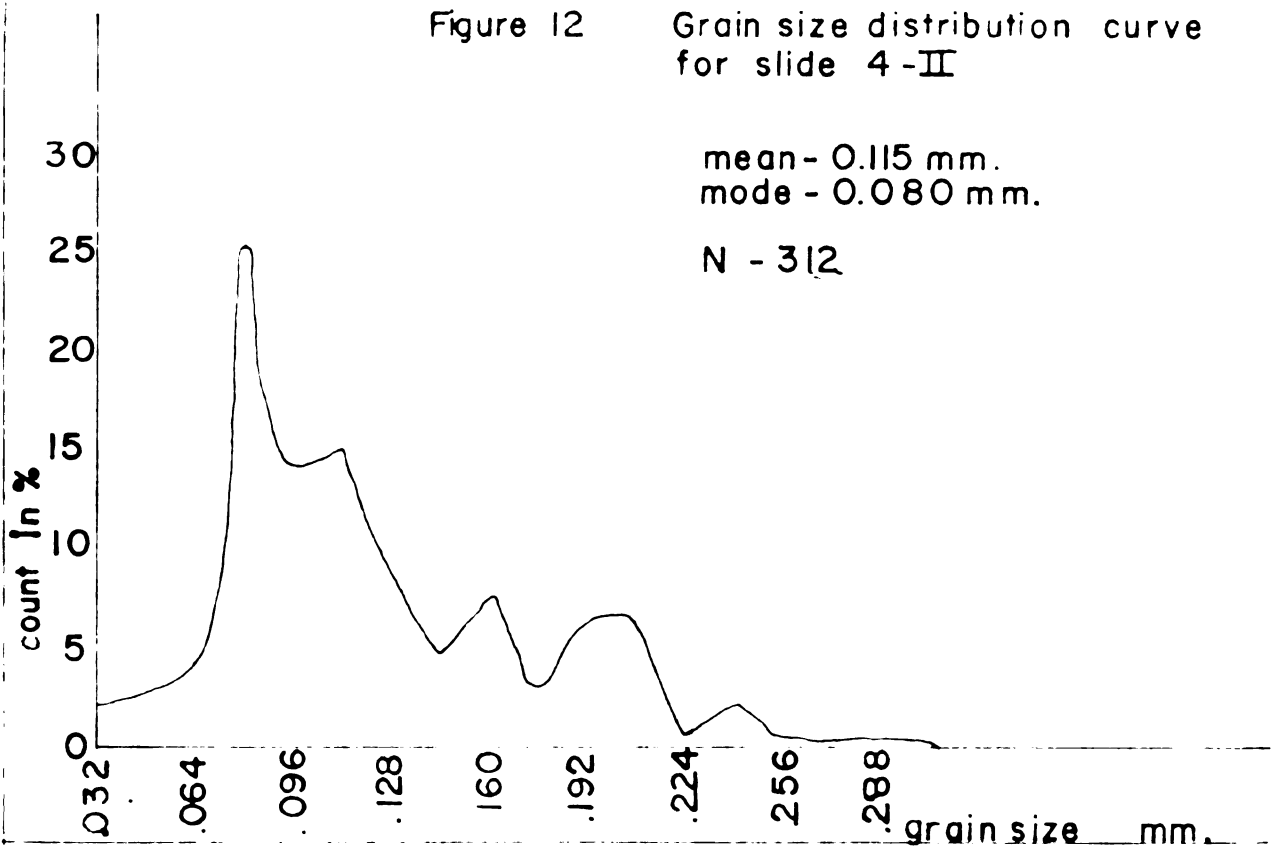


Figure 13

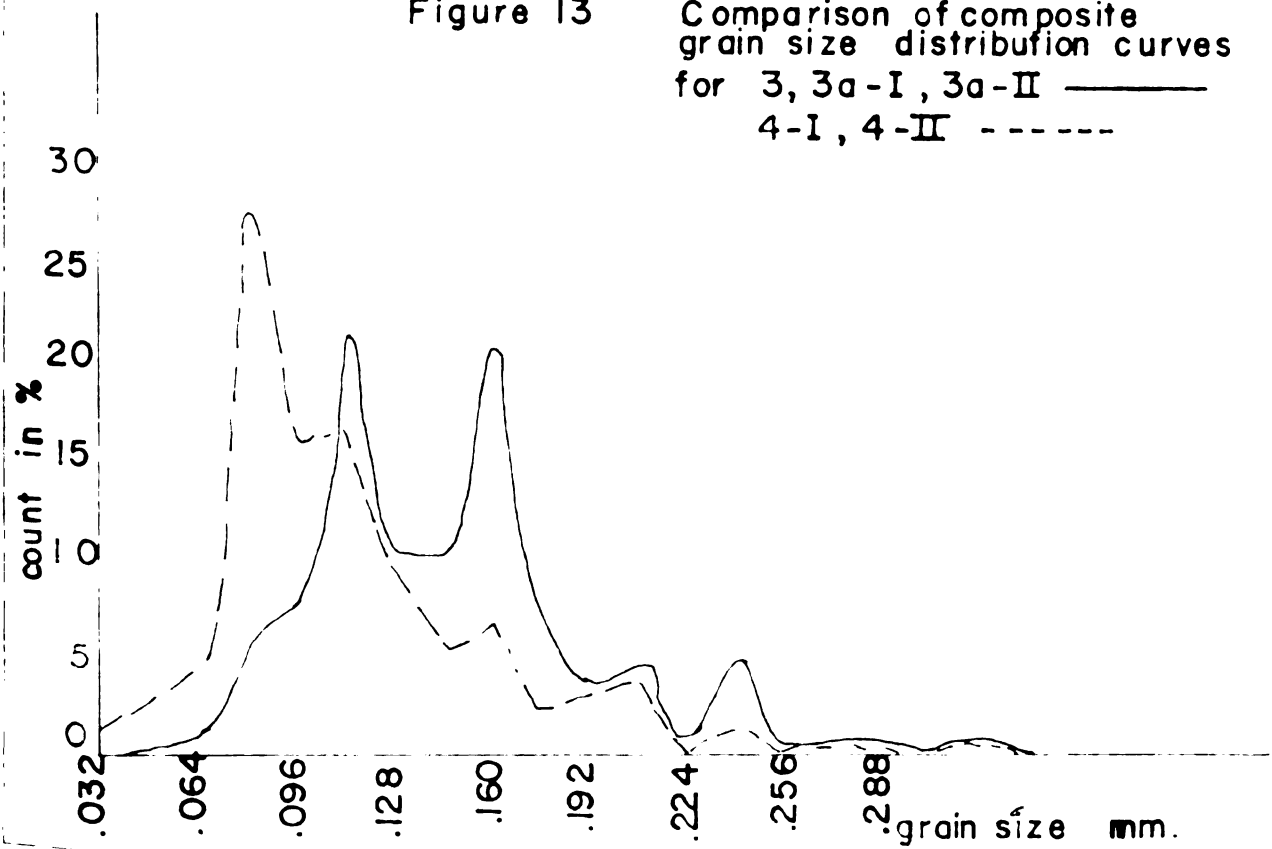
Comparison of composite
grain size distribution curves
for 3, 3a-I, 3a-II ———
4-I, 4-II - - - - -

Figure 14

Grain size distribution curve
for slide 5

mean - 0.082 mm

mode - 0.070 mm

N - 312

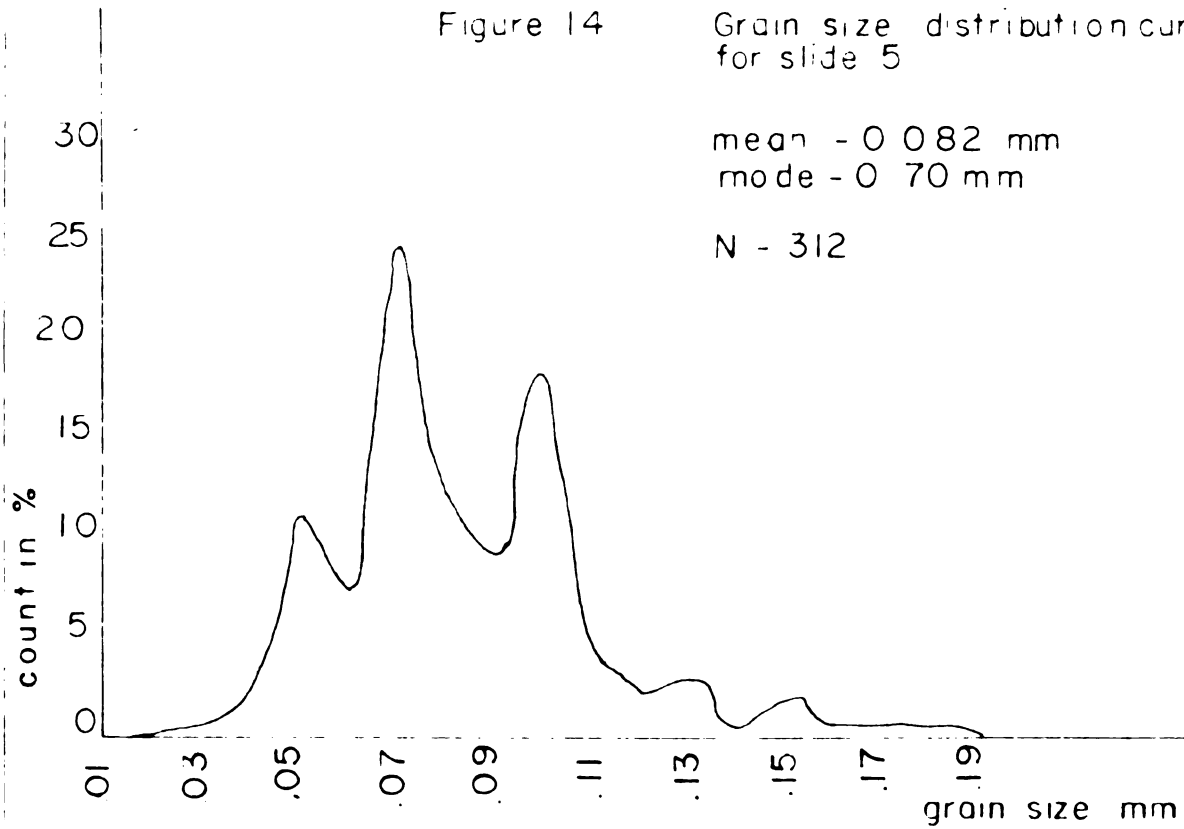


Figure 15

Grain size distribution
curve for slide 6

mean - 0.073 mm.

mode - 0.070 mm.

N - 312

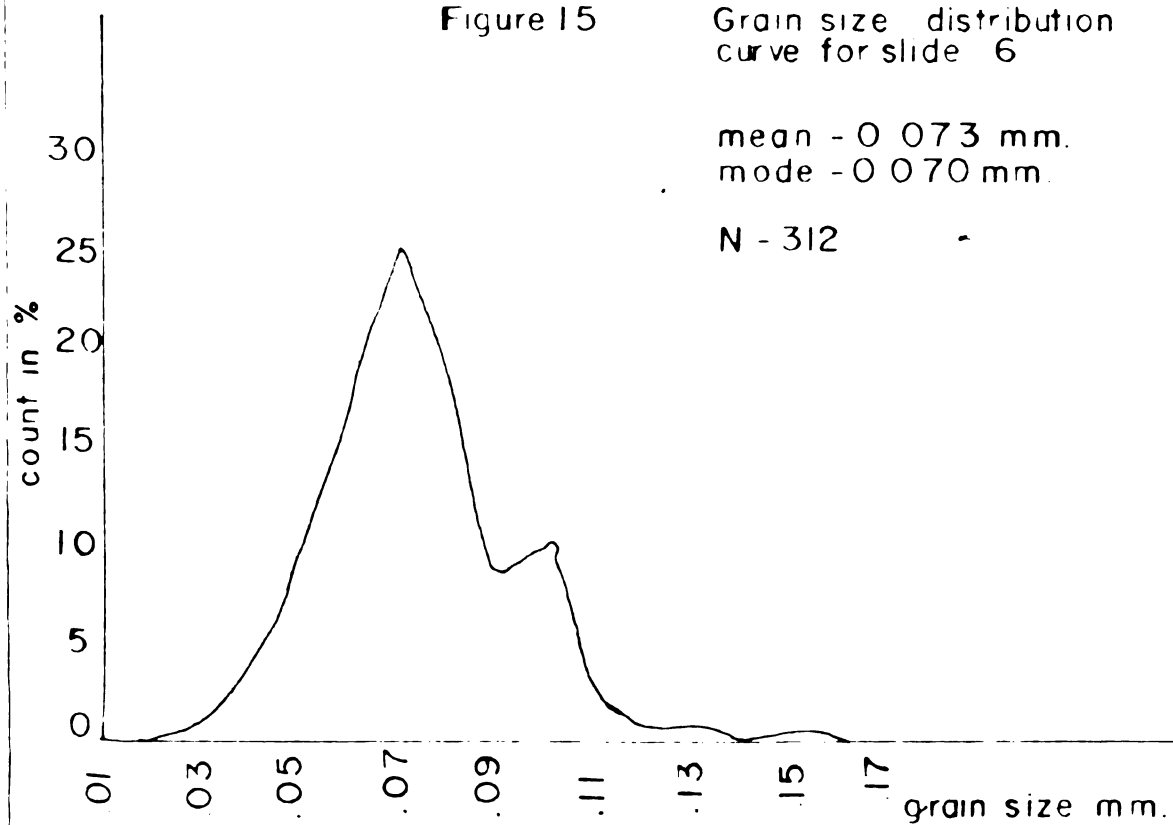


Figure 16

Grain size distribution
curve for slide 7-I

mean - 0.172 mm.

mode - 0.160 mm.

N - 584

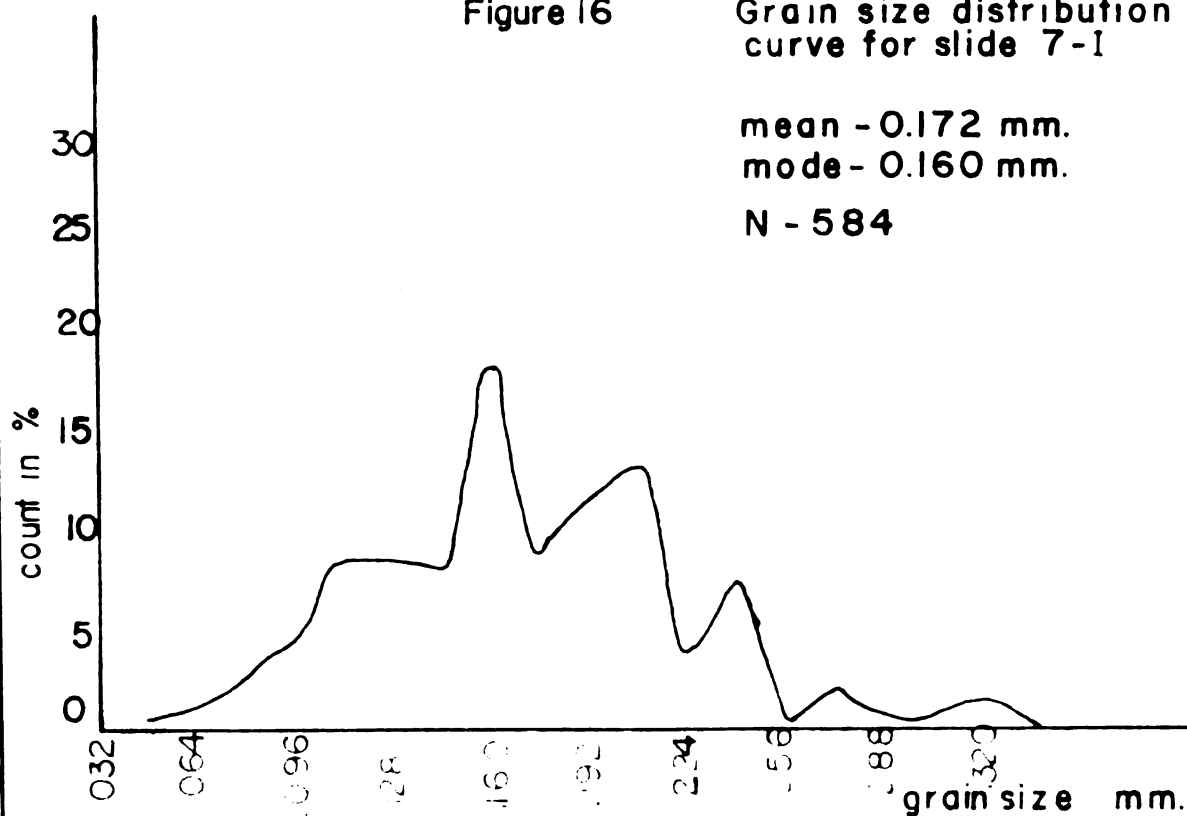


Figure 17

Grain size distribution
curve for slide 7-II

mean - 0.205 mm.

mode - 0.160 mm.

N - 312

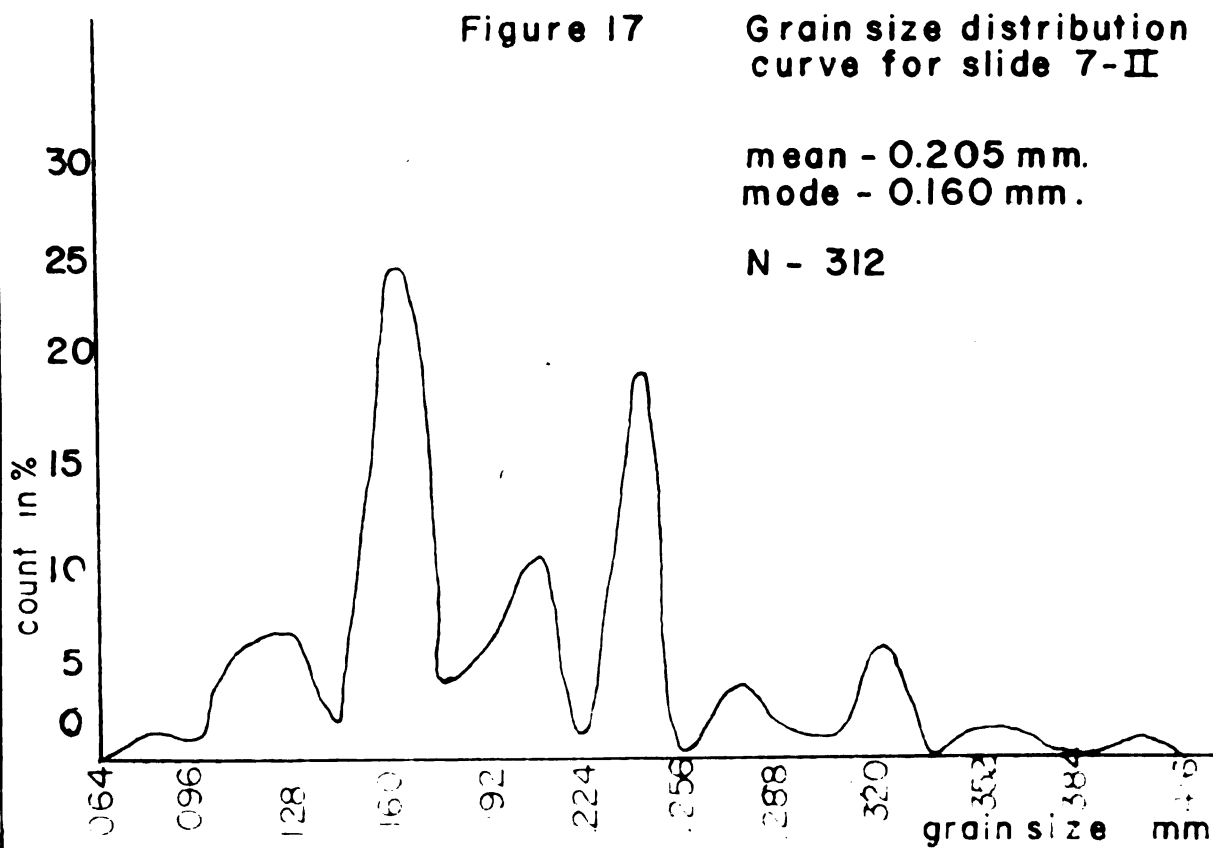


Figure 18

Grain size distribution curve
for slide 7 - III

mean - 0.252 mm.
mode - 0.320 mm.

N - 173

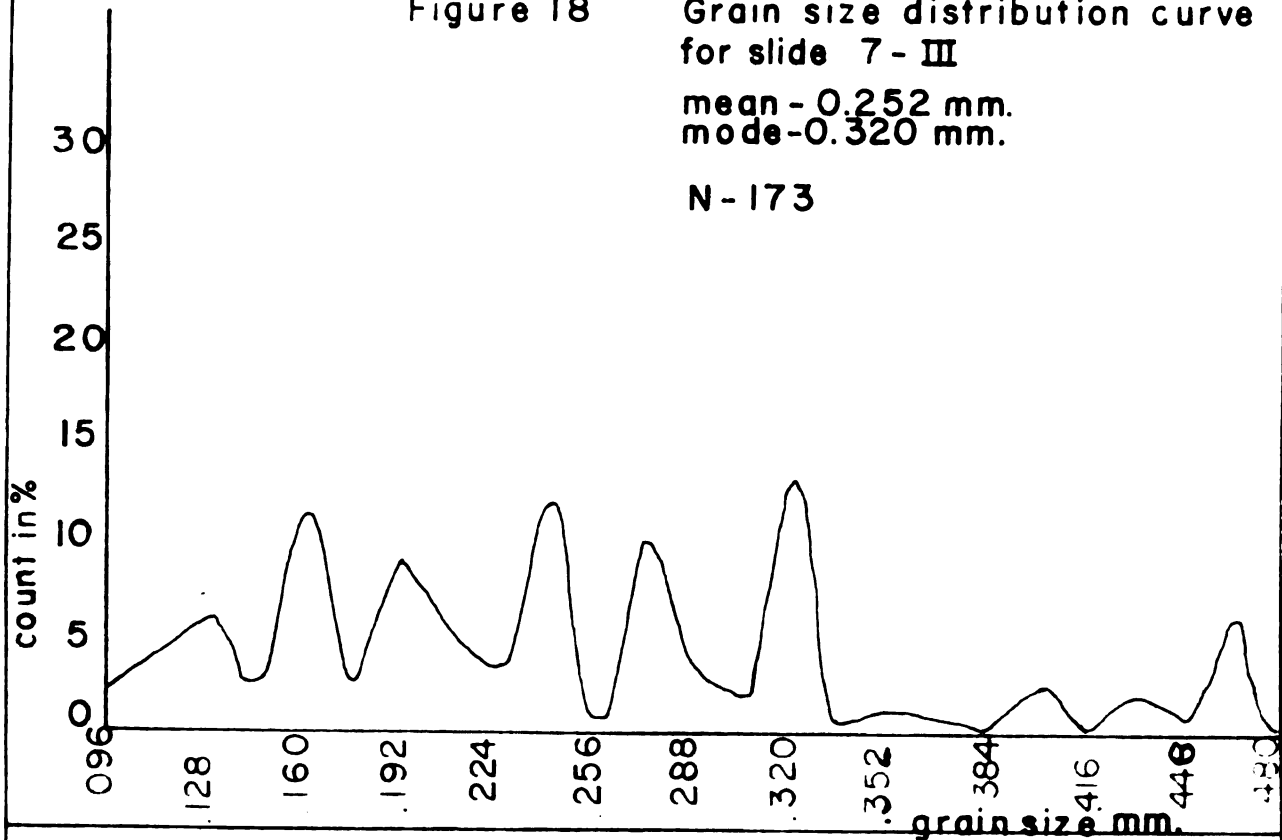


Figure 19

Grain size distribution curve
for slide 7 - IV

mean - 0.210 mm.
mode - 0.160 mm.

N - 383

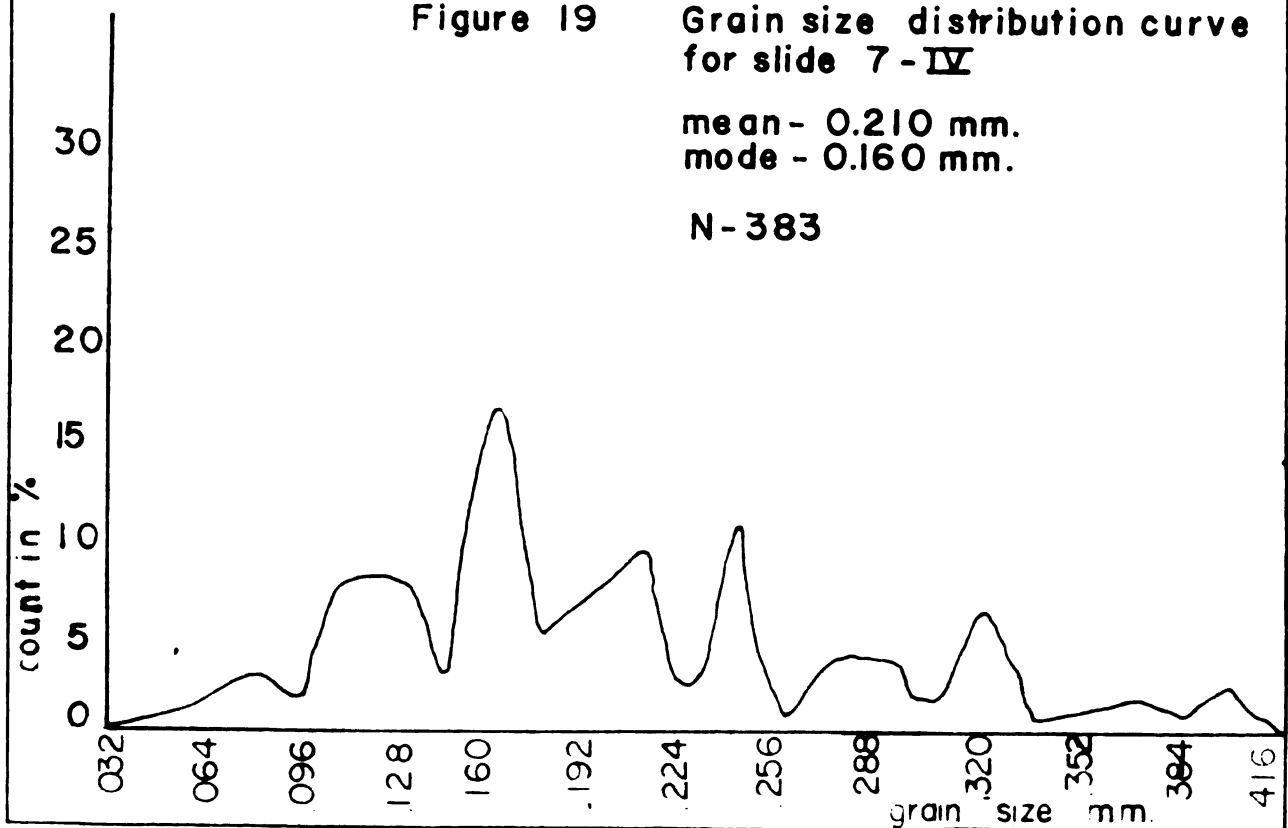


Figure 20

Grain size distribution
curve for slide 7-V

mean - 0.178 mm.

mode - 0.160 mm.

N - 432

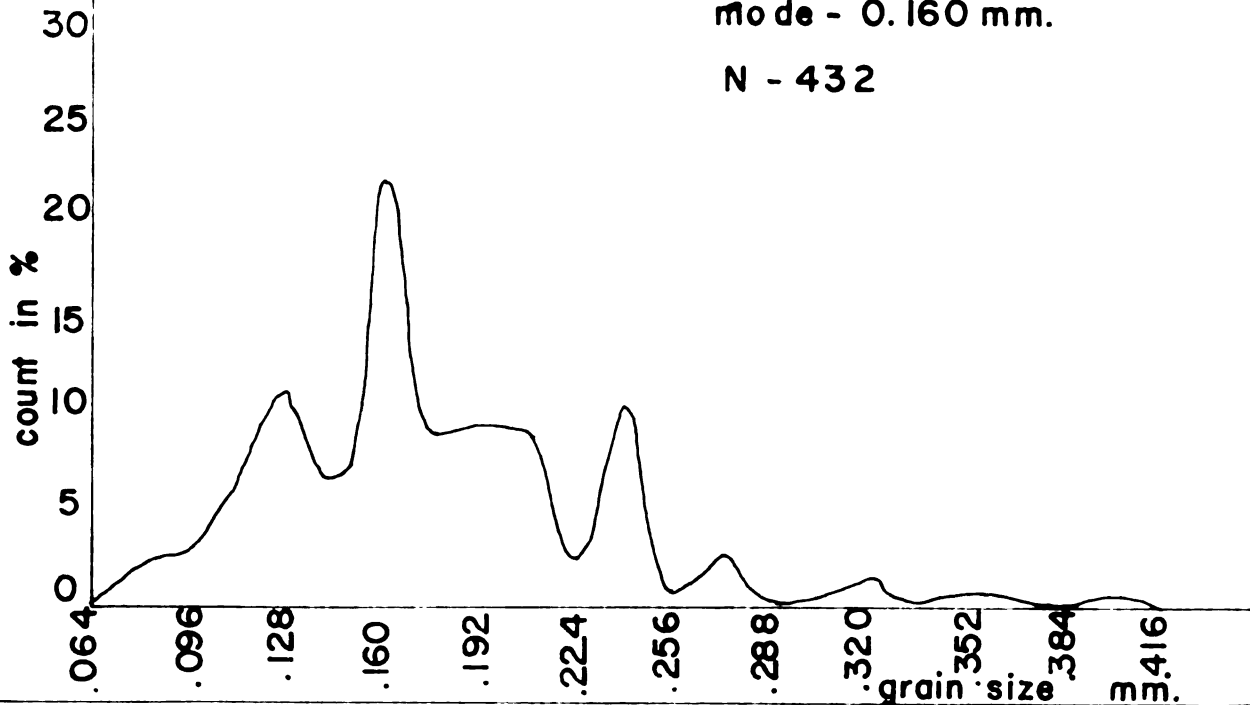


Figure 21

Composite grain size
distribution curve for slides
7-I, II, III, IV, V

mean - 0.190 mm.

mode - 160 mm.

N - 1884

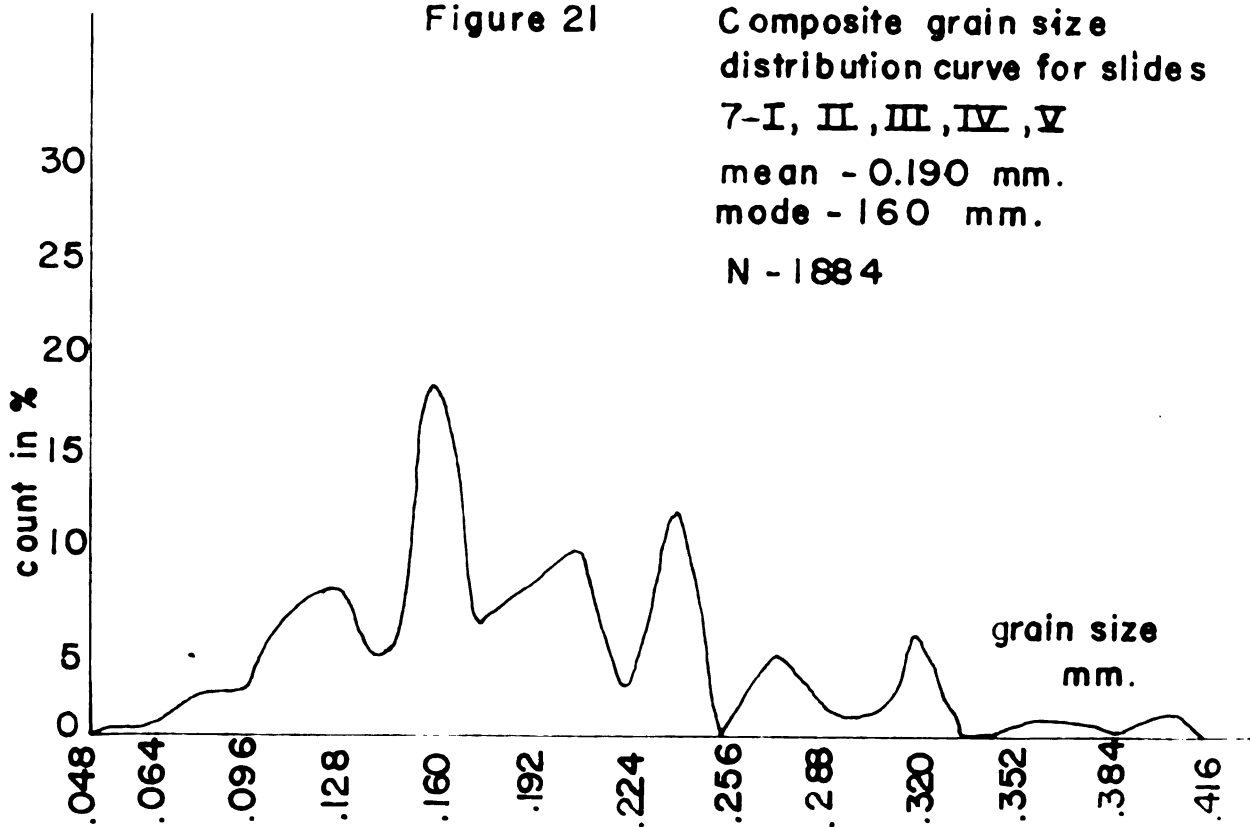


Figure 20

Grain size distribution
curve for slide 7-V

mean - 0.178 mm.

mode - 0.160 mm.

N - 432

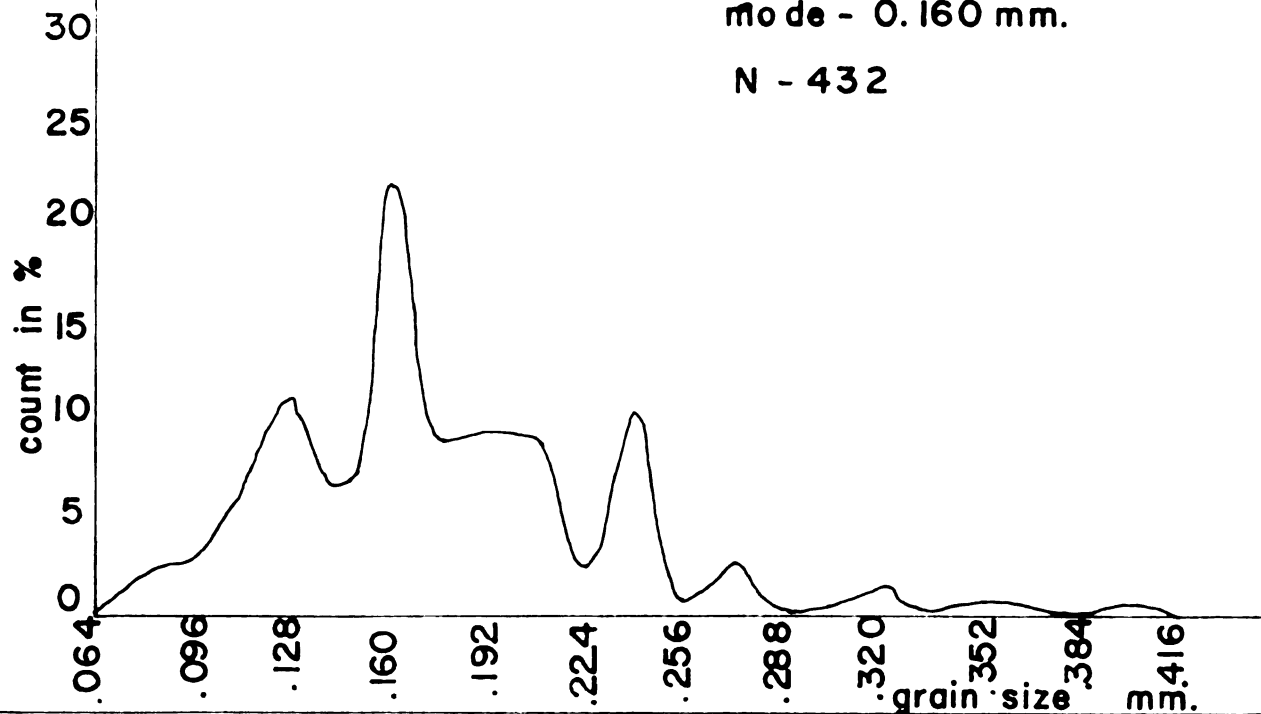


Figure 21

Composite grain size
distribution curve for slides
7-I, II, III, IV, V

mean - 0.190 mm.

mode - 160 mm.

N - 1884

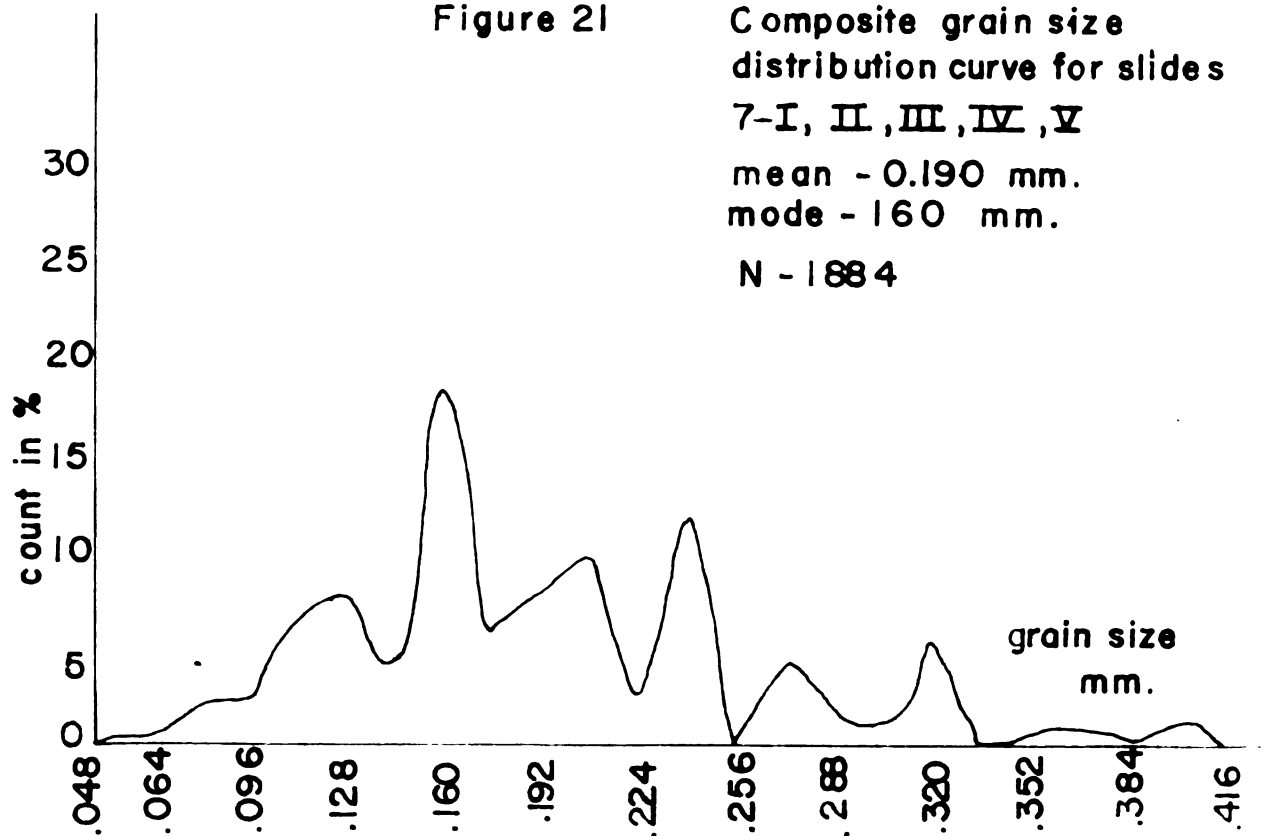


Figure 22

Grain size distribution curve
for slide 8

mean - 0.250 mm.

mode - 0.200 mm.

N - 312

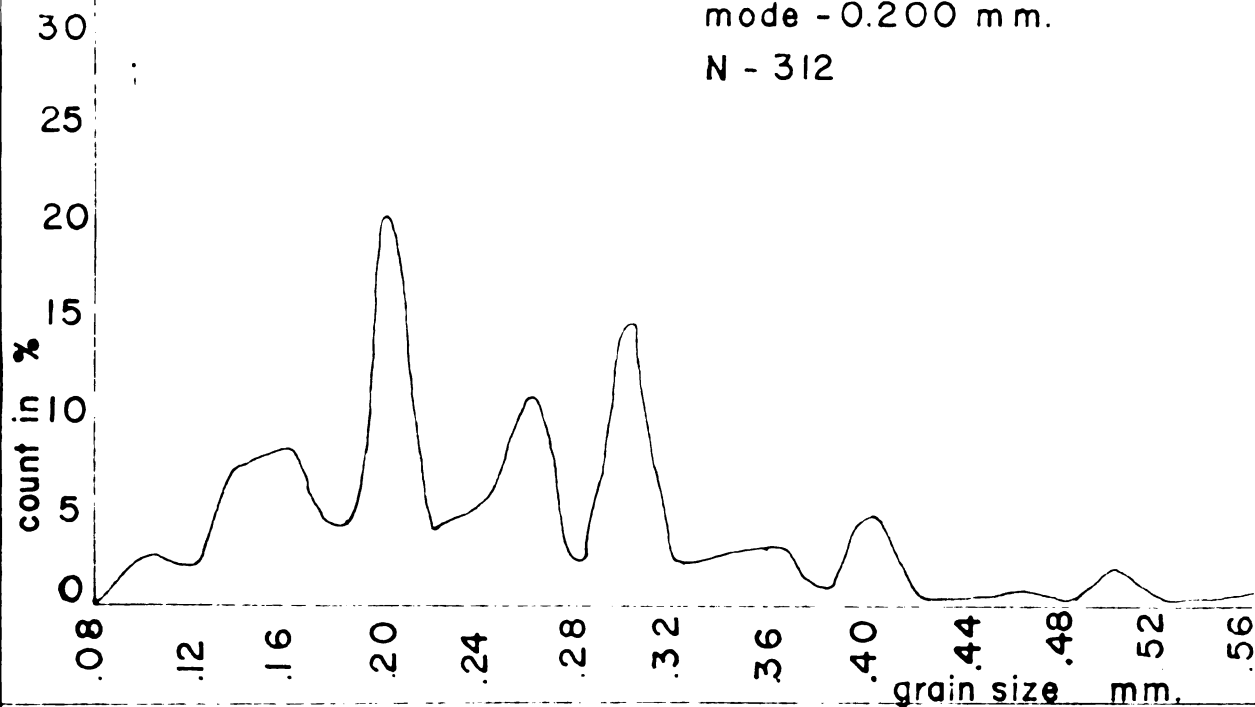


Figure 23

Grain size distribution
curve for slide 9

mean - 0.090 mm.

mode - 0.100 mm.

N - 312

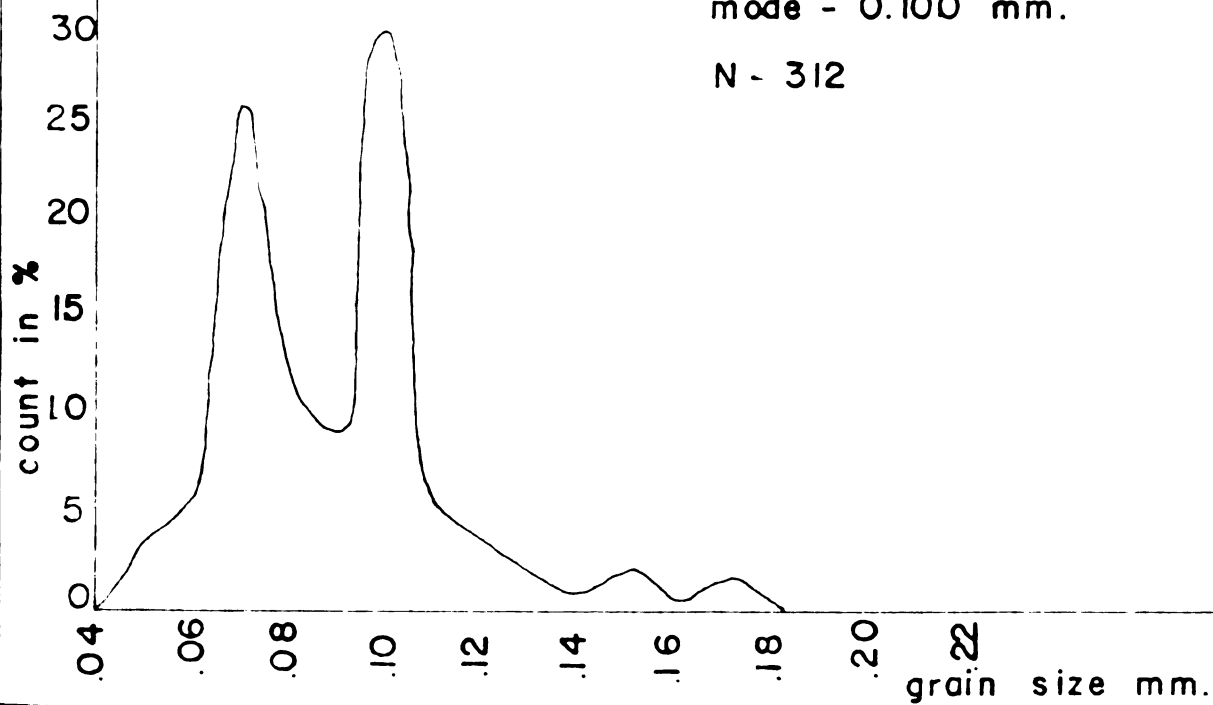


Figure 24

Grainsize distribution
curve for slide 10

mean - 0.111 mm.

mode - 0.100 mm.

N - 312

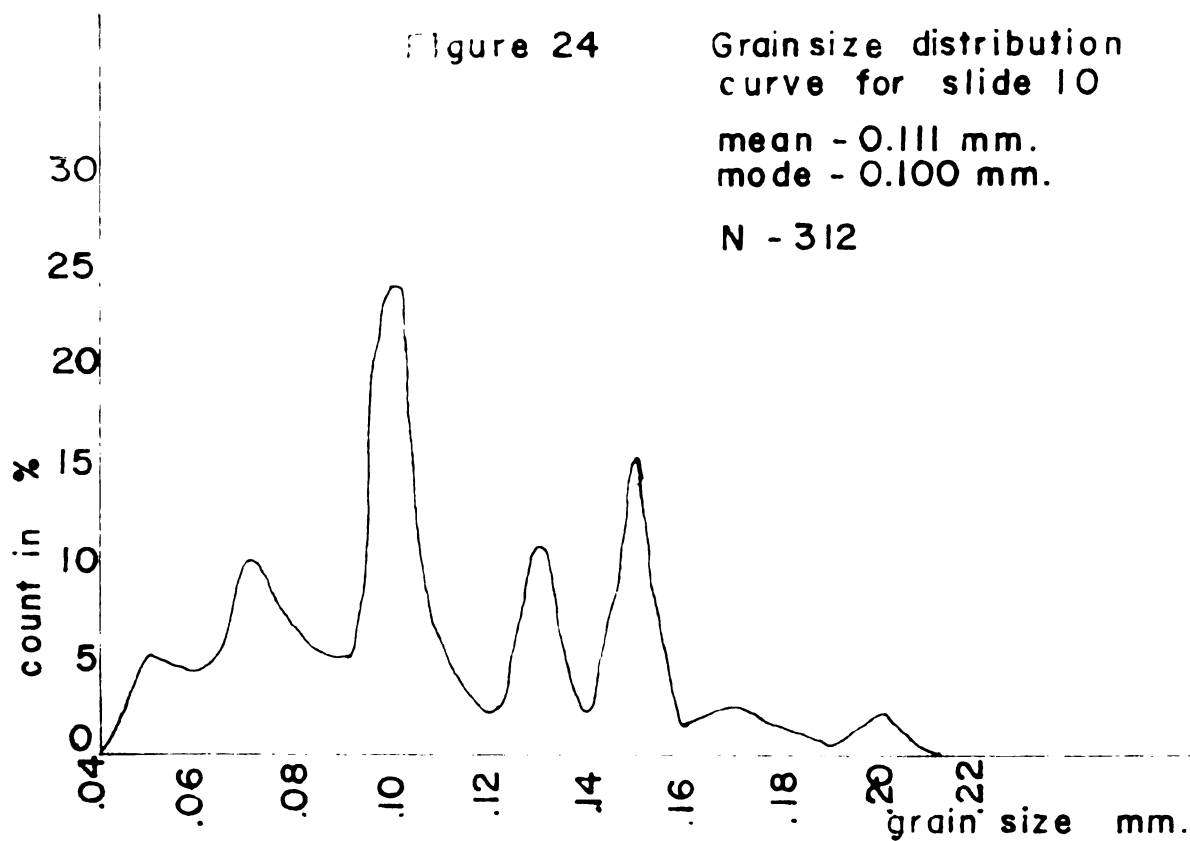


Figure 25

Grain size distribution
curve for slide 11

mean - 0.202 mm

mode - 0.160 mm.

N - 312

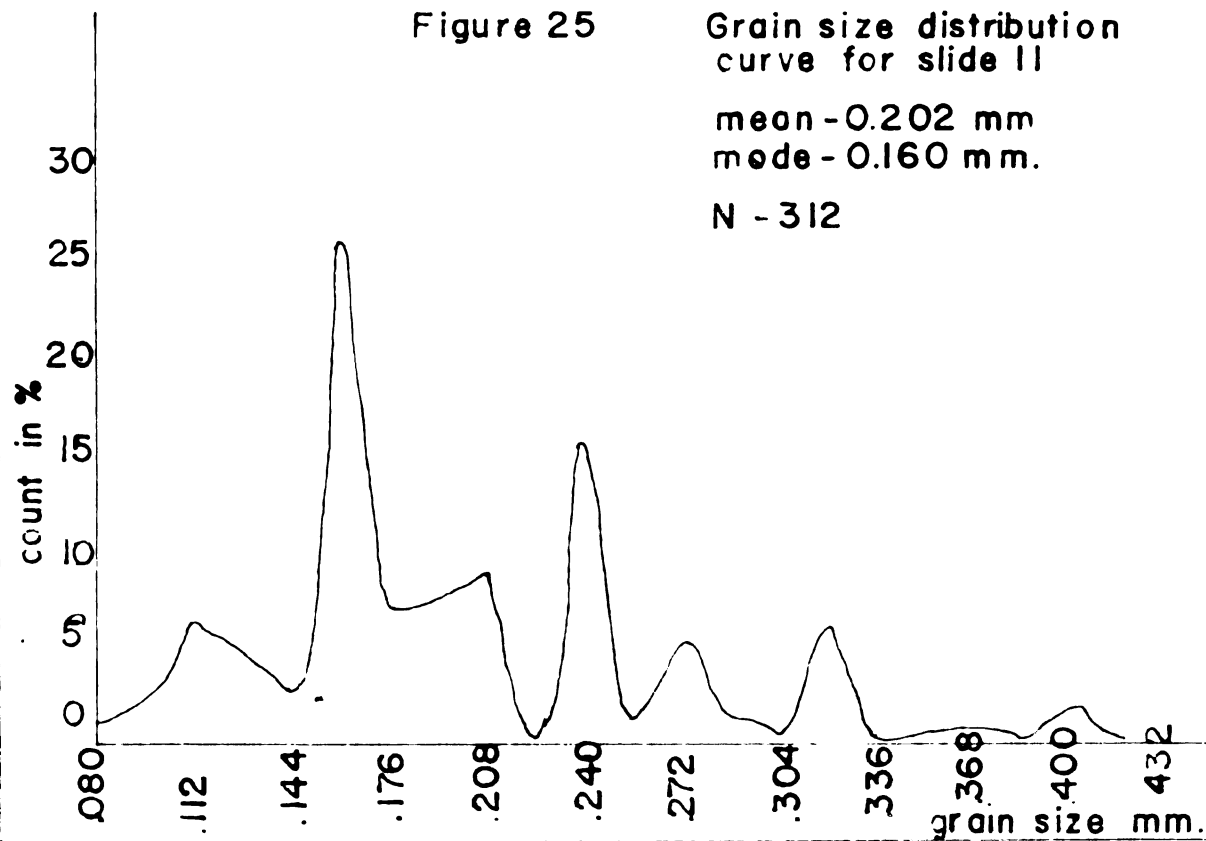


Figure 26 Plot of grain size means vs metamorphic grade

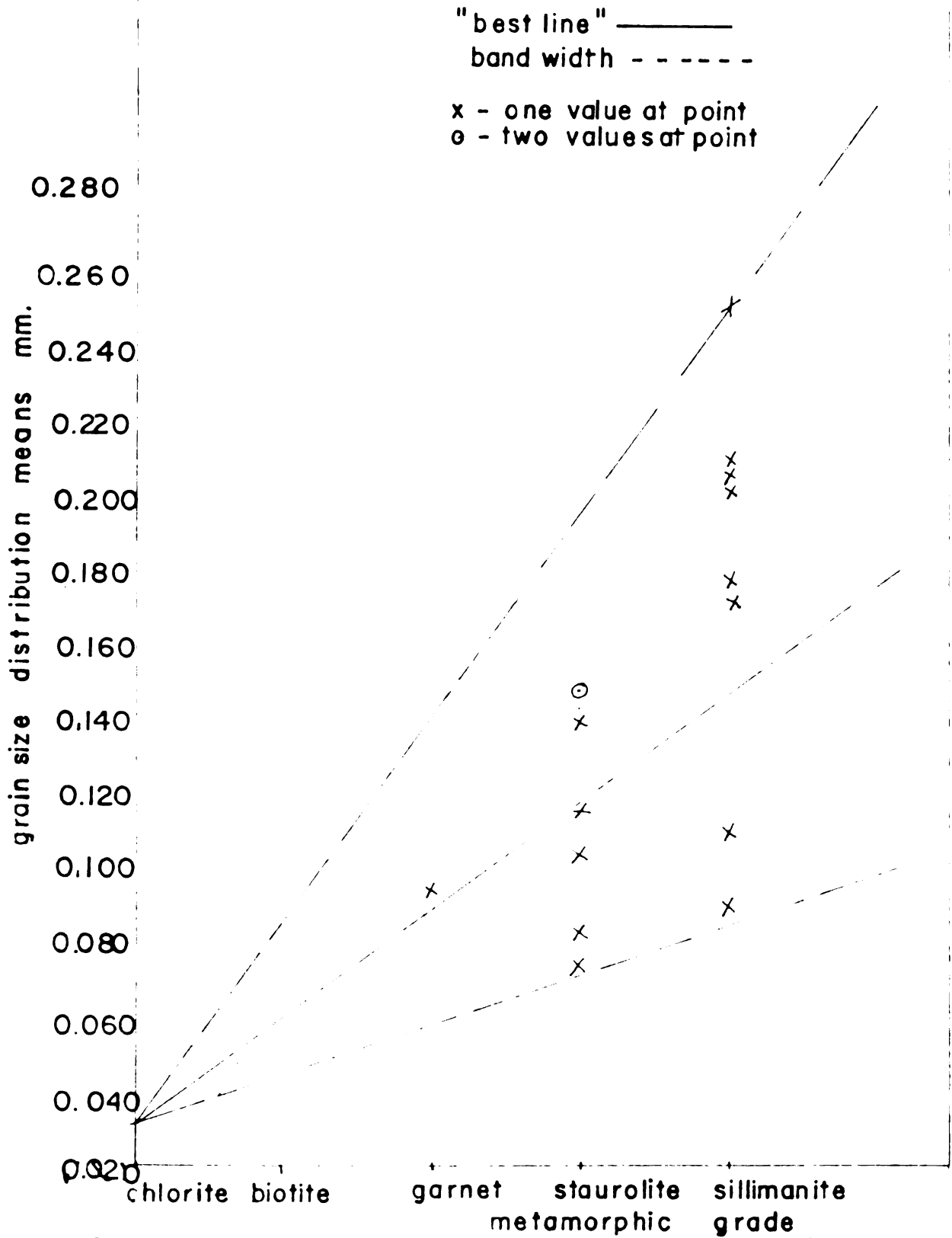
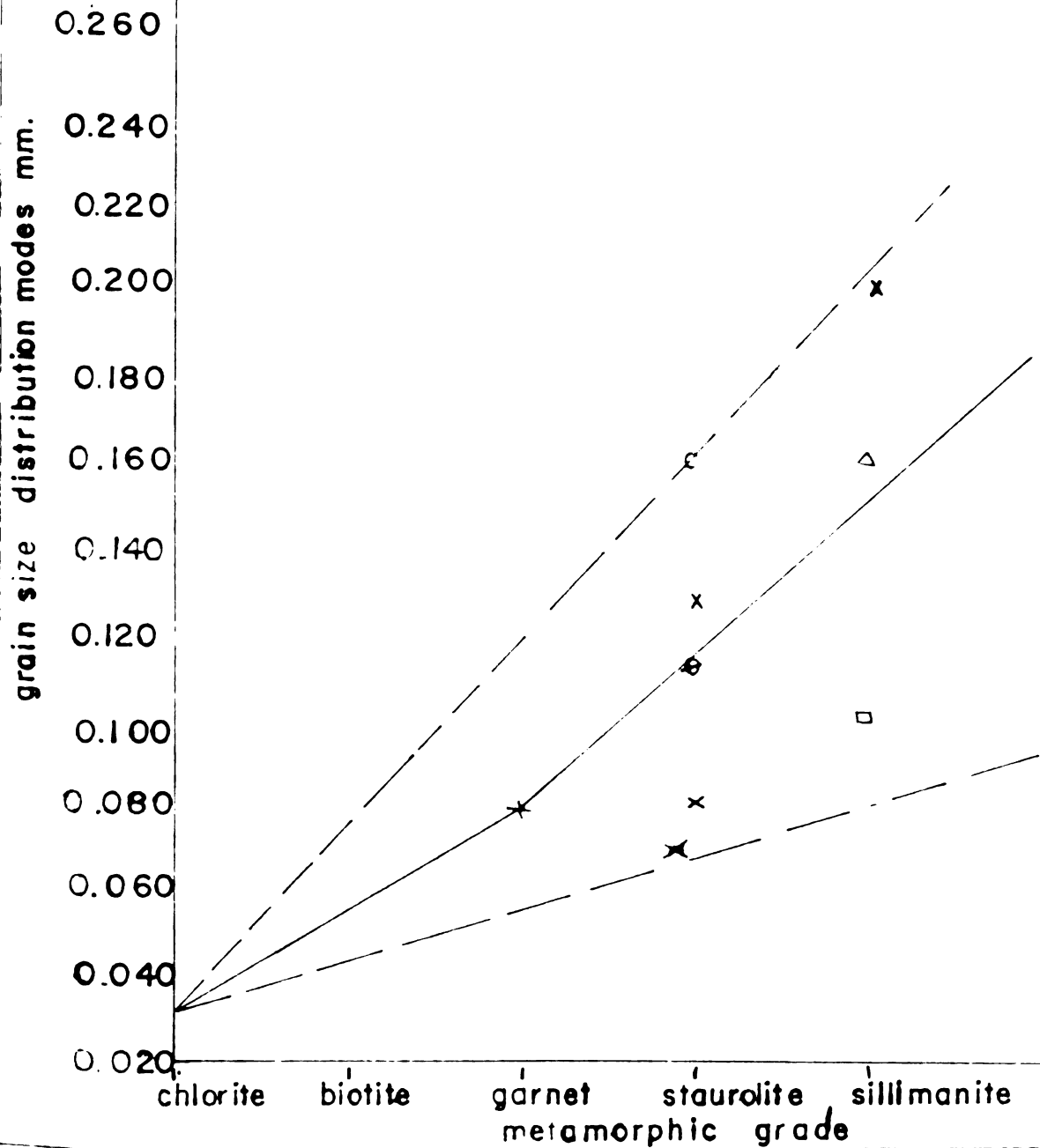


Figure 27 Plot of grain size distribution
mode vs. metamorphic grade

- x - one value at point
 □ - two values at point
 ○ - three values at point
 e - four values at point
 Δ - five values at point

"best line" ———
 band width - - - -



The distribution curves yield information both from their shapes and the parameters derived from them. The shapes of the curves are interesting in that they are quite similar to each other. Most of the curves are composed of two or more major peaks and a number of minor ones. It would appear that the curves could be approximated by a number of normal and log normal curves (Figure 28). If this is true, then the distributions can be described as groupings which peak at successively greater scale values and smaller amplitudes. Those curves that have only one major peak and few if any minor ones seem to approach the shape of a log normal distribution. Meijering (1953) determined, from mathematical considerations, that the grain size distribution of a freely growing crystal aggregate would be log normal in an ideal situation. While the present case is far from ideal, it would seem to support the thesis of Meijering.

The peaks on the distribution curves are fairly consistent across a metamorphic grade. A number of troughs are also consistent in this way (Table 11). The consistent peaks probably represent grain sizes that were more stable than the others; conversely, the consistent troughs represent very unstable sizes. The term stability refers to the thermodynamic and kinetic stability of the grains during the metamorphism of the Negaunee Iron Formation.

Differences between the modes and means are to be expected when a non-symmetrical distribution is found. The means reflect the "centers of gravity" of the curves while the modes show the major peaks. With the exception of slide number 6, the difference between the means and the modes is at least one scale unit. Except for slide numbers 3, 3a-I, 3a-II, 9, and 7-III, the values of the means are greater than those of the modes. This is due to the large number of grains having a greater diameter than the modal grain size. For the reverse cases, slides number 3, 3a-I, 3a-II, and 9 have two major

Figure 28 Approximation of grain size distribution curves by a succession of "normal" curves

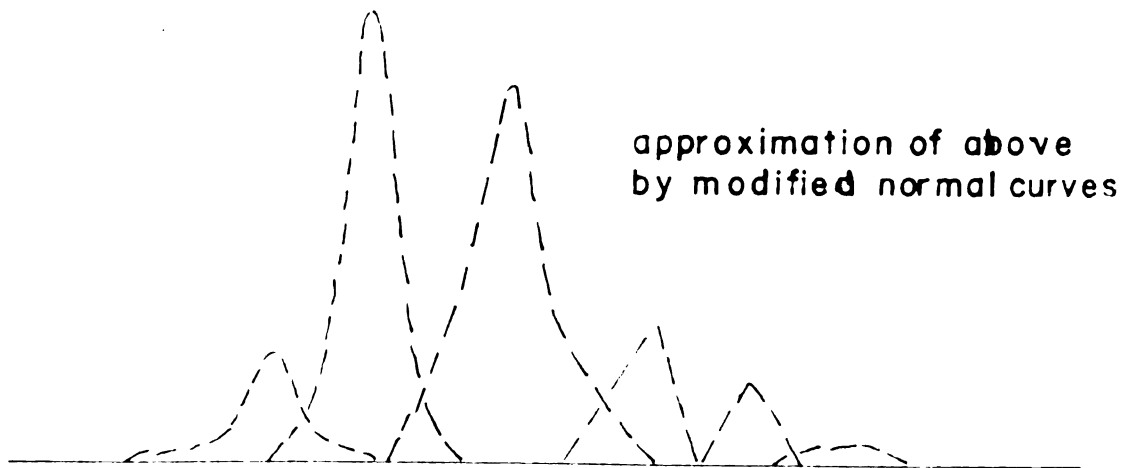
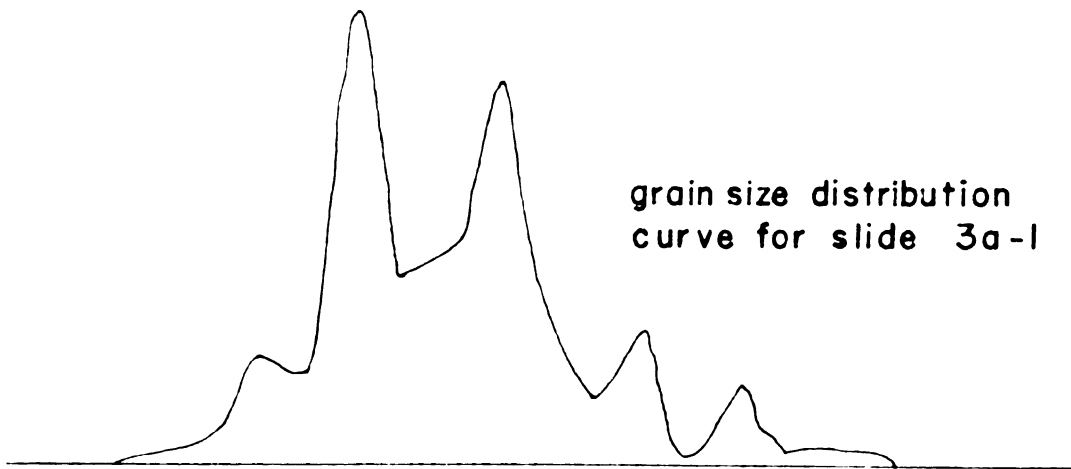


Table 11. Table Showing the Consistency of Individual Peaks and Troughs of the Frequency Distribution Curves Across Metamorphic Grade

Peak or Trough	Slides and Grades
peak 0.048 mm., 0.050 mm.	2 - garnet, 5 - staurolite
trough, 0.060, 0.064 mm.	2 - garnet, 5, 6 - staurolite
peak 0.070 mm.	5 - staurolite, 9, 10 - sillimanite
peak 0.080 mm.	2 - garnet, 4 - staurolite, 7-IV - sillimanite
trough 0.090 mm.	5, 6 - staurolite, 9, 10 - sillimanite
trough 0.096 mm.	3a - staurolite, 7-IV - sillimanite
peak 0.10 mm.	5, 6 - staurolite, 9, 10 - sillimanite
peak 0.112 mm.	3, 3a, 4 - staurolite, 7-IV, 11 - sillimanite
trough 0.12 mm.	5 - staurolite, 10 - sillimanite
peak 0.128 mm., 0.13 mm.	5 - staurolite, 10 - sillimanite
trough 0.14 mm.	5 - staurolite, 10 - sillimanite
trough 0.144 mm.	3 - staurolite, 7-I, II, IV, V, 11 - sillimanite
peak 0.16 mm.	3, 3a - staurolite, 7-I, II, IV, V, 11 - sillimanite
peak 0.20 mm.	3 - staurolite, 7-I, II, IV, 9, 11 - sillimanite
trough 0.224 mm.	3 - staurolite, 7-I, II, V, 9, 11 - sillimanite
peak 0.240 mm.	3 - staurolite, 7-I, II, 11 - sillimanite

peaks within a few percentage points of each other with the result that the mean falls between them. The difference in slide number 7-III is due to the small sample size.

Figure 12 shows a composite curve for slides 3 and 4, and Figure 20 shows a composite curve for slides number 7-I, 7-II, 7-III, 7-IV and 7-V. They are presented to show some of the differences between the slides; they were not statistically determined.

A plot of the means and modes of the Republic Group samples against the distance from the dike is presented in Figure 25. The dike is a metabasite which was intruded into the Negaunee Iron Formation prior to the metamorphism. Sample 14 was taken from the dike, and is described in Chapter III. The dike is about 100 feet thick and outcrops for about 50 yards along the road. The curve appears to be either parabolic or hyperbolic although a greater number of points could easily change the curve.

The results of the Analysis of Variance cannot, in most cases, be interpreted easily. The reason for this is that the data does not fit the assumptions required in most cases. Most of the slides for the Champion Group fit these assumptions. The results for the Champion Group show that slides 3, 3a-I, and 3a-II are not significantly different from each other. Slides 4-I and 4-II are significantly different from each other. This appears to be due to the differences in the amplitude of the minor peaks, and for the purposes of this study, they may be considered to be the same. Comparison of these two groups of slides show that they are distinctly different from each other.

The other groups that were studied did not meet the assumptions of the test, and can only be grouped. The reasons for the grouping have been given previously (page 36). In the Republic Group the apparent grouping is as follows; all of slide number 7, 8 and 11 as one group, and slide numbers 9 and 10 as another group. The comparison of slide

numbers 9 and 10 is considered to be a poor fit. The fit of the Michigamme slides is fair. The distribution curve for slide number 6 indicates a greater degree of size uniformity than does that for slide number 5.

The results of the Analysis of Variance between the areas is shown in Table 7. Some of the apparent groupings are due to the double peaks of slide numbers 3, 3a-I, 3a-II, and 9 which can overlap enough to produce a fairly low F score. This is the case for the grouping of 4-I, 4-II, 9 and 10, and for slide numbers 2 and 9. Slide numbers 5 and 9 may also be grouped. Slide number 9 represents a fuller development of the 0.010 mm. peak than does slide number 5. Slide numbers 4-I, 4-II, and 5 appear to form a group. With the exception of the 0.050 mm. peak in slide number 5 this is a fairly good fit. The fit of slide numbers 2 to 6 is good, and is probably due to the closeness of the means and the variances. This also holds for slide numbers 2, 5 and 6. The rest of the groups cannot be considered to fit.

Slide number 1 is not included in the test results because it was not possible to obtain a large enough sample to show a valid distribution.

A plot of metamorphic grade against the means and modes of the distributions is shown in Figures 26 and 27. The curves drawn are the "best" lines due to the spread of points. Other lines may also be drawn, and the points are best expressed as a band. The band width for these two graphs is great enough so that a number of different curves can be drawn. The increased band width with increase in metamorphic grade is due more to the greater number of determinations for the higher metamorphic grade than to any general trend. That there is a trend to increased grain size with increase in metamorphic grade can easily be seen from the graph. The difficulty lies in determining a valid parameter.

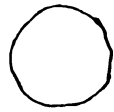
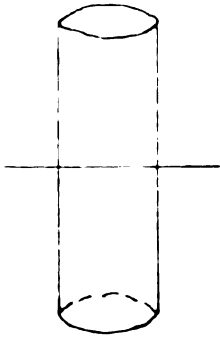
In a number of samples where the iron bed is a silicate, the writer observed that the mosaic quartz grains at the border of the iron and quartz beds are distinctly smaller than those in the body of the quartz bed. This difference in grain size is probably due to the removal of material from the quartz bed to form the iron silicates.

Effect of Quartz Grain Orientation

The effect of the orientation of the quartz grain on its diameter may be considered in two categories. The first is the effect of the orientation on the actual size and shape of the grain. This includes coalescence of grains and irregular shapes. The second category of effects includes those that are apparent rather than real. If one assumes a right circular cylinder as an idealized shape for a quartz grain, the shape of the surface measured will depend on the angle that the cutting plane will make with the cylinder (Figure 29). For a 90° angle the intersection is a circle with the diameter of the cylinder. A rectangular intersection results from an angle of 0° . The short direction is the cylinder diameter. An intermediate angle results in an ellipse with the short axis of the ellipse being the cylinder diameter. For quartz grains this is a fairly good approximation because the shape of the quartz crystal may be approximated by a right circular cylinder. The validity of this approximation for a crystal aggregate (e.g., quartz mosaic) was tested by determining the long and short diameters and the orientation of the grains for slide number 7-III (Figure 30). The diameter ratio d/d' was determined for each grain and compared with the cosine of the angle of the inclination of the quartz grain. After corrections for measurement error were taken into account, there still remained more than one value of d/d' for each angle

Figure 23

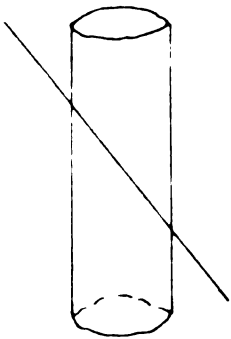
circular intersection



$$\text{diameter ratio} = \cos \theta = 1$$

angle of cutting plane with cylinder axis
 $\theta = 0^\circ$

elliptical intersection



$$\text{diameter ratio} = \cos \theta = X$$

$$0 < X < \infty$$

angle of cutting plane with cylinder axis
 $0^\circ < \theta < 90^\circ$

rectangular intersection



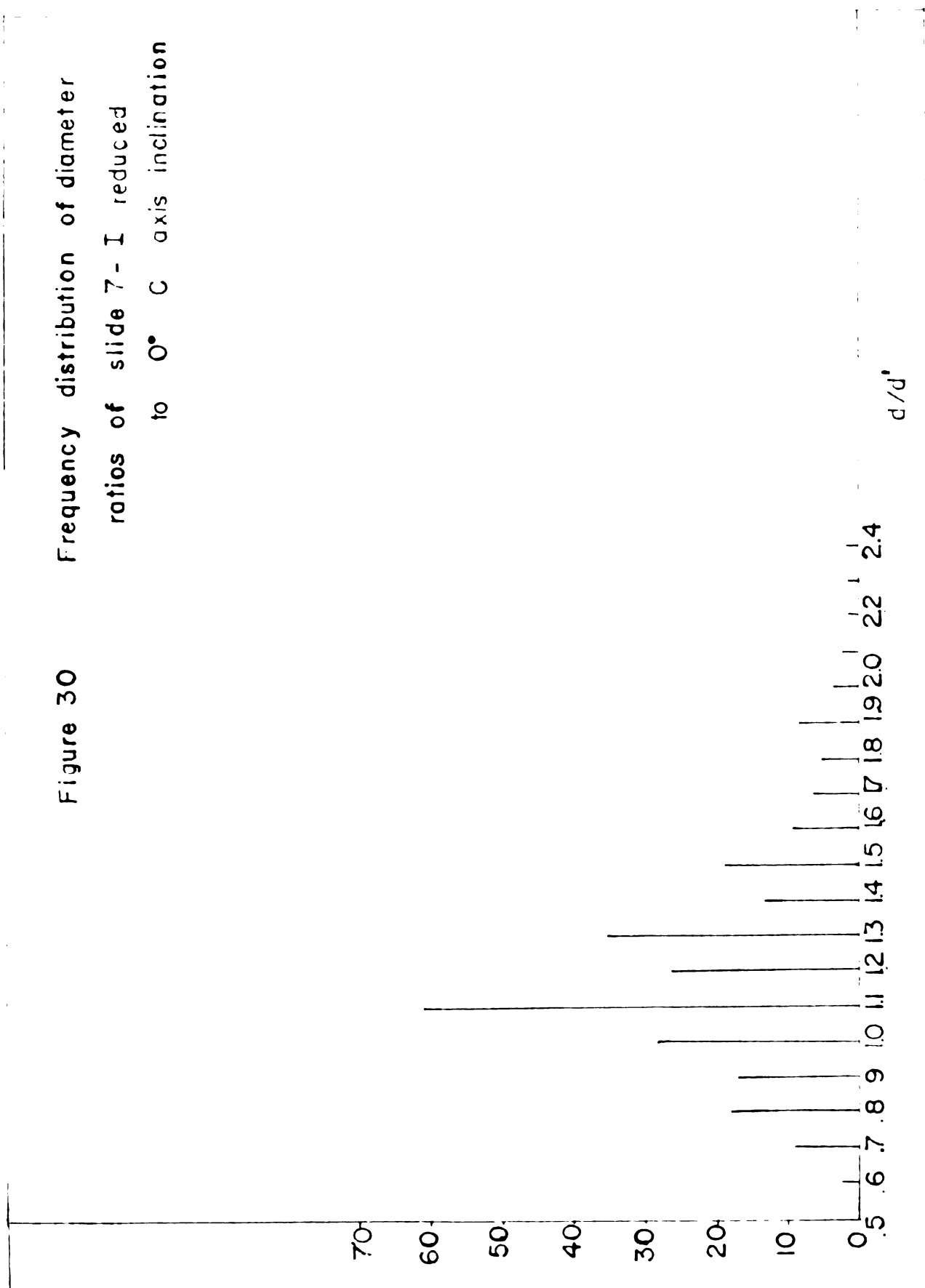
$$\text{diameter ratio} = \cos \theta = , \text{ for finite cylinder, axis ratio of cylinder}$$

angle of cutting plane with cylinder axis $\theta = 90^\circ$

Intersections between a right circular cylinder and
 a cutting plane at various angles

Figure 30

Frequency distribution of diameter
ratios of slide 7 - I reduced
to 0° C axis inclination



of inclination. These other values are probably due to the irregular shapes and interpenetrations of the grains although there may be other factors involved.

It was decided to use the short axis of the grains for the determination of the grain size distribution for the following reasons: 1 - for the idealized case, geometrical considerations show that this is the actual value of the diameter; 2 - average values of the diameters, $\frac{1}{2}(d+d')$, have no validity; 3 - the distribution of the large values is highly erratic, and the values themselves should depend on the orientation of the cutting plane.

Errors in Measurement

There are two types of errors involved in any measurement; these are observer error and instrument error. Instrument error is that error that is inherent in the equipment and material used. Observer error is that which is due to the observer, e.g., careless readings, between scale readings, etc. Both types of errors come into play in this study. Instrument error is found in the change of accuracy which accompanied different magnifications used, distortions in the optical system, and the size of the smallest scale division which can be read. The last consideration is quite important in this study for very few grains have a diameter that is exactly an integral number of scale divisions. In order to measure these grains it was decided that any grain with a fractional scale reading of $\frac{1}{2}$ or greater would be counted as the next larger size, and any less than $\frac{1}{2}$ with the next smaller size. This is an observer error due to limitations of the instrument and is probably the largest source of error in this study. Another observer error that is found in this study is more accurately called bias, for it involves the experimenter's judgment of which grains to

measure. Some grains were not measured because they appeared to be the result of introduced material, intersections of terminations, and removal of material at the boundaries of the beds (which has been discussed previously). Repeated measurements of the same grain are minimized with careful work and large samples. The effect of irregular shapes of the grains cannot be found because there is no way of knowing the actual diameter. The estimated error in measurement of the diameters is of the order of $\frac{1}{2}$ of one scale division. The effect of this on the distributions is probably not great enough to invalidate the study.

Further Discussion

In the preceding sections of this chapter the results of the study and a brief discussion of the results were presented. A number of points were considered which will be more fully discussed in this section.

The results of the Analysis of Variance between areas (Table 7) show that some slides from different areas are enough alike to be considered to be the same. This is true of a number of slides from Champion and Republic, Michigamme and Republic, Michigamme and Champion, Republic and Clarksburg, and Clarksburg and Michigamme. Tables 8 and 9 show that some slides from the same area are considerably different. This indicates that the relation between the grain size of the metamorphically recrystallized cherts in the Negaunee Iron Formation and metamorphic grade is quite complex and cannot be accurately used to determine metamorphic grade. It is also quite probable that there is a range of grain sizes for any one metamorphic grade, and as can be seen from Figures 26 and 27, these grain size ranges overlap. The amount of overlap of the grain sizes would also seem

to preclude the use of the grain size ranges to determine metamorphic grade.

Another factor which may be considered is that some of the slides studied from the staurolite zone may not all be of the same grade; that is, while all of them were taken from the same metamorphic zone, their relative position within the zone may be different. If this is true, two of the points on Figures 26 and 27 might be moved to the right to decrease the range. This does not hold for the sillimanite zone slides as they were all taken within a few feet of each other, nor does it hold for the Champion area slides for the same reason. It appears that while this factor may have some effect, it does not produce enough variation to change the grain size range to any great extent.

As was noted previously, most of the distributions have two major peaks. In some cases they are approximately equal while in other cases they differ by as much as ten percent. These peaks represent grain sizes that were the most stable for the rock when it was metamorphosed. The consistent appearance of a number of troughs in the distribution curves indicates, conversely, the instability of certain grain sizes. A number of possible reasons for these phenomena may be offered. These are:

- 1 - One of the multiple peaks might be due to the development of that grain size which would be most stable under the next highest metamorphic grade.

- 2 - While the larger grain size should be more stable than the smaller, both may have stabilities that are very close. This would result in a double peak instead of a single one.

- 3 - The instability of certain grain sizes (expressed as troughs in the curves) may be due to a greater stability of sizes on either side.

- 4 - Some types of distributions may be more stable than others.

5 - The kinetics of grain growth may favor certain sizes over others. Whether one phase (or, in this case, one size) will be more stable than another depends primarily upon the Gibbs Free Energy, and the kinetic energy and rate associated with the reaction. Since a system tends to the direction of the lowest energy and highest entropy, it is possible that entropy considerations would favor a complex over a simple distribution which would result in a number of peaks, some of which would be major ones and others which would be minor ones.

6 - A possible reason for the double major peaks is that the growth rates for the various faces are not the same. The growth normal to the " a_1 " crystallographic axis might produce one peak while growth normal to the " a_2 " crystallographic axis produced the second. This might be tested by determining the axis orientations and the diameter normal to each axis.

CHAPTER VI

SUMMARY AND CONCLUSIONS

It has been established for many years that the grain size of a mineral will increase with increase in metamorphic grade provided that the mineral is stable and that there is enough material for growth to proceed. This study was undertaken to determine whether or not the increase in grain size of metamorphically recrystallized chert with metamorphic grade was regular and consistent. The Negaunee Iron Formation was ideal for this study in that it is composed of beds of iron minerals and beds of quartz. The quartz was originally chert. Since the chert is cryptocrystalline, the problem of original grain size does not appear. In a study such as this the metamorphic grade must be known with a fairly high degree of accuracy.

Henrickson (1956) determined the metamorphic zones for the Marquette District. On the basis of his isograds, samples were collected from the iron formation for the determination of grain size and from the metabasites for the determination of the metamorphic grade. Samples for the determination of the metamorphic grade were used as a check on Henrickson's work. The results of the study of the metamorphic samples were presented in Chapter III. Of those samples that showed an assemblage distinctive enough to be placed in a metamorphic zone, the majority of them agreed with Henrickson (samples number 12, 13, 15, 17, 18).

The major difference occurred in the samples from Republic. Of the four samples from the Republic area, two had assemblages indicative of the staurolite zone, and two were characteristic of the

sillimanite zone. The sillimanite isograd drawn by Henrickson does not go through the Republic area. The author does not consider that the redrawing of the sillimanite isograd is warranted on the basis of these four samples. Henrickson's isograds were, therefore, retained with the change in the position of the sillimanite isograd being considered.

The samples of the iron formation which were used to determine grain size were grouped by geographic location. The grain size distribution for each slide was determined, and Simple Analysis of Variance was used to determine closeness of fit of the various curves. The number of grains needed to form a valid distribution was determined by means of the Chi-square test. The results of the Analysis of Variance test showed that although the grain size of the metamorphically recrystallized cherts increased with increase in metamorphic grade, it is not possible to use the grain size of the recrystallized cherts to determine the metamorphic grade due to the range of grain sizes present in any one metamorphic zone and the large amount of overlap of grain size between zones.

It can be concluded that the grain size of metamorphically recrystallized cherts cannot be used to determine the metamorphic grade.

On the basis of results of this study, further work on this subject is not warranted until more is known about the basic quantitative aspects of metamorphism. A number of points considered in this study offer avenues for further research although methods are not known for the investigation of them. These points are; 1 - the reason for the two major peaks and the consistent peaks and troughs of the distribution curves, 2 - the reason for the similarity of the various distribution curves, 3 - a fuller investigation of the effect of quartz axis orientation on both the measured diameter and the actual diameter, and 4 - an investigation of the quantitative aspects of crystal growth during metamorphic conditions.

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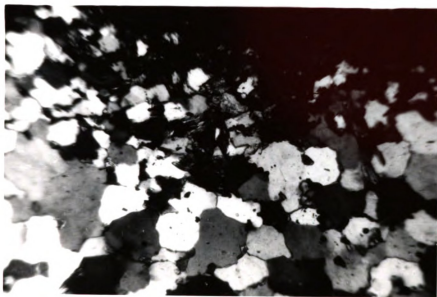
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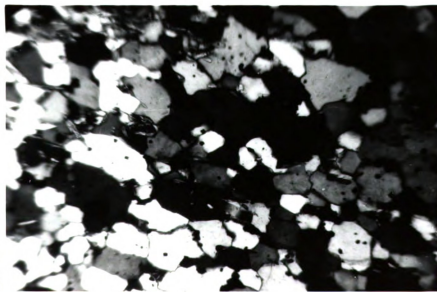
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APPENDIX

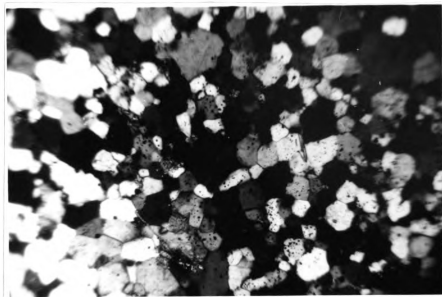
Photomicrographs of various iron formation slides showing the mosaic texture and grain size range.



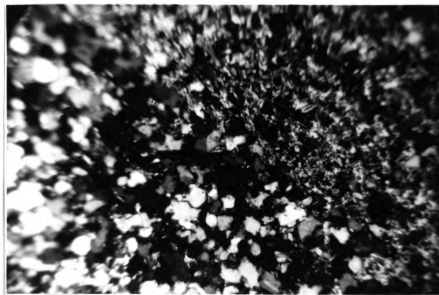
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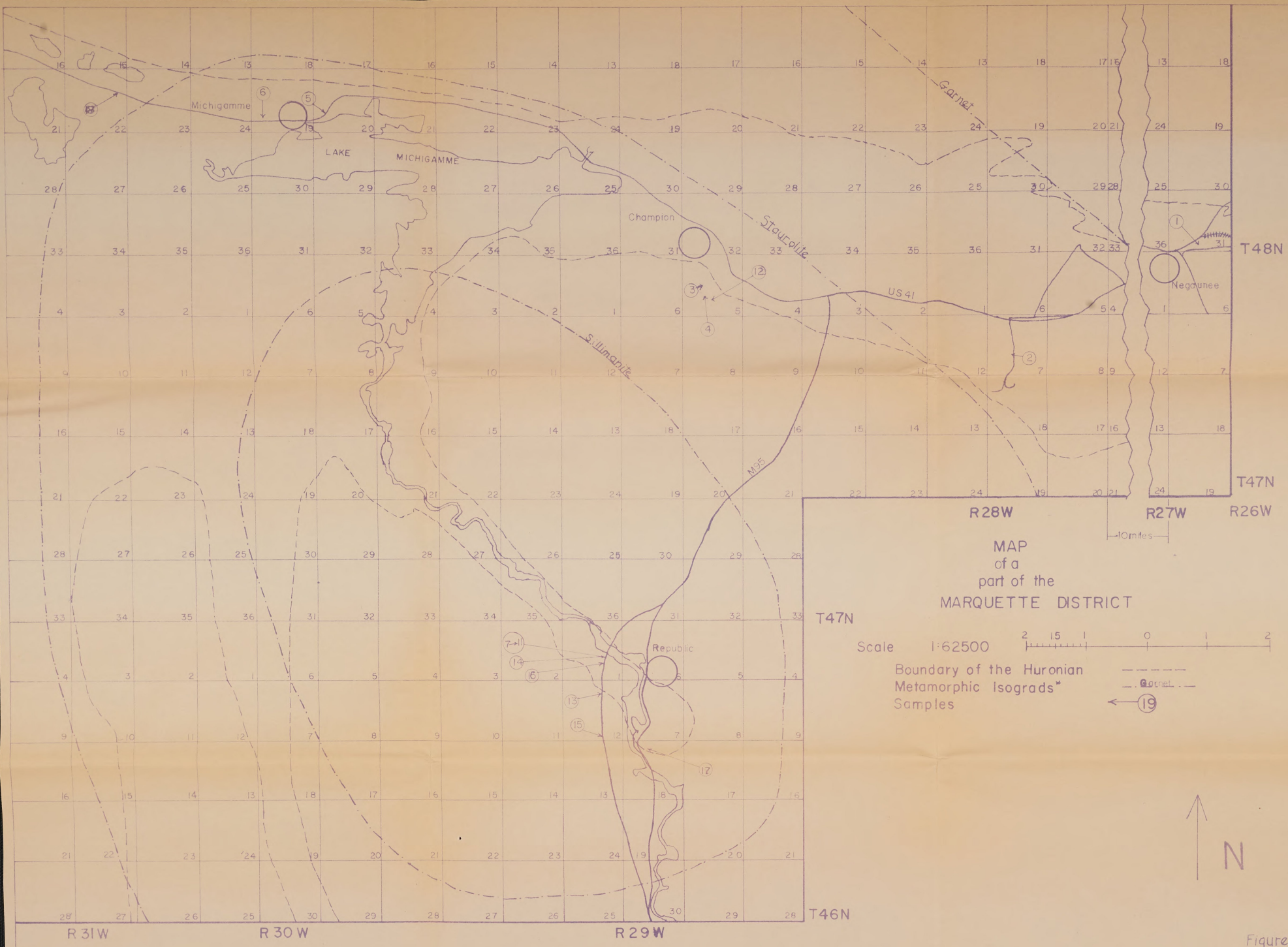


Figure 1

*Isograds after Henrickson 1956

