

A STUDY OF CLASTICS IN THE
NEGAUNEE IRON FORMATION NEAR
PALMER, MICHIGAN

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY

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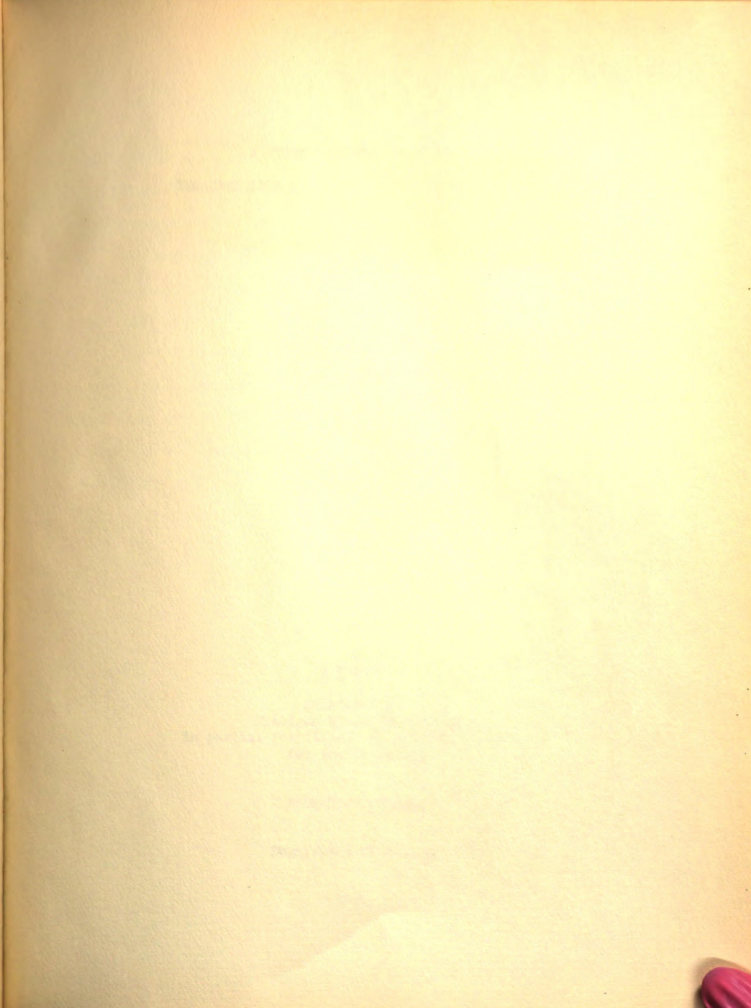
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ACKNOWLEDGMENTS

The author wishes to express his appreciation for the confidence and assistance of the Michigan Geological Survey in the research by the late Professor R. W. Henry.

The author is also grateful to Dr. R. W. Henry, Dr. T. Schuchman, Dr. H. Stonehouse and Dr. W. J. Tracy for their assistance throughout this study.

Special appreciation is due to Dr. R. W. Henry for the many hours of discussion in the field and in the laboratory, and for his assistance in the various field areas of the Michigan State University Geology Field Camp who helped in surveying for the Regional and Local Geology, the author expresses his gratitude.

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology

1970

11

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation for the confidence shown and for the guidance given since initiation of this research by the late Professor Justin Zinn.

The author is also grateful to Drs. W. J. Hinze, B. T. Sandefur, H. B. Stonehouse and J. W. Trow for their helpful assistance throughout this study.

Special appreciation is expressed to J. T. Mengle for the many hours of discussion in the field and for the use of thin sections and base maps of the area. And to the members of the various field crews of the Michigan State University Geology Field Camp who helped in surveying for the Regional and Moore Mine Maps, the author expresses his gratitude.

Using the above relationships, mechanisms of deposition are postulated for each lens type. The analysis is then applied to several other elastic zones in the beach area with local correlations made.

Conclusions would support a shallow water environment of deposition where chert and hematite are deposited in association.

ABSTRACT

An investigation was conducted on the relationships between a number of clastic lens-shaped bodies and a portion of the Negaunee Iron Formation. The principal study area was located at the abandoned Moore Mine in the Palmer Range, a downfaulted block on the southern flank of the Marquette Synclinorium, approximately 12 miles south of Negaunee, Michigan. Here the iron formation is continuously exposed in cross-sectional profile along its strike for a distance of 0.3 mile.

More than forty clastic lenses ranging from a foot to over three hundred feet in length and up to fifty feet in width were mapped in detail. The depositional relationships between the lenses and the iron formation are varied; the majority of lenses are essentially conformable with the iron formation. Some of the conformable lenses are gradational at their lateral boundaries, some exhibit miniaturized on-lap off-lap features, while others have merely warped the underlying layers of iron formation. The unconformable lenses are of three types: channel fills, isolated blocks, and oblique gradations.

The iron formation contains a two percent background of rounded sand grains which are equally dispersed among the chert and hematite layers. This percentage of sand grains is observed to increase noticeably when a clastic lens is approached from beneath.

The clastics consist of metamorphized mixtures of rounded and angular fragments of chert, hematite, quartz, quartzite and granite, together with varying quantities of sand all in a matrix consisting of varying proportions of shale, chert and hematite. Petrographic and binocular analyses were used to divide the clastics into five lithological groups and a number of sub-groups on the basis of their mineralogical and textural characteristics. It is deemed significant that only one lithology is found in a given lens and that a particular lithology always maintains the same depositional relationship with the iron formation. A method for chemically disaggregating some of the clastics was developed enabling roundness, sphericity, and size distribution analyses to be made. Results showed the sand grains to be similar to those found in typical beach washed sands.

Using the above relationships, mechanisms of deposition are postulated for each lens type. The analysis is then extended to several other clastic zones in the immediate vicinity with areal correlations made.

Conclusions would support a shallow water environment of deposition where chert and hematite were deposited in alternating

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layers under proper environmental conditions. The major source of clastics was derived from a low lying land mass to the south. Except for one occurrence all the clastics observed appeared to have been well worked sediments prior to their transportation into the basin. Re-worked beach sands were regularly supplied to the basin while occasionally off-shore currents created lenses and beds of sands out into the basin. The dispersion of these sands appears to have been a normal condition in the area since they are observed throughout the area.

During intervals when portions of the basin were above wave base or even above water level, clastics were introduced to the basin by stream transport. Finally at a few localized areas large masses of clastics were rapidly deposited via slides and/or turbidity currents.

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LIST OF MAPS

(located in map pocket)

CS: Cherty series

I. Regional Geologic Map

II. Moore Mine Map

Kq: Quartile Kurtosis

Ma: Arithmetic mean

Ms: Median

Mg: Geometric mean

Mo: Mode

cs: Cube diameter

Qd: Arithmetic quartile deviation

Qs: Serialistic quartile

s: Standard deviation

s^2 : Variance

Sk: Arithmetic skewness

Sk_g: Geometric skewness

Sc: Sorting coefficient

Vd: Percent disturbed volume

Wt: Weight

ϕ : Sand grain diameter

NOTATIONS

CS:	Cherty sericite
CQ:	Cherty quartzite
CQS:	Cherty sericitic quartzite
Kqa:	Quartile kurtosis
Ma:	Arithmetic mean
Md:	Median
Mg:	Geometric mean
Mo:	Mode
n:	Cube dimension
QDa:	Arithmetic quartile deviation
QS:	Sericitic quartzite
s:	Standard deviation
s ² :	Variance
Ska:	Arithmetic skewness
Skg:	Geometric skewness
So:	Sorting coefficient
Vd:	Percent disturbed volume
Wt:	Weight
δ:	Sand grain diameter

SECTION I

INTRODUCTION

A. Problem

During the past 100 years there has been a continuing controversy concerning the Precambrian Iron Formation Problem. Debate has been centered around questions involving the location and lithology of the source rock, the mechanics involved in extraction and concentration of the source material, the transport mechanisms, the physical and chemical environment during deposition and the processes responsible for post-depositional alteration.

Although there have been numerous investigations directed toward the Problem, the Problem remains basically unsolved. Perhaps a prime reason for this state of affairs is the fact that there is no Precambrian type iron formation being deposited today and there has been none deposited since Precambrian times.

During the summer of 1959 the writer, while attending the Michigan State University Geology Field Camp, was introduced to the Precambrian rocks surrounding Marquette Michigan including the Negaunee Iron Formation, a chemically deposited unit consisting principally of interbedded layers of hematite and chert. A particularly interesting feature of a portion of the Negaunee Iron Formation is the occurrence of interbeds, lenses and inclusions of various kinds of clastic sediments.

selected for the detailed study portion of this research for the following reasons:

B. Approach

It is the author's opinion that by applying modern sedimentary principles to these clastics certain conclusions concerning their origin can be drawn, conclusions which in turn should be pertinent to the origin of the iron formation itself. It is the objective of this thesis to obtain information on the geologic history, provenance, dispersion and physical environment affecting the accumulation of clastics in a portion of the Negaunee Iron Formation.

Following the selection of the study area the investigation was conducted in three logical steps, results of which are presented in Sections II, III and IV respectively:

(1) A regional study to determine the geology and structure of the area and in particular to ascertain the lithologies present prior to Negaunee Iron Formation deposition

(2) A detailed analysis of a suite of clastic deposits and their relationships to the surrounding iron formation to determine the mechanics and environment of deposition.

(3) A correlation of clastic deposits along a broad horizon to determine the dispersive nature of the clastic deposition.

C. Study Location

The Moore Mine, located within the Negaunee Iron Formation on a down-faulted block (Palmer District) of the southern limb of the Marquette Synclinorium in the Upper Peninsula of Michigan, was selected for the detailed study portion of this research for the following reasons:

- (1) Large quantities of a number of different types of clastics are preserved in cross section.
- (2) There is close proximity to the base of the iron formation.
- (3) There are excellent exposures in three dimensions.
- (4) There is relatively uncomplicated structure and stratigraphy.
- (5) The area is readily accessible.

The Moore Mine is located in the south-central portion of section 28, T47N, R26W, Michigan. The area of regional study includes sections 27, 28, the north one-half of 32 and 33, and portions of 26, 34, and 35. Figure 1 gives the location and general geology of the Palmer District after Van Hise and Leith (1)*. The present study areas are outlined where the roman numerals correspond to the appropriate maps: I-Regional Geologic Map (Map I), II-Moore Mine Map (Map II) and III-Clastic Horizon Map (fig. 24). Maps I and II are located in the map pocket.

D. Previous Investigations

It is intended to review briefly those articles which in the author's opinion represent milestones in the development of thought on the origin of the iron formation in the Palmer District. References prior to 1897 have been extracted from Monograph 28 "Marquette Iron-Bearing District of Michigan" by Van Hise and Bayley (2).

During the year 1820 Henry Schoolcraft (3) traveled along the Michigan shore of Lake Superior. Included in his subsequent report,

*Numbers in parantheses refer to similarly numbered entries in the reference section.

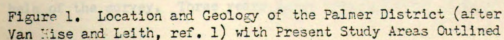


Figure 1. Location and Geology of the Palmer District (after Van Wise and Leith, ref. 1) with Present Study Areas Outlined

the first reference to the geology of the Marquette Region is found. From 1820 on there has been an ever increasing flow of literature published dealing with the numerous geological problems of the Marquette District.

The occurrence of Hematite in the Marquette Area was reported in 1841 by Houghton (4) - "Although the hematite is abundantly disseminated through all the rocks of the metamorphic group, it does not appear in sufficient quantity at any one point that has been examined to be of practical importance". In 1846 a comprehensive geological survey of the Lake Superior district in Michigan was initiated for the United States Treasury Department under the direction of Dr. Jackson. Two years later the first report (5) under this program was published by Locke; in the report he refers to a number of very pure iron ore deposits in the area which is now occupied by the town of Negaunee, particular emphasis was made to the ore at the then operating Jackson Mine. Burt, working under Jackson, also issued a report that year although not published until 1850 (6). After studying some fourteen exposures of iron ore along his traverses he concluded that the region contained the greatest abundance of high quality iron ore in the United States. Another of Jackson's assistants, J.W. Foster, provided the first ideas as to the origin of the iron formation when he stated that they derived their origin from "aqueous" causes while "igneous" causes have since operated to modify their character. This report is dated 1850 (7).

In that same year Foster and Whitney succeeded Jackson at the helm of the survey. Three years later they published a paper summing

up their work on the Lake Superior Region in connection with the Chippewa Land District Survey (8). This report presents the first detailed study of the geological relationships; the rocks are classified and a rather detailed map is presented. Concerning the iron ore, they state that it is igneous material although some action of segregation was present during and after deposition. These segregating forces were needed to explain the banded nature of the jasper ore, however, they refuse to accept a sedimentary origin for the jasper - "at first glance the banded structure might be regarded by some as the result of aqueous deposition "...but..."if these were really the result of aqueous deposition we should expect from analogy with other deposits of similar character that some of the layers would be of more considerable thickness than others"...and..."in some cases at least the foldings would exhibit a considerable radius of curvature, which is not the case here."

The first definite statement favoring sedimentary deposition for the iron ores was published in 1865 by Kimball (9) where he concluded that since the iron formation was intimately associated with the other sediments it therefore must have undergone similar conditions of deposition. A pyroclastic origin was proposed by Daddow and Bannan (10) a year later in which they conclude that the iron ores are volcanic in origin but sedimentary in deposition. In 1882, Columbia University published a report describing the iron formation near the Champion Mine as being deposited in an E-W trending river or series of lakes (11).

Rominger (12) as State Geologist of Michigan, published a comprehensive report dated 1881 on the lithological and structural relationships

in the Marquette Synclinorium. This study stood as a basic reference until the publishing of U.S.G.S. Monograph 28 in 1897. Reference is made to the Palmer geology and to the granite knobs in section 22 and 23.

Winchell (13) made an important contribution to the stratigraphy of the area when in 1887 he described a conglomerate (Goodrich Conglomerate) near Palmer as containing jasper, chert, and hematite pebbles. Although this same conglomerate was described by Foster in 1849, Winchell was the first to recognize its unconformable relationships to the underlying iron formation. The iron formation... "must have been constituted in pretty nearly its present state prior to the formation of the conglomerate." Wadsworth, the last major proponent of the igneous origin for the iron formation was converted in 1892 (14). He published a paper stating that the sedimentary origin of the jaspilites is plainly shown in the Cascade Range, south of Palmer, where they are found intermixed with quartzites. Most of the interlaminated jaspilites appear to be composed of fine jaspilite derived from parent debris.

In 1897, Van Hise and Bayley (2) published a monumental work - Monograph 28, "Marquette Iron-Bearing District of Michigan," which is still considered a standard reference for the area. The main body of the report is concerned with the detailed description of the various formations in the Synclinorium, their distribution, topography, structure, thickness, petrographic characteristics, relation to other formations, descriptions of particularly interesting locations, etc. The Palmer District is described as a detached appendage of the Marquette Synclinorium preserved due to down-faulting. Only the

Ajibik, Siamo, Negaunee, and Goodrich formations were found in the area, all lying unconformably upon the Archean Basement.

Of particular interest is the Palmer Gneiss which is described as a highly schistose, strongly foliated rock with varying amounts of quartz in a "hydromicaeous" groundmass showing much mashing. When the quartz is in excess it approaches a "squeezed" quartzite, when not it approaches a fine grained gneiss. This inability to distinguish in the field between some of the phases of the Palmer Gneiss and ordinary quartzite, coupled with the fact that even when studied in thin section the gneiss can often be equally well described as silicified, weathered granite or as granitized quartzite has provided a fundamental basis for the Palmer Gneiss dispute. After noting that the Palmer Gneiss is never observed grading into the overlying formations, Van Hise and Bayley concluded that the gneiss is a silicified, weathered granite of Archean Age.

Other interesting localities discussed include the Ajibik Hills, the north block of the Volunteer fault and the type location for the Ajibik Quartzite. The Negaunee Iron Formation in the Palmer District is described as being no different from that in the main synclinorium except that in the lower horizons fragmental quartz is seen as individual grains and in small beds. An excellent exposure of the Goodrich conglomerate is noted south of the town of Palmer.

The United States Geological Survey Monograph 52, "The Geology of the Lake Superior Region," was published in 1911 by Van Hise and Leith (1). In the chapter on the Marquette District little is changed from the earlier monograph. The Palmer Area, however, was significantly

reinterpreted. The quartzite forming the Ajibik Hills was renamed the Mesnard and it was indicated that the Palmer Gneiss contains some pockets of Huronian sediments. Structurally the Palmer and Volunteer faults were identified. Another large chapter is devoted to iron ores in general including discussions on the conditions of deposition, the chemistry of the ores, their alterations and the method of secondary concentration.

Between 1931 and 1937, Lamey (15, 16, 17, 18, 19, and 20) published a number of papers principally concerned with the geological interpretation of the Southern Complex and in particular with the Palmer Gneiss. After considerable field and laboratory study he reached the conclusion that some of the rocks delineated as Palmer Gneiss were actually metamorphosed Lower Huronian sediments and that this metamorphism occurred by intrusion of the Republic Granite during the interval between Lower and Middle Huronian.

Dickey (21, 22) took exception to Lamey's conclusions regarding the Republic Granite and pointed to other evidence which he believed indicated that the major portion of the Southern Complex was composed of pre-Huronian granites.

Tyler and Twenhofel in 1951 (23) reported on the Marquette District; they presented their views on the environmental conditions governing the deposition of each of the lithological units. In particular they refer to the iron formation in the Palmer District as the Goose Lake Iron Formation, a unit of the Siano Slate. This has since been shown to be in error. They also state that there is no evidence for an unconformity between Lower and Middle Huronian.

Marsden (24) made minor contributions to the stratigraphy of the Palmer District in 1955. In 1956, Vickers (25) identified monazite as occurring in quartzite near Palmer and also at the New Richmond Mine associated with feldspar clastics, indicating that pegmatites locally contributed debris to the sedimentary basin.

In 1956, Mengle (26) studied the clastics in the Palmer District and specifically at the Moore Mine. He mapped iron formation - clastic relationships at the Moore Mine and speculated as to the conditions of the iron and chert during deposition. Considerable study was also devoted to the nature of the iron formation in the area. Mengle's work represents the best summary of the clastic - iron formation relationships to date.

Sahakian (27) studied a portion of the Palmer Gneiss situated several miles east-southeast of the Moore Mine. A petrographic and structural analysis indicates similarity to the granite knobs a few miles north, in section 22 and 23.

During the summer of 1958, Long (28) studied a portion of section 34 in the Palmer District. He identified a green slaty material cut by an orange granite which in turn was cut by an early Keweenaw type dike. The granite was believed to have undergone a major period of deformation and was placed as Huronian in age.

Rosenberger (29) in 1960, mapped sections 22 and 23 where he found the hills designated as Palmer Gneiss eroded and overlain by Mesnard Quartzite. The base of these hills contained a large number of granite cobbles. His findings indicate that the Palmer Gneiss, at least here,

has not intruded the Lower Huronian. In the Mesnard formation he was able to differentiate three distinct members, a slate, a slate conglomerate, and a true quartzite.

A. General

During the summers of 1959 and 1961, field areas from the Michigan State University Geology 499B course, held at Northern Michigan College, Marquette, Michigan, under the direction of Dr. Justin Zinn and the author, were used to study an area east of Palmer, Michigan. The purpose of the regional geologic study of that portion of the Huron-Michigan is, specifically, the area studied included sections 27 and 28, the entire area of sections 32 and 33, part of section 34, and the adjoining portions of sections 26 and 35, all located in 1878, 1879, Michigan. Work completed on sections 27, 28, 32, and 33 is completed from the field notes of the Michigan State University field areas. The portion in section 34 is taken unmodified from a 1959 unpublished master's thesis by Long (28). The controversial outcrops in the west corner of sections 26 and 35 were first mentioned by Laney in 1935 (19). Due to their stratigraphic significance this writer re-examined the outcrops in 1961 and included the observed relationships in the regional map. See Figure 1 for location of the regional study area (1).

B. Method of Survey

The surveying was carried out by pace and compass using either a Brunton or sun-dial compass depending upon the local magnetic interference encountered. Approximate mean declination in the area is $1/2^{\circ}$ (USGS, 1932), a negligible value for such methods. The

SECTION II

REGIONAL GEOLOGY

A. General

During the summers of 1960 and 1961, field crews from the Michigan State University Geology Field Camp were stationed at Northern Michigan College, Marquette, Michigan. Under the direction of Dr. Justin Zinn and the author, several sections in an area east of Palmer, Michigan were mapped as part of a regional geologic study of that portion of the Palmer District. Specifically, the area studied included sections 27 and 28, the northern one-half of sections 32 and 33, part of section 34, and the adjoining corners of sections 26 and 35, all located in T47N, R26W, Michigan. Work completed on sections 27, 28, 32, and 33 is compiled from the field notes of the Michigan State University field crews. The portion in section 34 is taken unmodified from a 1959 unpublished master's thesis by Long (28). The controversial outcrops in the west corner of sections 26 and 35 were first mentioned by Lamey in 1935 (19). Due to their stratigraphic significance this writer re-examined the outcrops in 1961 and included the observed relationships in the regional map. See figure 1 for location of the regional study area (I).

B. Method of Survey

The surveying was carried out by pace and compass using either a Brunton or sun-dial compass depending upon the local magnetic interference encountered. Approximate mean declination in the area is $1/2^{\circ}W$ (USGS, 1952), a negligible value for such methods. The

standard pacing technique was used where 2,000 paces are set equivalent to a mile, resulting in a pace equal to 2.64 feet - the standard pace. The sun compasses were checked along a north-south line established by the author near the site of the Isabella Mine just south of Palmer and about two miles west of the sections mapped. The following restrictions were placed upon sun compass use to insure reliable readings:

- (1) Compensation curves were computed for each instrument and used throughout the surveying period.
- (2) Each morning prior to beginning field work the compasses were checked against the established north-south line.
- (3) Use of the sun compasses was restricted to the middle seven hours of each day.
- (4) Sun compasses were checked against the north-south line at the end of each day.

The Brunton compass indicated one major and several minor magnetic disturbances over the area mapped. The principal anomaly was located in the southwest corner of section 28; it is believed to have been caused by magnetite banding in the Ajibik, (see Section II-F).

Topographic maps and aerial photos of the area were carefully studied before going into the field. In the field all section corners were found and positively identified with the exception of the northwest corner of section 32. Base lines were laid off along the north and south section lines, on which the intersection of planned traverse lines were marked; these were later used to correct for the traverse-line drift. Eight north-south traverses were run per section taking maximum benefit of the east-west topographic trends

Each crew consisted of at least four men: a pacer, a compass man who was also party chief, and one geologist on each side of the traverse line. Outcrop locations were accurately recorded in the field notes together with their descriptions, strikes, dips, and general trends. Samples were taken from each outcrop for further study with a binocular microscope at field camp headquarters during the evenings, after which representative samples were indexed and stored for later study. Location of cultural objects (houses, roads, railroads, mine pits, etc.) and topographic features (swamps, rivers, fault scarps, hills, etc.) were recorded in the field notes to aid in plotting and interpretation of the traverse data.

C. Method of Plotting

All outcrops on the regional map were replotted from original notes on a base map prepared from the U.S.G.S. and U.S.C. & G.S. Palmer Quadrangle map of 1952, 7-1/2 minute series. Distances between cultural points were measured from the Palmer Quadrangle map. Differences between these and paced distances were computed and drift curves prepared for each traverse assuming a linear error between control points. Outcrops were plotted on the actual traverses paced, as determined from starting and finishing points of each traverse and again assuming a linear error. Where areas of continuous outcrop existed--such as hills, fault scarps or iron mine excavations--only one outcrop was plotted covering the entire area. A total of over 700 outcrops are identified and plotted on the regional map.

D. Topography

The major topographic feature in the area mapped is the prominent Volunteer Fault trending east-west along the northern parts of sections

27 and 28 where it is exposed as a 150-foot near-vertical cliff. A series of parallel faults cause the land surface north of the main fault scarp to rise in step-like fashion, forming the imposing Ajibik Hills. Immediately south of the fault lies an extensive, swampy grassland drained by a few sluggish streams. This covers the central portions of sections 27 and 28. Further south the land rises out of the swamp becoming a hilly terrain continuing south well beyond the area studied. Glaciation is in marked evidence throughout the area. Glacial grooves extensively mark the rocks to the north and south of the swamp area. Drift cover probably begins in the swampy areas and becomes noticeable as it thickens towards the east where sand plains eventually cover all outcrops.

The topographic trend is then east-west, with low land in the middle and high land flanking to the north and south. With few exceptions, outcrops are found only in the high land.

E. Structure

The Palmer District is a down-faulted appendage of the Marquette Synclinatorium, being on the south limb of that westward plunging, asymmetrical trough. The dominant strike of the formations is $N70^{\circ}W$; the dips range from 30 to 70 degrees north. Superimposed upon this trend are numerous secondary strikes and dips due to both primary deposition and to later folding and faulting. At one location along the southern edge of the New Richmond Mine the iron formation appears to be dipping southward. Again in the northern portion of section 27 a minor fold exposes the Negaunee and Ajibik dipping southward.

The dominant structural feature, the Volunteer Fault, is not a single fault as reported by previous workers, but rather a fault system with parallel secondary faults extending northward and probably southward. A series of these secondary faults can be seen ascending in step-like fashion past the north section lines of 27 and 28. Branching off from many of these E-W striking faults are a series of high angle faults striking NW-SE. There may also be faults parallel to the E-W faults extending south at least to the Palmer Complex. Indeed, at the Moore Mine there is a fault that parallels the Volunteer Fault for a while then strikes SE through section 34. Lamey (19) describes several contacts of the Palmer and Huronian rocks as fault scarps which are parallel to the Volunteer.

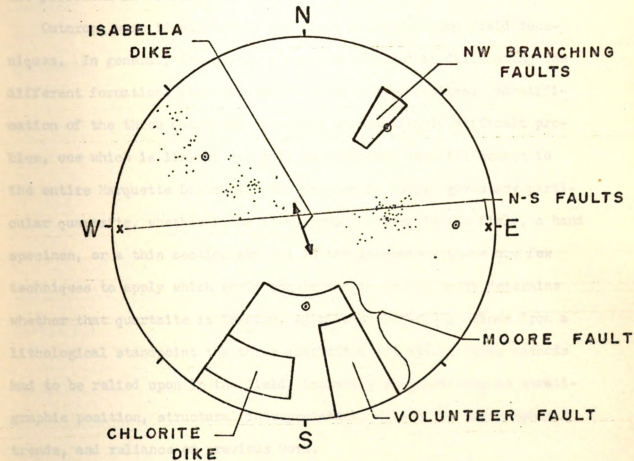
Finally, a N-S vertical fault is well exposed in the east-central portion of section 28 where it cuts through a massive quartzite outcrop resulting in a horizontal displacement of approximately 300 feet. One-half mile directly north an identical N-S vertical fault results in a horizontal displacement of approximately 180 feet.

Three joint sets are found at the Moore Mine: N35°E, 37°E; N35°E, 78°E; and N9°W, 50°W. These joints are most prevalent in the large clastic bodies and appear to terminate at their boundaries.

Figure 2 is a point diagram of the normals to 300 joints associated with clastic lens #2 at the Moore Mine; each point represents 3 joints. Plotted on the same diagram are prominent structural features observed in the area. It can be seen that the joints form a well defined girdle essentially perpendicular to the strike of the iron formation, the Moore Fault, and the Volunteer Fault.

7. Stratigraphy

The stratigraphic column of the Moore Mine is shown in U.S.G.S. Monograph #52 (1950) and is also outlined delineated in the present map. The lithology of the various rock types is presented in U.S.G.S. Monograph #52 (1950) and is also outlined delineated in the present map. The lithology of the various rock types is presented in U.S.G.S. Monograph #52 (1950) and is also outlined delineated in the present map.



In general the Moenard was differentiated from the Moore Mine arbitrarily using the Volunteer Fault. The joints in the Moore Mine below (south of) the fault are termed Moenard. The joints in the Moore Mine above (north of) the fault are termed Moenard. The Moenard and Goodrich using different criteria are presented in U.S.G.S. Monograph #52 (1950) and is also outlined delineated in the present map.

Figure 2. Point Diagram of 300 Joints from Lens #2, Moore Mine with Regional Structural Features Superimposed

F. Stratigraphy

The stratigraphic column for the Marquette District modified from U.S.G.S. Monograph #52 (1) is presented in table I. The formations delineated in the present study are presented in table II. Detailed megascopic and microscopic descriptions of the general lithologies are presented in U.S.G.S. Monograph #28 (2).

Outcrops were identified in the field using standard field techniques. In general, few problems were encountered in delineating the different formations with the exception of the quartzites. Identification of the three quartzites presents an exceedingly difficult problem, one which is limited not only to the study area but common to the entire Marquette District. The problem is this: given any particular quartzite, whether it be an outcrop observed in the field, a hand specimen, or a thin section studied in the laboratory there are few techniques to apply which would enable one to sufficiently determine whether that quartzite is Mesnard, Ajibik, or Goodrich. Since from a lithological standpoint the three quartzites are alike, other methods had to be relied upon in the field, including such criteria as stratigraphic position, structural interpretation, observable topographical trends, and reliance on previous work.

In general the Mesnard was differentiated from the Goodrich by arbitrarily using the Volunteer Fault as a cutoff point; i.e.: quartzites below (south of) the fault are termed Goodrich, quartzites above (north of) the fault are termed Mesnard. The Ajibik is differentiated from the Mesnard and Goodrich using inferred stratigraphic position. Detailed criteria are presented below for specific exposures observed.

Table I
STRATIGRAPHIC COLUMN
OF THE
MARQUETTE DISTRICT*

Pleistocene	Glacial Till
-----UNCONFORMITY-----	
Cambrian	Upper Cambrian Sandstone
-----UNCONFORMITY-----	
Keweenaw	Olivine Diabase Dikes
-----UNCONFORMITY-----	
Killarney	Acidic Granites
-----UNCONFORMITY-----	
Upper Huronian	Upper Michigamme Slate Bijiki Iron Formation Lower Michigamme Slate Clarksburg Volcanics Greenwood Iron Formation Goodrich Quartzite
-----UNCONFORMITY-----	
Middle Huronian	Negaunee Iron Formation Siamon Slate Ajibik Quartzite
-----UNCONFORMITY-----	
Lower Huronian	Wewe Slate Kona Dolomite Mesnard Quartzite
-----UNCONFORMITY-----	
Algoman	Granites and Syenites
-----UNCONFORMITY-----	
Laurentian	Palmer Complex
-----UNCONFORMITY-----	
Keewatin	Kitchi Schist Mona Schist

*Modified from U.S.G.S. Monograph #52, ref. 1.

Table II

Following is presented a correlation of the lithological units mapped along with their correlation with other neighboring areas. The stratigraphic column is the regional geologic

STRATIGRAPHIC COLUMN
OF THE
PALMER DISTRICT

Pleistocene	Glacial Till
-----UNCONFORMITY-----	
Keweenawan	Olivine Diabase and Diabase
-----UNCONFORMITY-----	
Upper Huronian	Goodrich Quartzite
-----UNCONFORMITY-----	
Middle Huronian	Negaunee Iron Formation Ajibik Quartzite
-----UNCONFORMITY-----	
Lower Huronian	(Granite) Kona Dolomite Mesnard Quartzite
-----UNCONFORMITY-----	
Laurentian	Palmer Complex (meta-igneous) (meta-sedimentary)
-----UNCONFORMITY-----	
Keewatin	Hornblende Schist Granite Gneiss

This rock type occupies a very distinct belt between the sedimentary and the main granitic body to the south, extending for at least a quarter-of-a-mile south of the Huronian sediments. This horizon has been the focal point for continuous debate ever since first studied in 1895 by Van Rize and Bayley (2). Due to the complexity of the problem, the Palmer was mapped as an entire unit aside from the several pockets of Huronian sediments to be discussed.

Following is presented a field description of the lithological units mapped along with distribution and correlation with other neighboring areas. The reader is referred to the Regional Geologic Map, Map I located in the map pocket. The Archean Gneiss, the granite, and the diabase and hornblende schist dikes were not studied by the author; their descriptions are abstracted from Long's unpublished master's thesis (28).

ARCHEAN GNEISS

A group of highly deformed and banded schists and gneisses have been studied just north of Lake Gribben (section 34) by Long (28) and Sahakian (27). They are thought to have been originally sediments or eruptives which were subjected to fluid invasion and intense metamorphism. More recently, granitic intrusions have transformed them into younger injection gneisses.

PALMER COMPLEX

The Palmer Complex is a term used by the author to indicate that portion of the Southern Complex which lies immediately below the Huronian formations and to include part or all of the Palmer Gneiss. This rock type occupies a very indistinct belt between the sediments and the main granitic body to the south, extending for at least a quarter-of-a-mile south of the Huronian sediments. This horizon has been the focal point for continuous debate ever since first studied in 1895 by Van Hise and Bayley (2). Due to the complexity of the problem, the Palmer was mapped as an entire unit aside from the several pockets of Huronian sediments to be discussed.

MESNARD QUARTZITE

The Mesnard quartzite is found along the northern one-quarter of sections 27 and 28 where it appears as a massive, vitreous quartzite with colors ranging from white in the east to dark grey in the west and superimposed with varying degrees of ferruginous staining.

The formation is exposed in a series of northwardly ascending fault blocks, where the beds strike essentially east-west and dip 20 to 30 degrees north. Along the fault-faces are found fault breccias and hydrothermal quartz veins. Some of these quartz veins are up to five feet thick and contain quantities of micaceous hematite. In some of the higher quartzite blocks a clean, well-rounded quartzite conglomerate is found, which could be interpreted as being either an interformational conglomerate or the basal Ajibik. The latter hypothesis is favored since similar conglomerates are found in sections 33 and 35 described below. In a few isolated areas north of the main fault, in section 28, outcrops of ferruginous slate were found.

Rosenberger (29), during the 1960 field season, studied sections 22 and 23 in the Palmer District; he found eroded granite and granite gneiss hills partially overlain by Mesnard Quartzite. Ajibik and Kona formations were also identified. The Mesnard was divided into three units; a slate, a slate conglomerate containing granite and gneiss cobbles, and a massive quartzite. A slate conglomerate similar to this was found in the northwest corner of section 27. Further east, a large exposure of strongly foliated slate was found conformable to the Mesnard. The stratigraphic relationship is not very clear due to

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considerable faulting in the area. If the slates are older than the quartzite, they probably correlate with Rosenberger's slates. However, if they are younger than the quartzite, they could be equivalent to the purple slates of the upper Mesnard formation.

Two other important occurrences of Mesnard Quartzite were delineated. In the northwest corner of section 35 the author investigated a hill of quartzite protruding above the local sand plain. There is evidence of the existence of two different quartzites; one, a grey massive variety occupying the northern portion of the hill; the other, a clean massive variety occupying the southern portion of the hill. In one location the younger quartzite is seen as a conglomerate sheet lying immediately on the lower quartzite. Since the Negaunee Iron Formation lies to the north, the younger or northern quartzite must be Ajibik and the southern quartzite, the Mesnard. Lamey (19) studied the same ridge and reached the same conclusion. It is interesting to note that directly across the Marquette Syncline an identical relationship was reported by Seaman (1) in the Teal Lake Area. Tyler and Twenhofel (23) reported no unconformable relationship; but during the summer of 1961 an M.S.U. field crew remapped the Teal Lake Area using a telescopic alidade and found that the Ajibik does indeed abut against the Mesnard with a conglomerate in between, thus substantiating the unconformable relationship.

Another location of importance is found in the northern portion of sections 33 and 34. The following sequence of lithologies is found beginning with the Negaunee and going south (older rocks). The Negaunee extends south of section 29 for about 200 feet; for the next

200 feet, a grey massive quartzite with a good basal conglomerate is found. Immediately south of this is a valley devoid of outcrops. Further south there rises a large east-west trending hill composed of green slaty material, while still further south another quartzite much cleaner than the first is found. Stratigraphic relationships suggest that this lower quartzite is older than the Ajibik. Three interpretations are possible; one, that the quartzite is not a quartzite but, in fact, a fine-grained, highly siliceous granite; two, the rock represents a pre-Archean quartzite; and three, the quartzite is part of the Mesnard formation. Lamey (18) has found that many fine-grained samples of the Palmer Complex, when examined under the microscope, were, in fact, quartzites and vice versa. Therefore, although these outcrops have every appearance of being quartzites, one cannot dismiss the first possibility without detailed microscopic work. In support of the second possibility, Marsden (24) has indicated he believes that there are some pre-Huronian sediments in the Marquette Syncline. This has never been substantiated although some of the sediments between the Mesnard and the Greenstones north of Mud Lake in the Marquette Syncline may well be of this age. *reduction in weight of 20-30%. The ilmenitic staining is*

The author cannot understand why previous workers, Lamey excluded, have failed to identify the Mesnard as extending along the southern edge of the Palmer District; especially since the same workers have recognized the Mesnard as occupying the area immediately north of the Volunteer Fault, a distance of only one mile. Sedimentary distribution would suggest occurrence of the Mesnard along the southern border of the Palmer District. In addition, the Mesnard is found on the northern

border of the Marquette Syncline, a full two miles further west than the area in question, while scattered exposures extend another four miles further west. Therefore, while recognizing that more work in the area is needed, the evidence seems adequate for extending the Mesnard formation west along the southern border of the Palmer District from the Wewe Hills through at least section 33.

KONA DOLOMITE

In the northern portions of sections 33 and 34 a 65-foot high east-west trending ridge of steeply-dipping, dark-green slaty material was found which the writer believes to represent part of the Kona formation. Hand specimens show numerous distinct angular blotches of limonite stain inter-mixed with quartz grains and stringers of chert in a fine-grained groundmass of sericite and chlorite. A well developed foliation is evident striking E-W and dipping 70°N. Long (28) has mapped a similar rock in the north-central portion of section 34 where it is intruded by aplitic granite. He describes it as a "brown-weathering sericitic, chloritic schist."

A number of samples were placed in a concentrated HCl solution with a resulting reduction in weight of 20-30%. The limonitic staining is believed due to oxidation of ankerite crystals. Due to the general appearance, its high carbonate content, and its stratigraphic position, this formation is regarded as a slaty phase of the Kona. It should be added that Van Hise and Bayley (2) report that the Kona grades into calcareous shales southwest of Goose Lake in section 22. Rosenberger (29), studying the same area in 1961, also reports these calcareous shales.

GRANITE

An orange granite intruding the ancient gneisses and the green slate (Kona) was studied in detail by Long (28) in 1958. The granite ranges from medium to coarse-grained, but becomes aplitic where it intrudes the green slate. Prominent minerals present are quartz, potassium feldspar, plagioclase and biotite. Plagioclase is dominant over the potassium feldspar. Traces of zircon, magnetite, muscovite, chlorite, and hematite are also found. Long believes that these granites represent the top portion of a magmatic body intruding between Lower and Middle Huronian time.

AJIBIK QUARTZITE

The Ajibik Quartzite is found just south of the northern section lines of 32, 33, and 34 where it lies unconformably upon either the Palmer, Kona, or Mesnard formations. Exhibited in places is a narrow conglomeratic zone with sub-angular to rounded pebbles of vein quartz, quartzite, granite and green schist composition. Above this conglomeratic horizon the formation appears as a typical massive, dirty quartzite. Similarly related are the outcrops in the southwest corner of section 27, with the exception that here the quartzite overlies only the Mesnard resulting in a good basal quartzitic conglomerate.

In the northeastern part of section 27 the Ajibik is found again as a southward-dipping, dirty, massive quartzite, being differentiated from the Mesnard only by color and structural relationships. The previously mentioned quartzite hill in the northwestern part of section 35 shows the Ajibik lying unconformably upon the Mesnard.

Southwest of the Old Richmond Mine an interesting exposure was studied in some detail. Previous workers have mapped this as Ajibik

since it lies between a basal conglomerate and the Negaunee Iron Formation. The rock consists of sharply defined layers of magnetite and quartzite, each varying in thickness from $1/4$ to $3/4$ of an inch. A normalized modal analysis of each layer is included in table III. The quartzite bands consist of individual, well-sorted quartz grains (roundness = 0.7, sphericity = 0.8, average long diameter = 0.65 mm) in a matrix of chert, chlorite, and some fine grains of magnetite. At least one grain of clastic chert with long diameter of 0.6 mm was found. The magnetite band is actually a chert-magnetite band consisting of very fine grains of chert and magnetite along with some chlorite. No clastic quartz or clastic chert grains were found in the magnetite band. Superimposed on both types of bands are large, fresh, euhedral crystals of magnetite, evidently of hydrothermal origin. The demarcation between individual bands is very sharp; the quartz grains exhibit no gradation as they approach the boundary.

It would be difficult to account for this lithology without subscribing to a primary origin for the magnetite. The writer believes that this lithology represents a gradation between the Ajibik and the Negaunee formations.

NEGAUNEE IRON FORMATION

The Negaunee Iron Formation appears as an even-bedded ferruginous chert (interbedded layers of hematite and white chert), while locally it has been altered to jaspilite (interbedded layers of crystalline hematite and red chert). Distribution is confined mainly to the southern half of sections 27 and 28. The beds strike generally west-northwest and dip between 40 and 70 degrees north. Locally the beds

Table III

MODAL ANALYSES OF SELECTED SAMPLES

Sample:	44	66	317	318	319	321	457-A	457-B
Quartz								
clastic	50		50	69	41	53		60
hydro		5						
Sericite		56			59			
Chert								
clastic	1		7					3
matrix		30					50	24
	45		38	24		40		
Hematite		1						
Magnetite	5	6	5	1	1	5	46	6
Chlorite				5			2	6
Leucoxene		2			1			
Totals	101	100	100	99	102	98	98	99

Sample:	Clastic Lens	44:	Moore Mine, lens #1, CQA ₂
		66:	Moore Mine, lens #6, CS
		317:	New Richmond Mine, CQA ₁
		318:	New Richmond Mine, CQB
		319:	Moore Mine, QS
		321:	New Richmond Mine, CQA ₁

Ajibik Quartzite	457-A:	SW of Old Richmond Mine, magnetite layer
	457-B:	SW of Old Richmond Mine, clastic layer

exhibit numerous fluctuations due to minor folding and faulting. Extensive zones of brecciation occur throughout the formation. Interbedded within the iron formation are numerous clastic deposits, the study of which forms the principal portion of this thesis.

Economically the iron formation is poor due to its high silica content. There are no mining operations currently active although in recent years small tonnage has been shipped from the New Richmond Mine for use in blast furnace cleaning. Recently, extensive mining and concentration has been initiated west of Palmer. A more detailed description of the iron formation at the Moore Mine is presented in Section III.

PYROCLASTIC HORIZON

Striking approximately N70°W from the point where the railroad track crosses the 28-29 section line to just east of the Moore Mine is a highly conspicuous pyroclastic horizon. This horizon is located 400 feet above the base of the Negaunee Iron Formation and consists mainly of an agglomerate and a lithic tuff. This occurrence is described in greater detail in Section III.

GOODRICH QUARTZITE

The Goodrich Quartzite is restricted to the center of section 28 and to a small arm protruding into the north-central portion of section 32. An excellent exposure of basal conglomerate can be seen in section 28 just north of county road M.B. and west of the railroad crossing. Here subangular to rounded pebbles and cobbles of ferruginous chert, jaspilite, chert, vein quartz, and quartzite are imbedded in a matrix

of quartzite and sericite. Similar basal conglomerates are found in section 32 with the addition of granite and granite gneiss cobbles.

Above the conglomerate the formation grades into a typical massive, gray-white quartzite with varying degrees of hematite stain. Two distinct areas of outcrop are found in section 28 separated by a quarter-mile of swamp. No bedding planes were found, but all observed outcrops trended in an E-W direction.

In the west the outcrops are small, in the east they are dominated by a massive quartzite ridge. The isolation of this ridge, its parallelism with the Volunteer Fault (only 400 feet north), and its likeness to the other quartzites poses a question as to whether it is actually Goodrich. Detailed study is needed to answer this question. For the purpose of this report, the author chooses to follow the criteria established earlier and continue to designate this as Goodrich.

INTRUSIVES

Five dikes of consequence and a possible sill were mapped during this study. A large dike known as the Isabella Dike, several tens of feet wide, was observed at the north-west corner of section 32. Mengle (26) maps this dike from the middle of section 31 across the corner of 32 to the middle of section 29, about 1 1/2 miles. The Isabella Dike exhibits typical olivine diabase texture and composition. It is probably older than the olivine diabase dikes of Keweenaw age, being somewhat altered. Further, it does not possess the negative polarity characteristic of most Keweenaw dikes.

A somewhat similar rock type cutting the granite in section 34 has been described by Long (28) as a "fine grained, brown weathering, black

diabase." It would appear that if this is a dike, its width must be in excess of 40 feet. Samples were found to contain mostly serpentine and plagioclase, some epidote, chlorite, and muscovite; but no quartz or magnetite. The rock has undergone extensive alteration (the original olivine, if ever present, is completely absent) along with major deformation as evidenced by the high number of strain lamellae. The age relationship to the Isabella Dike is in question, but with the present information it is considered older.

A typical diorite dike, thoroughly sheared and chloritized, cuts east-west through the iron formation on the south side of the New Richmond Mine. The dike is a few feet wide and can be easily traced a distance of one-half mile; the dike is lost at either end of the clearing.

A twenty foot wide dark green to black, schistose, hornblende, biotite dike is reported in section 34 by Long (23). He states that "structurally it post-dates the Archean gneiss and predates the granite."

A light colored, highly weathered dike visible at the Moore Mine entrance is described in Section III.

Just off the southwest corner of the Old Richmond Mine there is a large outcrop of a dark-green, chloritic body thought to be a sill. It appears to be conformable to the surrounding iron formation while a faint columnar structure is in evidence. It was not possible to trace this outcrop laterally.

SECTION III
CLASTIC-IRON FORMATION RELATIONSHIPS
AT THE MOORE MINE

A. General

The Moore Mine is located in the south-central portion of section 28, T47N, R26W, Upper Peninsula of Michigan, and approximately two miles east of Palmer, Michigan (see fig. 1). Access to the area is east from Palmer via paved County Road MB; the last eighth of a mile being south along a well established trail to the mine site. The mine is located on the hilly terrain south of and overlooking the swampy central portion of section 28.

Geologically, the mine is located within the Negaunee Iron Formation at a position approximately 150 feet stratigraphically above the base of deposition. Locally, the Negaunee consists of alternating layers of chert and hematite striking between N55°W and N85°W and dipping between 40°N and 70°N. A thick pyroclastic horizon is present within the iron formation 400 feet above its base, immediately below which the iron formation has been altered to jaspilite. Parallel to and some 40 feet below the pyroclastic horizon, at the entrance to the Moore Mine, is the Moore Fault striking N65°W and dipping 45°N to 75°N. Fluids moving up and along this fault probably account for the jaspilitic zone, with the pyroclastic horizon acting as a stratigraphic barrier. A superdip survey traced this jaspilitic zone at least 400 feet further east. The Moore Fault can be further traced along a series of bluffs in section 34, a mile east, where it now is striking N55°W.

Within the iron formation there are unusually large quantities of clastics concentrated as lenses, beds, flood plains, channel cuts, and as isolated pebbles, cobbles, and boulders. A total of 42 clastic bodies were mapped during field work at the Moore Mine. The composition of these clastic elements consist primarily of quartz and chert fragments in a matrix of chert, sericite, hematite, and biotite-chlorite with minor amounts of magnetite, leucoxene, and zoisite. The area has been cleared of overburden for a distance of over a quarter of a mile parallel to and some 250 feet perpendicular to the strike, thereby exposing in cross-sectional view over 330,000 square feet of iron formation and associated clastics. Within this area are numerous mining cuts both parallel and perpendicular to the bedding, providing opportunity for a comprehensive study of iron formation-clastic relationships.

The Moore Fault is exposed as a series of branching faults approximately parallel to the Volunteer Fault. From Richard's Cut (see Map II) westward the fault cuts across the iron formation at low angles. It can be traced cutting the top of several upper lenses, but is lost near the middle of the stripped area. The fault is an important factor in controlling the shape of these upper lenses. The vertical displacement is estimated to be at least 30 feet. Although a horizontal displacement of only a few inches has been observed, the true displacement may be significantly greater.

Another small but well exposed fault occurs in the far western portion of the mine cutting through a small clastic lens. The fault

strikes $N79^{\circ}E$ and dips $88^{\circ}N$. The horizontal displacement exhibited by the clastic lens is 9 feet.

Three sets of joints are found at the Moore Mine: $N35^{\circ}E$, $37^{\circ}SE$; $N35^{\circ}E$, $78^{\circ}SE$; and $N9^{\circ}W$, $50^{\circ}W$. Those joints are prevalent in the large clastic bodies and appear to terminate at their upper and lower boundaries; only a few joints can be traced on into the iron formation. On the other hand, most joints traceable in the iron formation follow on into the clastic bodies. A point diagram of the normals to 300 joints associated with lens #2 at the Moore Mine is presented in figure 2. It can be seen that the normals form a tight girdle across the net and that these joints are essentially perpendicular to the strikes of the iron formation, the Moore Fault, and the branching faults north of the Volunteer Fault.

B. Mapping Procedure

Mapping was accomplished using a telescopic alidade and plane table at a scale of one inch equal to ten feet. Vertical control was obtained by level shooting from an established elevation point at the crossing of the Chicago and Northwestern Railroad and County Road MB. The Palmer Quadrangle 7.5 Minute Series Topographic Map of 1952 gives an elevation of 1,313 feet at this crossing. This elevation was carried 0.35 mile, using established foresighting and backsighting procedures, to a second order base station. From this station a network of 42 instrument stations covering the study area was established. Each station was permanently marked for reoccupation. After the traverse was closed detailed mapping from each of the stations ensued. The detailed surveying was divided into two phases;

the first being of a general nature to outline the stripped area and the numerous mining cuts, to locate iron formation-pyroclastic contacts, and to establish elevation control over the area. The second phase consisted of a detailed survey of the clastic bodies.

Outlines of the clastic bodies were mapped at intervals of no greater than three feet, while mining cuts, stripped borders, etc., were mapped at intervals of five to ten feet. Vertical control was established for each of these points using a standard surveyor's rod. Horizontal measurements were made with a 100-foot steel tape. Elevation contour lines were drawn in the field with a contour interval of ten feet. Clastic lenses with several layers of the surrounding iron formation were also sketched in the field. Whenever a map sheet was changed a minimum of three control points were used for reorientation. Map II (in the map pocket) is a copy of the field map.

C. Sample Collection and Preparation

During the detailed study of the Moore Mine area, 427 samples were collected from the iron formation and clastic bodies for laboratory study. Some of these were collected as representative of their particular lithology; some were gathered randomly throughout the study area; while others were collected at definite intervals along a particular traverse. In addition, 23 clastic samples were collected from the New Richmond Mine. All samples were accurately located using telescopic alidade and plane table or steel tape.

Each sample was prepared as a semi-polished section using standard procedures of diamond saw cutting and lapping. Lapping was carried down through the 400 grade corundum powder, providing a surface when

wet adequate for binocular study. All polished surfaces were de-stained to remove the prevalent hematitic stain, see Appendix A, experiment 2 for details.

D. Sample Analyses

1. Microscopic Analysis

Petrographic

Initially each polished de-stained specimen was briefly examined under a binocular microscope and placed in broad lithological groups. Forty-three thin sections were prepared from representative samples for petrographic analysis. It was found, however, that such a study was impractical due to intense hematitic staining. An attempt to de-stain the thin sections was not successful. Since only a few mineral species were present, all of which could be identified in polished section once initially identified in thin section, petrographic methods were used primarily to identify specific minerals and to perform modal analyses on selected specimens. Modal analyses were performed with a six-barrel integrating stage using ten traverses per section; results are presented in table III. In addition, a suite of some 70 thin sections covering the Palmer clastic horizon was graciously lent to the author by J.F. Mergle (Wisconsin State University) providing the chance for study of the iron formation-clastic relationships in the entire area.

Binocular

The binocular microscope was the principal tool used in studying and classifying the samples. A detailed analysis of each polished specimen was conducted including textural, structural, lithological and mineralogical relationships. All samples, especially the

iron formation samples, were examined for clastic chert; only minor quantities were found. A six-barrel integrating stage was adapted to the binocular microscope and used in determining the percent area of quartz grains per sample and to measure thicknesses of hematite and chert bands for selected ferruginous chert samples.

Petrofabric

A standard petrofabric analysis was performed on the c-axis orientation of quartz grains in a cherty quartzite sample from the New Richmond Mine. A maximum c-axis orientation of 6° was measured; but no clearly defined symmetry of fabric was seen. While the specimen was not orientated in the field and thus no conclusions can be made, petrofabric analysis may be worthwhile in studying the post-depositional history of the iron formation.

2. Sieve Analysis

A new technique was developed to facilitate the study of some of the clastic samples. Using a concentrated hydrochloric acid solution to dissolve the hematite followed by a boiling solution of potassium hydroxide to dissolve the chert a residue of "cleaned" sand grains were obtained. These sand grains were then studied by normal procedures of sieve analysis with conclusions applied to the clastic lenses.

In order to justify using the results, the relationship between the original deposited sand grains and the disaggregated sand grains must be resolved. That is, to what extent have the sand grains been altered since deposition and to what extent does the sampling and disaggregation processes affect the sand grains. The first question

involves the effect of diagenetic and metamorphic processes in operation since deposition and is a problem basic to the analysis of many sedimentary rocks. For this study it is tacitly assumed that any such alteration of the sand grains was minor and would result in an error less than those errors inherent in the mechanical sieving operation itself.

The second question involves errors introduced by mechanical breaking of grains during the field sampling and laboratory preparation. In removing a sample from an outcrop or when preparing a sample for disaggregation, a finite number of grains are broken. These broken grains will affect the measured size frequency distribution. For the case where a sample is broken with a hammer, jaw crusher or similar mechanism there is no way to easily determine the number of effected grains. To reduce damage, large field samples were taken from which small laboratory specimens were prepared. By cutting the sample, a controlled surface area is formed and the percentage of broken grains can then be estimated. To minimize this percentage of broken grains one must look for a specimen having the smallest surface area for a given volume, for practical laboratory work this is a cube.

Using a simplified cubic model where the sand grains are spherical and are arranged in a homogenous manner one has only to compare the shell volume to the total volume in order to estimate the maximum percentage of the sample disturbed. The following relationship expresses percent disturbed volume (V_d) as a function of cube dimension (n) and grain diameter (δ).

$$V_d = \frac{\text{shell volume}}{\text{total volume}} = \frac{n^3 - (n-2.5)^3}{n^3}$$

Using the median grain size, the percent disturbed volume for each disaggregated sample was computed and is listed in table IV.

The third and most important question was resolved by extensive laboratory testing showing that sand grains after being subjected to the developed disaggregation procedures were not measurably changed in any of the four parameters observed; size, shape, roundness, and surface texture. These experiments, including the developed disaggregation procedures, are documented in detail in Appendix A.

Standard sieve analyses were run on six samples (#45, #61, #174, #183, #303, and #322). Cubic specimens measuring between one and two inches on a side were cut from the original field sample using a standard diamond saw. Each specimen was disaggregated and sieved according to the procedures outlined in Appendix A. The specimens approximated the mathematical model to a high degree; the sand grain sphericity averaged 0.80, and the samples were quite homogenous throughout.

Statistical measures are generally used by geologists to conveniently express certain characteristics of a frequency distribution in a concise mathematical manner. Table IV contains a number of statistics for each of the sieved samples. This data is presented for the dual purpose of possible correlation with previously published sedimentary data and for comparison and evaluation between the samples themselves. In order to evaluate such data and to draw reliable conclusions one must be familiar with the fundamentals of

Table IV

SIEVE ANALYSTS STATISTICS

Sample Number	Wt (gm)	Vd (%)	Ma	Mg	Ma	Mo	QDa	So	S	S ²	Ska	Sk g	Kga
45	8.3	3.8	0.30	0.29	0.32	0.38	0.10	1.36	0.10	0.01	0.03	1.04	0.20
61	12.5	4.7	0.62	0.55	0.82	0.75	0.40	1.61	0.30	0.09	0.08	0.98	0.28
174	6.2	4.0	0.31	0.30	0.34	0.38	0.12	1.39	0.10	0.01	0.04	1.01	0.24
183	12.8	4.8	0.52	0.47	0.64	0.63	0.30	1.54	0.26	0.07	0.11	1.06	0.24
303	2.9	4.6	0.36	0.34	0.40	0.38	0.15	1.41	0.11	0.01	0.04	1.02	0.29
322	1.5	3.8	0.32	0.30	0.37	0.38	0.12	1.41	0.15	0.02	0.06	1.02	0.21

statistics and what they actually measure in geological terms. The reader is referred to Krumbine and Pettijohn (30), to Krumbine (31) and to Pettijohn (32) for a thorough treatment of this subject.

Figures 3 and 4 present histograms and cumulative curves of the size distributions.

Samples #45 and #174 are from lens #1, a well defined, ideally shaped lens at the Moore Mine. Samples #302 and #322 are from a well defined set of beds at the New Richmond Mine (see Section IV - Location 15) while samples #61 and #183 are from lens #3-4, a poorly defined zone of high sand concentration at the Moore Mine.

The size distributions tend to be similar for samples from the same deposit; but dissimilar for samples from different deposits. This would suggest that each of the deposits represent a singular event each governed by a particular set of source, transport or depositional conditions. Comparison of the size distribution plots to examples from Pettijohn (32) together with the high degree of sorting and lack of clays would indicate that the sands analyzed represent well worked beach sands.

In going from lens #1 to the New Richmond beds to lens #3-4 there is a steady increase in sand size with a corresponding decrease in the degree of sorting (increase in S_o) and overall shape quality of the deposit. If the same source is postulated for each deposit than these differences can be ascribed to differences in transport or deposition mechanisms.

Because lenses #1 and #3-4 were deposited at the same time (same horizon) and are physically close (within 120 feet) the sands were probably derived from the same local source. Differences in size and sorting characteristics are ascribed to differences in transport or deposition mechanism. The poor degree of sorting and larger mean

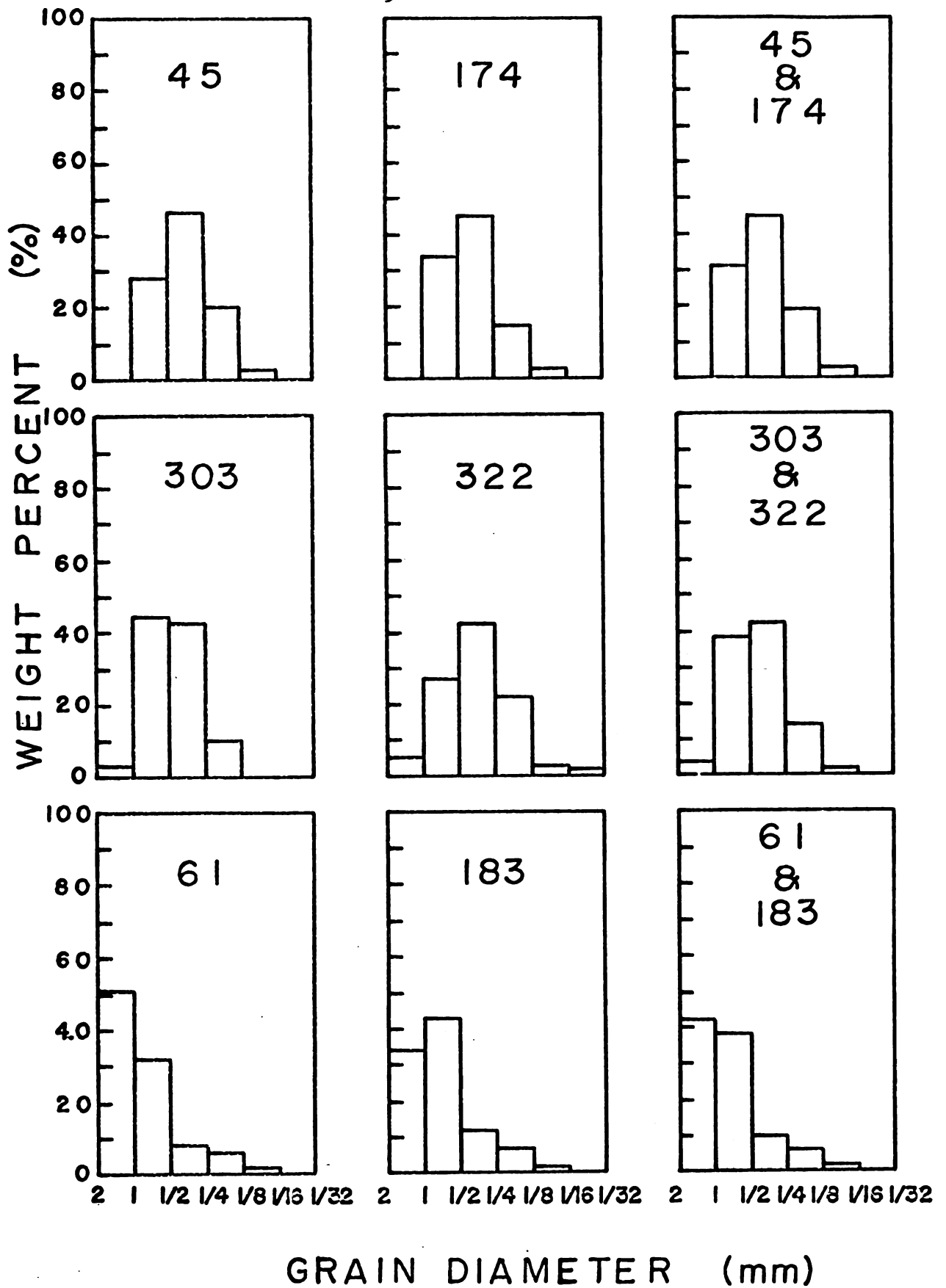


Figure 3. Size Distribution Histograms of Sieved Samples

TYPE - LOCATION - SAMPLE

CQA2
CQA2
CQA3

Lens 1 45 & 174
Lens 3 61 & 183
New Richmond 303 & 322

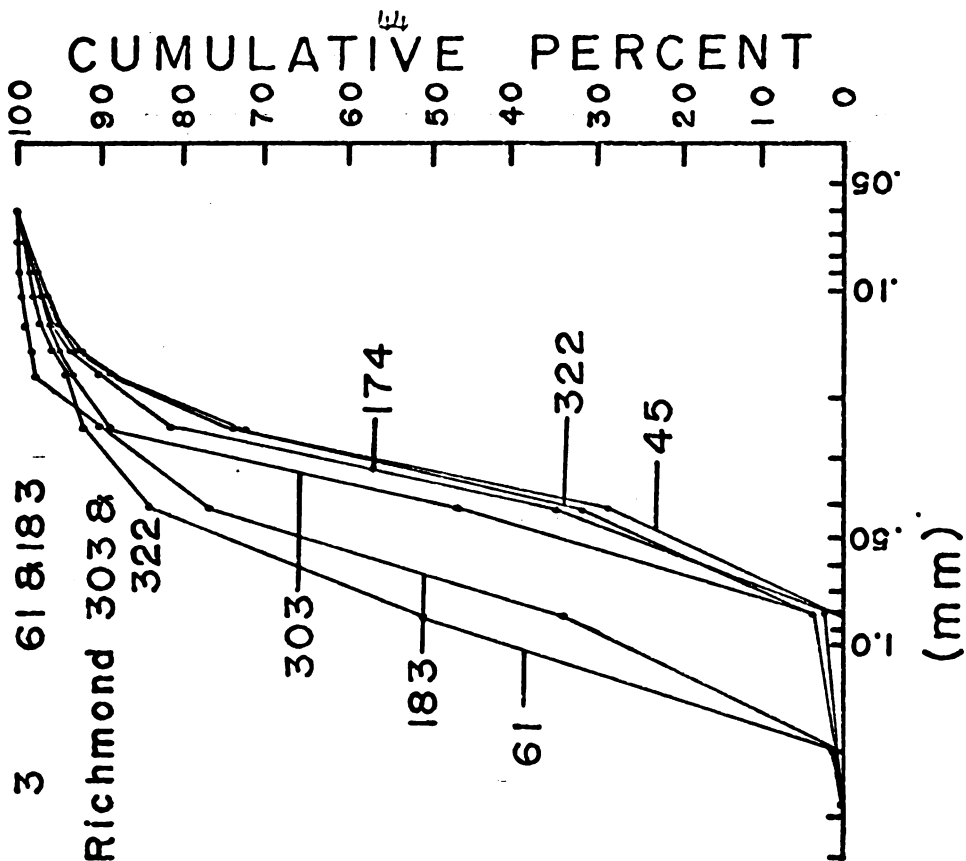
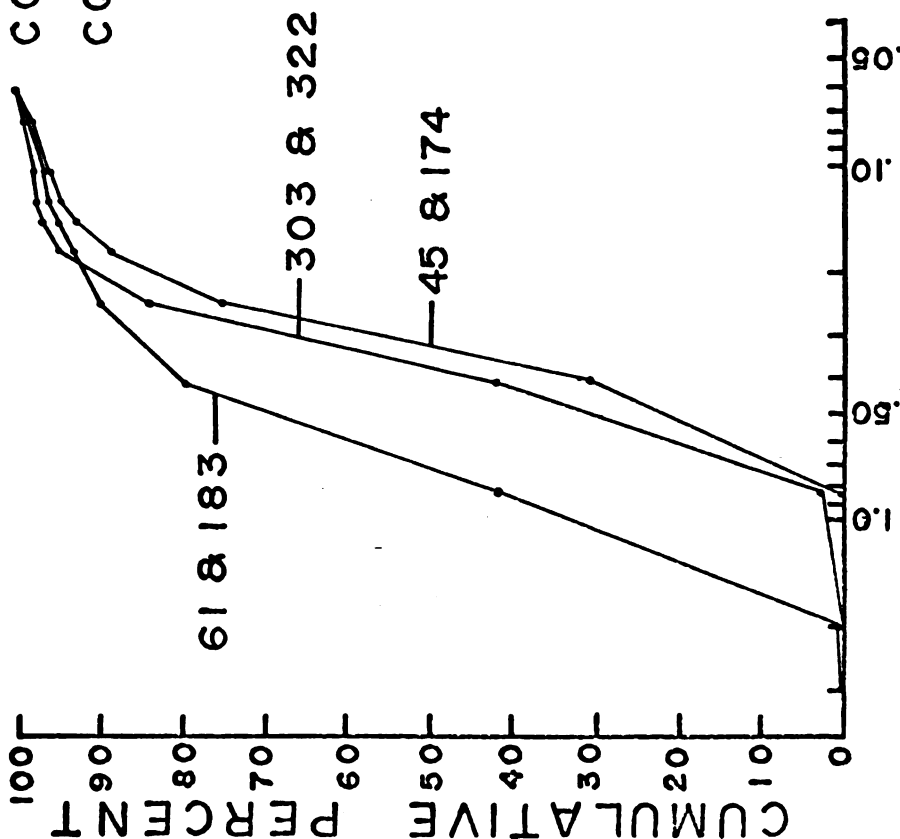


Figure 4. Cumulative Size Distributions of Sieved Samples

grain size of lens #3-4 would indicate a faster and/or more viscous transport fluid. The poorly defined shape would lend support to a sporadic or short-term depositional mechanism. The shape and size distribution characteristics of lens #1 is indicative of a current deposit along which a high degree of sorting was accomplished.

Because of the large separation distance involved, it is difficult to make a similar comparison between lens #1 and the New Richmond beds. These beds, in all probability, were derived from the same general source. The smaller grain size and poorer degree of sorting could be due to a lower transport velocity.

3. Roundness and Sphericity Analysis

Roundness and sphericity measurements were performed on sand grains from ten disaggregated cherty quartzite specimens. A minimum of 300 grains per sample were counted. Figure 5 presents roundness and sphericity histograms. Table V provides sample information and statistics.

There is little difference in the roundness and sphericity distributions from any of the clastic lens samples, all exhibit high sphericity (.8) and medium roundness (.45). This similarity is probably the result of a common local source of equally mature sands.

The cobbles, on the other hand, exhibit a lower sphericity (.6) and a higher roundness (.75). The higher roundness is probably not due to a greater maturity; but rather to the "softer" composition and larger size of the cobbles. The large spread in cobble sphericity could be the result of a greater variation in transport velocities.

The roundness and sphericity of the sands in the cobble lens matrix (sample #90) is similar to the other sands indicating a similar source.

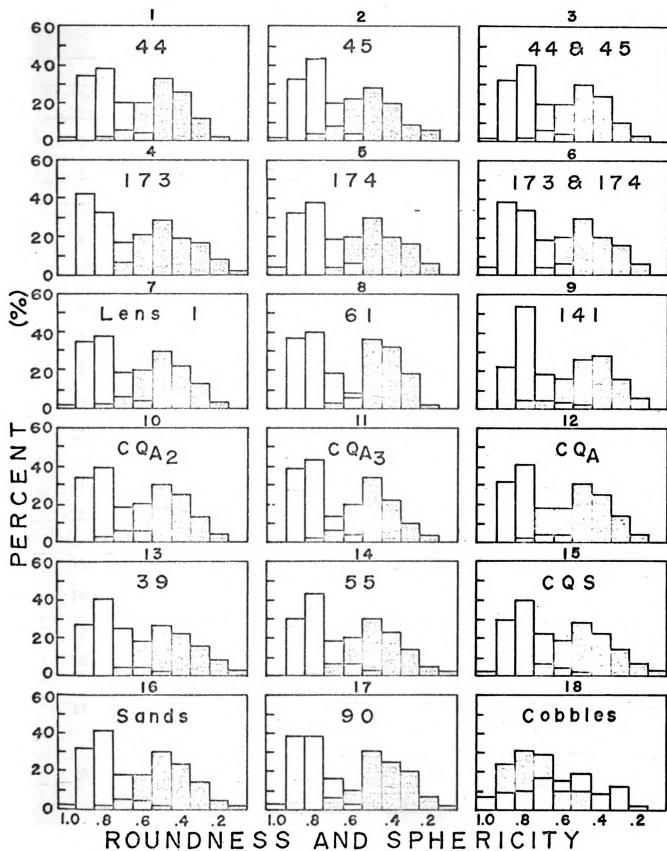
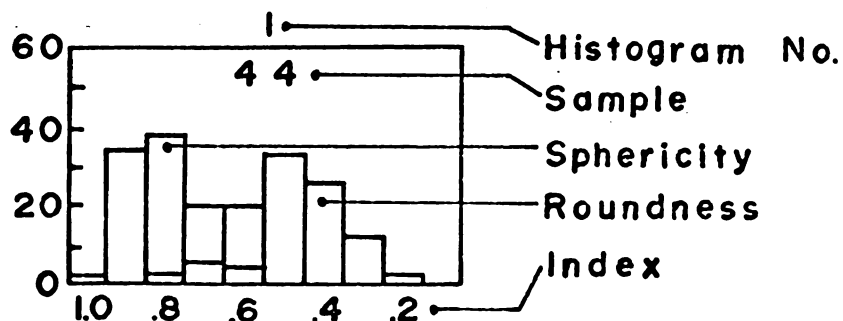


Figure 5. Roundness and Sphericity Histograms

Table V

ROUNDNESS AND SPHERICITY DATA

Histogram No.	Sample No.	Clastic Type	Location (Lens No.)	Roundness		Sphericity	
				Ma	S	Ma	S
1	44	CQA ₂	1 (east)	0.478	0.120	0.805	0.104
2	45	CQA ₂	1 (east)	0.491	0.146	0.803	0.095
3	44,45	CQA ₂	1 (east)	0.484	0.133	0.803	0.099
4	173	CQA ₂	1 (west)	0.456	0.148	0.823	0.094
5	174	CQA ₂	1 (west)	0.456	0.130	0.772	0.159
6	173,174	CQA ₂	1 (west)	0.456	0.140	0.815	0.099
7	44,45,173,174	CQA ₂	1	0.470	0.130	0.809	0.154
8	61	CQA ₂	3	0.435	0.108	0.807	0.093
9	141	CQA ₂	41	0.469	0.146	0.788	0.099
10	44,45,61,141,173,174	CQA ₂	1,3,41	0.464	0.140	0.806	0.078
11	137	CQA ₃	39	0.483	0.129	0.818	0.085
12	44,45,61,137,141,173,174	CQA	1,3,39,41	0.458	0.145	0.807	0.100
13	39	CQS	2	0.447	0.159	0.787	0.101
14	55	CQS	2	0.464	0.143	0.794	0.099
15	39,55	CQS	2	0.457	0.151	0.790	0.118
16	90	Cobble Matrix	18	0.433	0.131	0.818	0.093
17	39,44,45,55,61,137,141,173,174	all sands	1,2,3,39,41	0.461	0.140	0.803	0.110
18	---	cobbles	18,19,20	0.748	0.121	0.608	0.212



4. Heavy Mineral Analysis

Ten untreated samples, representing most types of clastics found, were prepared for heavy mineral analysis. Samples were mechanically crushed and ground with a ceramic mortar and pestle. The crushed samples were washed with distilled water, dried at 70°C for 24 hours, and weighed prior to separation.

Apparatus used during the heavy liquid separation was identical to that pictured in figure 153 of Krumbine and Pettijohn (30). Bromoform, with a specific gravity of 2.85, was the heavy liquid used. Techniques of separation followed those described by Krumbine and Pettijohn. After separation the "lights" and "heavies" were washed with alcohol and weighed. The light and heavy fractions of the samples were each split and mounted on permanent slides for petrographic analysis. Mounting medium used had an index of 1.68. Analyses of the heavy fractions yielded no heavy minerals other than magnetite, leucoxene and hematite. Percentage of heavies are recorded in table VI.

A thorough study of the heavy fraction was not conducted. It was noted, however, that each clastic group contained a distinct suite of heavy minerals, see III-E for details. Heavy mineral analysis would appear to offer a reasonable avenue for further study. Such a study should include analysis of earlier formations (Palmer Complex, Mesnard, Kona, Ajibik, etc.).

5. HCl and KOH Soluble Analysis

Ten different samples, representing most of the types of clastics studied, were mechanically crushed with a ceramic mortar and pestle. Crushed specimens were washed in distilled water, dried at

Table VI

DATA COMPOSITE - PERCENT HEAVIES,
HCl SOLUBLES AND KOH SOLUBLES

Sample No.	Location (Lens No.)	Type	% Heavies	% HCl Solubles	% KOH Solubles
21	2	CQSA		14.8	
40	2	CQSA		31.3	49.7
43	2	CQSC	1.5	1.0	8.4
44	1	CQA2		16.8	
45	1	CQA2		22.2	45.7
55	2	CQSA		31.8	
57	2	CQSA	1.1	0.9	
58	2	CQSA		11.9	
61	3	CQA2		58.2	
67	8	CS	4.8	2.9	27.7
73	7	QS		16.2	
83	14	CQSD	9.2	38.4	27.7
100	22	QS	5.1	3.2	1.0
135	38	CQA3	29.0	13.9	
136	39	CQA3		16.3	
137	39	CQA3		17.6	
138	40	CQA3		15.9	44.0
142	41	CQA2		47.2	
173	1	CQA2	46.2	31.3	30.3
183	3	CQA2		40.9	
199	11	CQSB	1.0	31.3	31.2
284	Moore	IF		52.8	
302	New Richmond	CQA1		27.2	47.6
303	New Richmond	CQA1		39.5	
305	New Richmond	CQA1		32.1	
318	New Richmond	CQB	16.6	12.5	29.2
322	New Richmond	CQA1	41.4	46.5	
430	Moore	Jaspilite		60.1	

70°C for 24 hours, and weighed. Samples were then placed in 200 ml beakers containing 150 ml of concentrated hydrochloric acid (36.5%). Enough stannous chloride was added to keep the iron in solution. Samples were stirred and new HCl was added as necessary. After two weeks samples were removed from the HCl solution, washed, dried at 70°C for 24 hours, and weighed.

During the disaggregation of the clastic samples the loss of HCl solubles was recorded. The process used is detailed in experiment 3, Appendix A. It should be pointed out that this process is inherently different from the above mentioned process in that here samples were placed in HCl solution whole while in the former they were first ground up into fine particles. It is believed that both processes yield results differing by only a few percent as indicated by samples treated with both processes. Finally a number of HCl residue samples were dissolved in an 80-20 solution of KOH, see Appendix A, experiment 4 for details. Results of the HCl and KOH soluble data is presented in table VI.

The percent HCl solubles is an indication of percent hematite present. Aside from the iron formation samples the CQ and CQS groups of clastics contained significant amounts of hematite. Hematite constitutes primary deposits in some of the CQ_A clastics.

The percent KOH solubles is an indication of percent crystalline chert present. Of the four clastic groups only QS does not contain crystalline chert. In groups CQ, CQS, and CS the chert is primary while in CQS it is also found as fragments.

E. Sample Classification

Using the results of previously described analyses with emphasis on the binocular analysis, clastic samples are categorized into four main lithological groups some of which are further subdivided. The type names are chosen from the prevalent lithologies now present. A generalized summary of the data with descriptions of each particular rock type encountered during the study is presented here. Each group and sub-group has been designated by a formulated notation for ease in presentation. Table VII presents the range in composition for each lithological group.

Cherty Sericite (CS)

The cherty sericite (CS) group is found in only a few locations at the Moore Mine. CS lenses are singular in character, all being nearly equi-dimensional in cross section and entirely conformable with the surrounding iron formation. As the name implies chert and sericite are the predominate components of this rock type. The general composition is tabulated below with range of percentages included:

Quartz	clastic - - - - -	0
	hydrothermal- - - - -	2-6
Sericite- - - - -		50-65
Chert		
	clastic - - - - -	0-0.5
	matrix- - - - -	20-40
Hematite- - - - -		1-3
Magnetite - - - - -		5-9
Leucoxenó - - - - -		2-9

The chert is visible as small mosaic ovals averaging between 0.51 - 1.01 mm in long diameter while the chert particles composing the mosaic are smaller in size by a factor of two to three. These

Table VII

SUMMARY OF SAMPLE CLASSIFICATION DATA

Component	Lithological Groups									
	CS	CQ			QS	CQS			CQS ₁	CQS ₂
		CQ ₁	CQ ₂	CQ ₃		QS ₁	QS ₂	QS ₃		
Quartz clastic hydrothermal	0 2-6	34-60 0	34-60 0	65-75 0	20-55 10-30	5-40 0-20	15-35 15-55	0-20 2-50	30-60 0-2	
	50-65	0	0	0	30-60	10-25	10-25	40-80	0-5	
Chert clastic matrix	0-05 20-40	4-8 35-55	0-0.5 30-65	2-4 20-30	0 0-3	0-27 20-65	0 20-60	0-5 3-15	0-3 20-30	
	1-3				1-4	0-6	0-6	0	10-30	
Magnetite	5-9	1-3	1-7	1-2	0-3	0-4	0-4	0-3	0-3	
Leucoxene	2-9	0	0	0	0-12	0-3	0-3	2-13	0-1	
Biotite-Chlorite	0	0	0	2-7	0	0	0	1-8	0	
	0	0	0	0	0	0	0	1-12	0	

chert ovals are usually outlined by titaniferous magnetite and its alteration products of hematite and leucoxene while lying in a ground-mass of minute sericite crystals. The sericite crystals are typically blade-shaped with their longest dimension on the same order of magnitude as the chert mosaic. The outlining magnetite is of hydrothermal origin although there are isolated, slightly worn crystals with average dimensions of 0.03 mm x 0.01 mm. Most of the magnetite is in the process of altering to hematite. Some of the leucoxene fragments also exhibit a typical clastic appearance and are probably either primary clastics or less likely complete alteration products of magnetite. It is significant to note that there are no instances where magnetite crystals are observed in the process of altering to leucoxene, either the crystals are magnetite or leucoxene. Hydrothermal quartz appears in randomly distributed blotches throughout the samples observed. Hematite stain is superimposed upon the entire rock.

In most samples the chert granules are orientated with their long axis parallel to the long axis of the lenses in which they occur, which is also parallel to the strike of the iron formation. This coupled with the oval shape presents a textural appearance very similar to the pillow lavas of the Northern Marquette District. The author is not suggesting that the similarity of appearance is in any way indicative of a similarity in origin, they are without doubt clastic. Rather the texture of the rock suggests that blobs of chert were deposited individually one on top of the other, each being viscous enough when deposited to support the newly deposited oval with minimum resultant deformation.

Cherty Quartzite
(CQ)

The cherty quartzites (CQ) are found abundantly throughout the clastic horizon in the Moore Mine. This group, consisting primarily of chert, quartz, and varying percentages of hematite, is readily divided into two sub-groups one of which contains three classes. These four distinct lithologies, designated CQA₁, CQA₂, CQA₃, and CQB, are listed with their compositions tabulated below; all are conformable with or grade into the iron formation:

		CQA ₁	CQA ₂	CQA ₃	CQB
Quartz	clastic- - -	34-60	34-60	34-60	65-75
Chert	clastic- - -	4-8	0-0.5	0-0.5	2-4
	matrix - - -	35-55	30-65	35-55	20-30
Hematite					
Magnetite - - - - -		1-3	1-7	1-7	1-2
Chlorite- - - - -		0	0	0	2-7

For the CQA's, the quartz present is primarily clastic sand grains of the clear variety along with a few isolated fragments of milky quartz; no hydrothermal quartz has been found in any of the samples observed. Clastic grains range from 0.12 to 1.30 mm in size, the average being 0.50 mm. Average measured roundness and sphericity of these grains is 0.45 and 0.80, respectively. Due to the extensive amount of hematite, hand specimens appear to exhibit sand grains that are corroded. In destained polished sections the grains are found not to be corroded but rather to be "floating" in a matrix of hematite and chert. There is no preferred shape orientation observable; one sample from the New Richmond Mine, however, did have a 63° maximum C-axis orientation.

Finally, most grains show the typical undulatory extinction of metamorphized quartz. A few angular quartz fragments observed have average dimensions of 4.57×2.19 mm.

All gradations of clastic chert are found from fragments down to granules. The average size of the fragments is 3.08×1.41 mm; the granules range between 0.30 and 0.50 mm in longest diameter. Shape of the granules are either oval or spherical all with near perfect roundness. The chert crystalites measure between 0.04 and 0.07 mm independent of whether they are constituents of the fragments, granules, or matrix of the specimens. All chert exhibits extensive undulatory strain.

Magnetite is hydrothermal in origin appearing as well developed crystals, blotches, and dike-like-stringers surrounding, but never cutting through the quartz grains. The chert granules, curiously, do contain minute specks of magnetite intermixed with the chert crystals. The general appearance of the magnetite is fresh although some can be seen altering to hematite and leucoxene. Hematite blankets all the samples; once the staining has been chemically removed the residual hematite is found to be an integral component of the matrix. Figure 6 shows a photomicrograph of a CQ_{A2} sample from lens #1. Quartz grains in various stages of undulation are seen floating in a chert (mosaic) and hematite (opaque) groundmass.

The CQ_B sub-group varies slightly from the CQ_A 's. Quartz is present both as clear and milky sand grains. The mean size is slightly larger $0.12 - 2.00$ mm, while the sphericity and roundness of the clear grains are the same. The quartz grains are packed closer than the

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CQ_A's resulting in undulatory extinction and interlocking texture with suture structures in conspicuous evidence. Again no preferred shape orientation is observable. Unlike the former, milky quartz is found as rounded grains up to twice the size of the clear quartz grains. Petrographic study indicates that these are rounded fragments of quartzite (possible Mesnard source).

The chert, magnetite, and hematite content is observed to be similar to the CQ_A's except for the fact that magnetite is not observed altering to leucoxene. The primary difference noticed between the two sub-groups is the presence of chlorite in the CQ_B's. Chlorite is seen as sheafs and plates intermixed throughout the matrix, it is light brown to bright green to dark brown, has a biaxial negative optical character and is slightly pleochloric. The above properties would indicate thuringite similar to that discussed by James (34). A typical occurrence of a CQ_B clastic is shown in figure 8, containing interbeds of chert (light), hematite (dark) and CQ_B.

While each of the four lithologies possess the same general characteristics they differ from each other in one or more specifics. For instance only CQ_B contains chlorite, only CQ_{A2} shows evidence of significant primary hematite, while only CQ_{A1} and CQ_B contain significant amounts of clastic chert. CQ_{A3} is similar to CQ_{A1}, except for the lack of chert and closer packing. Figure 7 shows the close packing of the CQ_{A3} lithology. Further each of the sub-groups seem to be restricted to a definite geographical location; CQ_{A1} and CQ_B are located at the southern extent of the New Richmond Mine; CQ_{A2} and CQ_{A3} are located at the Moore Mine, the former in the eastern and central portion the latter

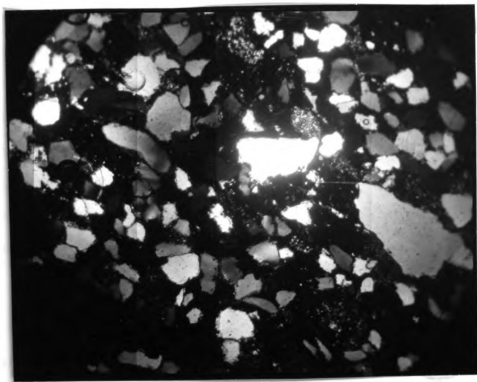


Figure 6. Photomicrograph of a CQA₂ Specimen Showing Sand Grains Floating in a Chert (mosaic) and Hematite (opaque) Groundmass, Crossed Nicols, 10X

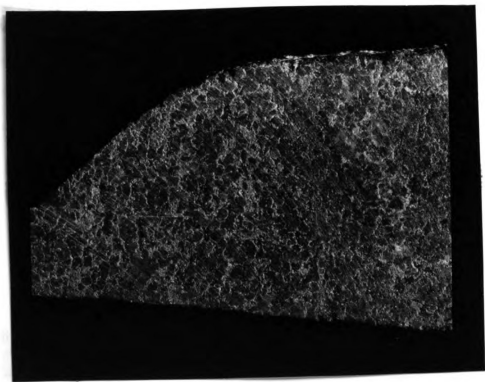


Figure 7. CQA₂ Semi-polished Specimen with Etched Surface Showing Close Packing of Sand Grains, 2X

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in the western portion (one small CQ_{A2} lens #41 is found in the far western extremity of the Moore Mine). Finally, each of the lithologies are found in a particular physical setting. At the New Richmond Mine CQ_{A1} and CQ_B are interbedded with the iron formation, most beds being only a few inches thick. The CQ_{A2} type is typically found as long, narrow, perfectly formed lenses; while the lateral edges of the CQ_{A3} grade by "on-lap off-lap" into the iron formation.

Sericitic Quartzite (QS)

The sericitic quartzites (QS) are composed primarily of quartz grains in a sericite matrix with minor amounts of magnetite, hematite, and clastic leucoxene all in various degrees of alteration by hydrothermal quartz solutions. The range from sample to sample and from lens to lens is high. A typical semi-polished specimen is shown in figure 9. Note the apparent lineation and corrosion of the quartz grains. This group could probably be subdivided into several subgroups with more detailed study. A tabular composite is presented below:

Quartz		
	clastic - - - - -	20-55
	hydrothermal - - - - -	10-30
Sericite-	- - - - -	30-60
Chert		
	matrix- - - - -	0-3
Hematite-	- - - - -	1-4
Magnetite -	- - - - -	0-3
Leucoxene -	- - - - -	0-12

The clastic quartz grains differ from similar grains in the other groups in being oval in shape with average roundness and sphericity of 0.63 and 0.50, respectively. Grains range between

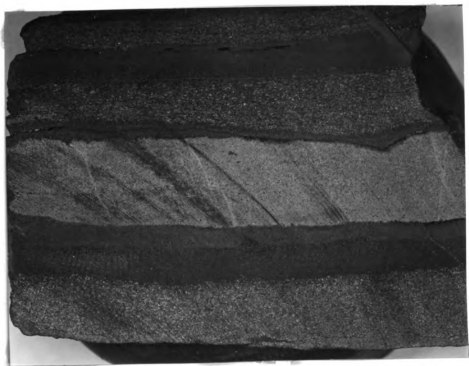


Figure 7. CQ₂ Semi-polished Specimen Showing Interbeds of Chert (light) Hematite (dark) and Sand Grains in a Chloritic Cherty Matrix, 2X

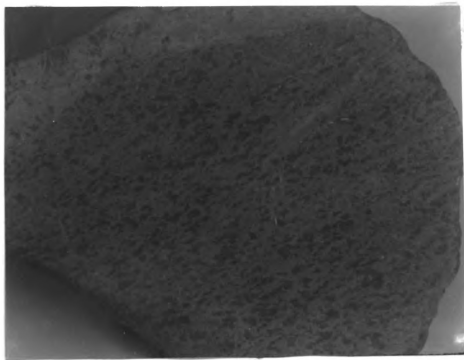


Figure 8. CQ₂ Semi-polished Specimen Showing Apparent Lineation and Corrosion of the Quartz Grains, 2X

0.20 and 0.63 mm in size with 0.45 as the average. Hydrothermal solutions have cut throughout the specimens significantly altering the granular texture. Many instances are observed where solutions have extensively corroded grains. All clastic quartz grains show strong undulatory extinction and interlocking textures. In places the grains are highly fractured and filled with hydrothermal quartz, magnetite, hematite, and even sericite. Only in a few instances can quartz be seen partially replaced by sericite.

The matrix is composed of over 85% sericite in the form of rectangular sheafs. Occasionally a few small grains of chert can be identified. In the vicinity of the hydrothermal veins there is a noticeable enlargement of the sericite grains.

Magnetite is observed as long stringers winding around the clastic quartz grains and being altered almost completely to hematite. Another form of magnetite is in evidence, that of rounded and semi-rounded rectangles averaging 0.07 by 0.02 mm in size. These shapes would indicate a clastic origin; the grains show no signs of alteration. Hematite, aside from the usual stain, is visible as an alteration product of the hydrothermal magnetite; no primary hematite is present.

Leucoxene grains are found abundantly throughout the samples as semi-rounded rectangles averaging 0.03 mm in length. There are approximately four times as many leucoxene grains as magnetite grains in any given sample; further, none of these grains show any alteration relationship to the magnetite and hematite. Many of the samples show definite shape orientation with the long axis of the grains parallel to the observed long axis of the lenses.

Cherty Sericitic Quartzite (CQS)

The dominant clastics, by volume, at the Moore Mine are the cherty sericitic quartzites (CQS). This group is readily divided into four sub-groups described below.

(CQS_A)

The most prominent of the CQS sub-groups is the cherty sericitic quartzite conglomerates (CQS_A) consisting of various sized fragments of chert, quartzite, sericite, iron formation and QS randomly deposited in a fine grained matrix of chert and sericite. Due to the nature of this sediment there is a large variance from sample to sample. Figures 10 and 11 show two typical textures for the CQS_A lithology. No attempt was made to subdivide this sub-group. A table of the range in composition is presented below:

Quartz	clastic-	- - - - -	5-40
	fragment	- - - - -	0-25
	hydrothermal	- - - - -	0-20
Chert	clastic-	- - - - -	0-27
	fragment	- - - - -	0-25
	matrix	- - - - -	-20-65
Sericite	fragment	- - - - -	0-25
	matrix	- - - - -	-10-25
Magnetite	- - - - -	- - - - -	0-4
Hematite-	- - - - -	- - - - -	0-6
Leucoxene	- - - - -	- - - - -	0-3

Quartz appears in a gradation of sizes from cobble-size down to fine sand grains. Roundness and sphericity also vary over the entire range. Hydrothermal quartz is visible as veins and blotches throughout the lenses, in places completely surrounding clastic

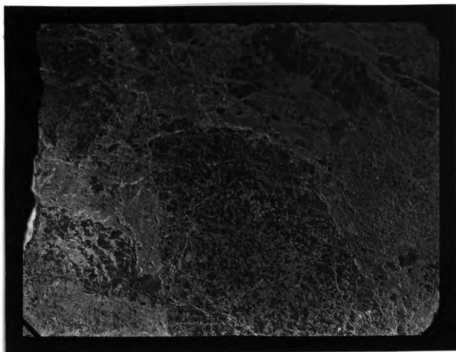


Figure 10. Typical CQS_A Semi-polished Specimen Showing Sub-rounded Fragments of QS, Chert and Sand Grains in a Sericitic Chert Matrix, 2X

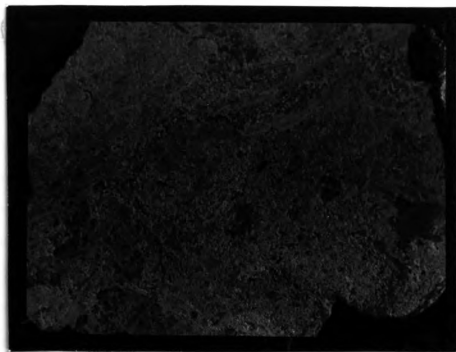


Figure 11. Semi-polished CQS_A Specimen Showing Turbulent Textures Common Near Lower Boundaries of Lenses, 2X

fragments. Locally the clastic fragments reveal intensive dynamic action being strained and crushed, and subsequently intruded by solutions of quartz and magnetite.

Chert is present primarily as a fine grain matrix. Near the bottom of the lenses, the underlying ferruginous layers of iron formation can be seen in varying stages of "decay", the hematite eventually being leached out, the chert being reduced from coarse fragments down to small granules. Most of the fragments and granules contain small percentages of sand grains. Chert fragments with sub-angular shapes are found throughout the lenses, usually no larger than a square inch.

Sericite is also primarily found as matrix; but there are numerous fragments with inclusions of chert, quartz, etc. A few isolated sheafs of biotite-chlorite in the early stages of alteration are found throughout the lenses.

Magnetite is found only as hydrothermal veins and poorly developed crystals altering to hematite. Neither magnetite nor hematite give any appearance of being primary in origin.

(CQS_B)

Composition wise, the CQS_B sub-group is nearly identical to the CQS_A sub-group, the primary difference being the lack of fragments and fines. In hand specimen this rock type has the appearance of a "true quartzite"; when studied in thin section specimens are seen to contain low percentages of clastic quartz grains while being extensively soaked by hydrothermal solutions. Percentage compositions are presented below, similarity to the CQS_A sub-group is noted:

Quartz	clastic- - - - -	-15-35
	hydrothermal - - - - -	-15-55
Chert	matrix - - - - -	-20-60
Sericite	matrix - - - - -	-10-25
Magnetite - - - - -		0-4
Hematite- - - - -		0-6
Leucoxene - - - - -		0-3

Quartz grains are similar to those in CQS_A specimens except that they exhibit a pronounced dynamic history. The chert and sericite compose the matrix and are found as fine grains and sheafs respectively. Occurrences of magnetite and hematite are also similar to those described in the previous section. The occurrence of leucoxene is slightly different from that of the CQS_A sub-group; it is observed only as an alteration product of magnetite.

(CQS_C)

This sub-group is found intimately associated with the CQS_A sub-group while being different both from a standpoint of lithology and texture. The percentage composition is given below:

Quartz	clastic- - - - -	0-20
	hydrothermal - - - - -	2-50
Chert	matrix - - - - -	3-15
	fragment - - - - -	0-5
Sericite- - - - -		40-80
Biotite-Chlorite- - - - -		1-8
Zoisite - - - - -		1-12
Leucoxene - - - - -		2-13
Magnetite - - - - -		0-3

All CQS_C samples studied are found to consist of assorted clastic fragments mostly (sand grains) in a matrix primarily of sericite

impregnated with slender sheaths of leucoxene (see fig. 12). There is no observable evidence that the leucoxene resulted from alteration of the magnetite; all grains are 100% leucoxene. A few quartz grains and quartz and chert fragments are present. Samples studied are soaked with hydrothermal quartz. Also, significant quantities of chlorite-biotite, pyrophyllite, and zoisite have been identified. Pyrophyllite appears to be concentrated along joint planes and is believed to be of hydrothermal origin.

(CQS_D)

The CQS_D sub-group has a composition and texture between the CQ_{A2} and CQS_A lithologies. This lithology appears as a loosely packed CQ_{A2} with minor but noticeable percentages of small chert, sericite, and hydrothermal quartz fragments along with an equally small influx of sericite. The average composition of the sub-group is presented below:

Quartz	clastic	- - - - -	-30-60
	fragment	- - - - -	0-5
	hydrothermal	- - - - -	0-2
Chert	clastic	- - - - -	0-3
	fragment	- - - - -	0-7
	matrix	- - - - -	-20-30
Sericite	fragment	- - - - -	0-5
	matrix	- - - - -	-10-25
Magnetite	- - - - -	- - - - -	0-3
Hematite	- - - - -	- - - - -	-10-30
Leucoxene	- - - - -	- - - - -	0-1

F. Lens Descriptions

During the detailed study of the Moore Mine, 42 clastic bodies were identified, sampled, and studied. On the basis of their

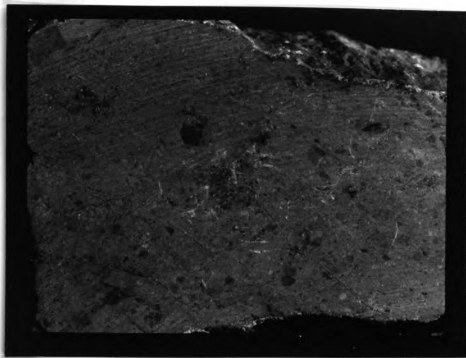


Figure 12. Semi-polished Q35, Specimen Consisting of Assorted
Fragments (mostly sand grains) in a Sericitic Matrix, 2X

lithological and textural properties each lens has been categorized and placed into a lithological group or sub-group. Lenses #1, #2, #8, #11, #14, #19, #30, and #38 are the type lenses for the CQ_{A2} , CQS_A - CQS_C , CS , CQS_B , CQS_D , cobble, QS and CQ_{A3} groups and sub-groups, respectively. Presented below is a description of each lens studied in numerical order, see Map II for their location. Table VIII contains tabulated data for each lens, while table IX contains a summary of lens data by lithology.

LENS #1

Clastic lens #1 is the type lens of the CQ_{A2} sub-group. The dimensions are approximately 40 feet by 4 feet and thus a shape index of nearly 0.1. Although the general shape is that of a double convex lens, the western portion exhibits a slightly greater width. The lower boundary varies from 1.9 to 4 feet above lens #2. The exposed surface consists of crumbled material and, due to the subsequent erosion, is slightly depressed below the surrounding iron formation. The actual contact, however, can readily be observed and is conformable.

The average composition of the lens is identical to that of the CQ_{A2} lithology; the sand grains "float" in a matrix of chert and hematite. The lens exhibits good sorting and medium packing of the sand grains, the texture is homogeneous. Analysis of data indicates a slight increase in percentage of quartz grains and primary hematite from the bottom to the top of the lens.

LENS #2

Lens #2, the main lens, is the largest clastic body at the Moore Mine. This is the easternmost lens extending from the eastern edge

Table VIII

CLASTIC LENS DATA

Lens #	Lithology	Length (ft)	Width (ft)	Shape (w/l)	Quartz		Size (mm)	% HCl Solubles	% Heavies
					R	S			
1	CQA ₂	37.5	3.8	0.10	43.0	0.47	0.80	0.29	46.2
2	CQSA-CQSC	302.4	46.8	0.16	0.0-54.5	0.46	0.78	0.58	1.3
3	CQA ₂	16.5	2.0	0.12	47.9	0.45	0.80	0.55	49.6
4	CQA ₂	11.8	1.2	0.10	11.9	0.44	0.79	0.20	40.9
5	CQSA	23.8	2.5	0.11	0.0-37.6	0.46	0.75	0.30	
6	CQSA	4.1	0.5	0.12	41.2	0.45	0.73	0.30	
7	CQSA-CQSC	173.3	14.2	0.08	0.7-39.5	.46	0.81	0.51	
8	CS	6.3	3.5	0.56	0.0	N/A	N/A	2.9	4.8
9	CS	5.8	1.0	0.17	37.2	0.62	0.50	0.35	
10	CQS _B	9.5	2.2	0.23	41.7	0.46	0.81	0.50	
11	CQS _B	3.0	1.2	0.40	36.6	0.47	0.81	0.54	1.0
12	CQSA-CQSC	173.3	14.2	0.08	0.7-38.5	0.46	0.81	0.51	
13	CS	7.8	0.8	0.10	0.0	N/A	N/A	N/A	
14	CQS _B	43.9	4.0	0.09	33.6	0.49	0.94	0.59	

Table VIII (cont'd)

Lens #	Lithology	Length (ft)	Width (ft)	Shape (w/l)	Quartz		Size (mm)	% HCl Solubles	% Heavies
					R	S			
15	CQSA	6.5	2.0	0.31	17.7	0.47	0.81	0.39	
16	QS	2.0	6.5	0.72	44.8	0.60	0.52	0.60	
16A	CQSA	24.0	3.5	0.15	0.9	0.47	0.78	0.42	
17	Cobble	13.8	1.9	0.14	31.9	0.45	0.81	0.29	
18	Cobble	34.6	2.9	0.08	30.6	0.46	0.81	0.32	
19	Cobble	28.4	4.0	0.14	30.7	0.47	0.82	0.31	
20	Cobble	27.5	6.5	0.24	28.7	0.45	0.84	0.37	
21	Cobble	4.3	1.5	0.35	32.4	0.48	0.80	0.29	
22	CQSA	4.5	0.9	0.20	7.8	0.45	0.77	0.81	
23	CQSA	4.3	0.8	0.19	No Samples Taken				
24	CQSD	71.5	3.1	0.04	52.6	0.40	0.80	0.57	
25	QS	46.5	2.1	0.05	47.2	0.67	0.48	0.40	2.2
26	CQSA	66.5	3.8	0.06	13.8	0.46	0.79	0.39	5.1
27	QS	2.5	0.5	0.20	48.6	0.62	0.49	0.50	
28	CS	2.1	0.4	0.19	0.0	N/A	N/A	N/A	N/A

Table VIII (cont'd)

Lens #	Lithology	Length (ft)	Width (ft)	Shape (w/l)	Quartz			Size (mm)	% HCl Solubles	% Heavies
					R	S	W			
29	QGS ₂	20.0	4.3	0.22	48.5	0.44	0.79	0.55		
30	QS	77.5	5.2	0.64	33.9	0.59	0.52	0.26		
31	QGS ₂	37.9	3.4	0.09	49.2	0.46	0.83	0.49		
32	QS	11.2	1.0	0.09	27.6	0.64	0.51	0.46		
33	QGS _A	1.2	0.4	0.33	0.8	0.46	0.84	0.48		
34	QGS _A	0.9	0.2	0.22	-	-	-	-	No Samples Taken	-
35	QGS _A	3.3	0.4	0.12	-	-	-	-	No Samples Taken	-
36	QGS _D	41.3	2.7	0.06	34.1	0.47	0.76	0.72		
37	QGS _A	10.6	2.8	0.26	58.2	0.40	0.76	0.50		
38	QQA ₃	76.5	7.3	0.09	55.6	0.46	0.83	0.65	13.76	29.00
39	QQA ₃	78.1	10.3	0.13	53.3	0.48	0.81	0.69	17.57	
40	QQA ₃	75.4	18.1	0.24	47.0	0.48	0.81	0.68		
41	QQA ₂	23.7	1.4	0.06	65.4	0.44	0.73	0.77	47.18	

Table IX

CLASTIC LENS DATA SUMMARY

Lithology	Length	Width	Shape	%	R	Quartz		% HCL Solubles	% KOH Solubles
						S	Size		
CQA	54.3	7.1	.16	0-58.2	.46	.79	.44	0.9-31.8	1.3
CQA ₂	16.8	2.3	.24	42.2	.46	.82	.51	1.3	1.0
CS	34.4	2.2	.24	39.9	.63	.50	.45	2.2	5.1
CS	5.4	1.6	.28	0.0				2.9	4.8
CQA ₂	22.4	2.1	.10	42.2	.45	.79	.45	40.3	46.2
CQA ₃	76.7	11.9	.15	52.0	.47	.82	.67	15.7	29.0
IF (pop I)	--	--	--	2.0	.44	.43	.15	--	--
Cobble	21.7	3.4	.19	30.9	.46	.82	.32	--	--
CQA ₂	45.1	3.8	.11	42.2	.45	.80	.57	--	--

of the stripped area westward 302 feet to a point just beyond Richard's Cut. This type lens of the CQSA and CQSC sub-groups, is conspicuously exposed as a gently rolling mass rising in some places well above the surrounding iron formation. Figure 13 shows a view looking north across lens #2 from the southern edge. The glacial molding and hematitic staining is prominent. The over-all shape approaches that of a double convex lens; however, on detailed examination, there do appear to be several discrepancies. After correcting for elevation and dip the lens assumes a more symmetrical shape. The contact between the lens and the enclosing iron formation is usually marked by a zone of brecciated material a few inches in width. At the lateral borders of the lens the iron formation bedding can be seen to arch around the bottom and top, coming together within a few inches at the western end and a few feet at the eastern end. Only a small triangular zone of brecciated material marks these areas.

Ninety percent of the iron formation-elastic contact can be classed as conformable; only five areas (one on the top) pose apparent problems. Of these, two can be explained by movement along existing joint planes. The one area on the top is in a structurally disturbed position where the upper portion of the lens has been displaced by the Moore Fault. This fault can be traced 75 feet west to Richard's Cut where it is well exposed in cross section and is seen cutting the iron formation at an angle of 24 degrees. The two remaining zones, which are the two major areas with contact discrepancies, can also be explained by movement along existing joint planes although with not the same degree of confidence as the others.

A triangular shaped fragment of banded iron formation (3 ft x 3 ft x 3 ft) located four feet above the base of the lens was deposited contemporaneously with the rest of the clastics. Its well banded texture abuts sharply against clastic material. This was the only observed occurrence of such a large iron formation fragment lodged within a clastic lens.

Structurally, the lens has been distorted by folding and faulting. The Moore Fault trending along the northern edge of the lens can be traced both east and west for some distance and appears to be a major lineation in the area. Besides the fault there are a great number of joints criss-crossing through the lens proper, some of which are seen to pass uninterrupted into the iron formation below. Few pass into the iron formation above.

The surface coloration is predominantly whitish-yellow superimposed with numerous random blotches of hematitic stain, producing a leopard-like design (fig. 14). Several areas are characterized by a green coloration, probably zoisite. In addition there is a moderate quantity of pyrophyllite occurring along surface joint planes. Another surface feature deserving mention are the quartz "plasters" found throughout the lens surface. It is interesting to note that, while some exist along the boundaries, none have been found to cross over onto the iron formation. These plasters consist of hydrothermal quartz now averaging from 1/2 inch to 3 inches in thickness and covering several square yards in area. They appear to be a surface phenomena and to be lithologically unrelated to the lens, having formed at a time when the lens had reached its present position.

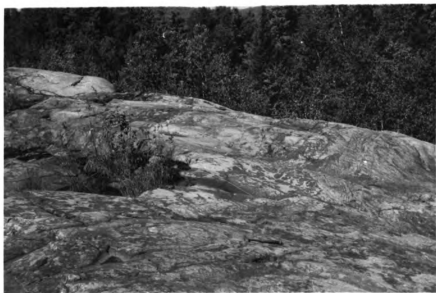


Figure 13. Clastic Lens #2 Looking North from the Southern Edge

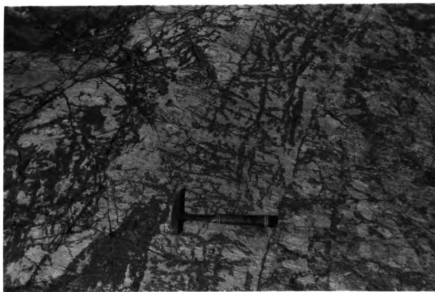


Figure 14. Joint and Fracture Controlled Hematitic Staining in Lens #2

Relationship of these quartz plasters to hydrothermal quartz veins is possible, one vein measuring 2 feet wide and 10 feet long passes a few inches from one of the prominent plasters.

On first examination, the lens appears to be a dense conglomerate containing angular and rounded pebbles, cobbles, and boulders of quartz, chert, iron formation, etc. Close inspection, however, discloses that only a small percentage (less than 20%) of these pseudo-fragments are actually fragments. The coloration, particularly the hematite coloration, is very misleading in this respect. Many stains follow fracture patterns thereby outlining angular closed areas which take on the appearance of angular fragments. Further, the previously mentioned quartz plasters were found to fill in any surface irregularities. When eroded away, these pockets of remaining quartz tend to give the illusion of bona fide pebbles. A close-up of the surface of lens #2 showing a semi-rounded rectangular cobble and numerous pseudo-pebbles is shown in figure 15.

The composition of lens #2 is within the range of compositions for the CQS_A and CQS_C lithologies described previously. The CQS_C sub-group is found in the central portions of the lens, always several feet from either end. Observations of the cross section at Richard's Cut shows that the CQS_C extends down dip without appreciable change. This lithology typically takes on a yellow-green coloration.

The CQS_A sub-group presents a problem in correlation due to its extreme variation throughout the lens. Essentially, there are three textural types which can be used to categorize the collected specimens; turbulent, fragmental, and fine grained. Figures 10 and 11 present

typical examples of the fragmental and turbulent varieties. The turbulent textures are found primarily along the bottom of the lens, within a few feet of the contact. The groundmass is composed of chert and sericite containing fragments of quartz and chert; the latter are angular the former not. Superimposed upon these are swirls of sand grains winding throughout the specimen some forming pocket-like deposits, others forming randomly orientated arcs. The sand grains average from 0.2 to 0.6 mm in long diameter. Hydrothermal quartz, magnetite, and leucokene are at a minimum.

The fine grain textures are not restricted to any particular location except that they are absent near the base. They contain about an equal percentage of chert and sericite, a high percentage of hydrothermal quartz, and a low percentage of what appears to be primary hematite. Few fragments of any kind have been found in these samples.

The most prevalent texture is the fragmental type which is found throughout the lens. Again, the matrix is primarily chert and sericite in equal amounts, with little magnetite and leucokene and only traces of chlorite-biotite and zoisite. The fragments consist of pink and white chert, clear and milky quartz, and sericitic quartzite. Sizes range from sand grain up to pebble size. Other angular fragments much larger, some up to several inches in cross section, are also present. Their composition is identical to the CQS_A lithology. The sorting is poor; the matrix usually composes 50% of a specimen.

LENSES #3 and #4

Lenses #3 and #4 are areas in the iron formation with a high density of sand grains. Careful study in the field allows one to

determine possible tops and bottoms of these lenses, but the lateral edges grade imperceptibly into the iron formation. It is difficult to define the lens since, more often than not, fragments of iron formation are included within. These fragments have bedding parallel to the surrounding iron formation bedding; indicating little movement.

Study of polished sections reveals two basic types of textures. One, best exemplified in lens #3, contains interbedded layers of chert and hematite. In the hematite layers large percentages of sand grains are found; some of these layers approach several inches in thickness. A series of these layers make up the lens. The chert layers can be seen to pass down through all gradations to small rectangular fragments. Evidence for transportation is lacking; rather, the relationship present would indicate that they were broken up in-situ and "drifted" down through the underlying hematite layer prior to complete solidification.

Another structure found in #4 is entirely different. It is not conformable but unconformable. Here clastic grains can be seen cutting the chert layers at angles up to 75° . Again, chert fragments can be seen breaking away from their parent layers and floating in the underlying clastic layers; these are orientated with long axis perpendicular to the over-all iron formation bedding. Within the clastic portion cross bedding was observed - one exhibits an angle of 20° to the bedding.

LENS #5

This lens is in the CQS_A sub-group differing from lens #2, in containing many angular fragments of sericitic quartzite (QS). One of these fragments measures 2.0 x 1.9 inches. In addition, fragments of chert up to an inch across along with a small percentage of sand grains are present. There also appears to be a minor quantity of primary hematite in the matrix. Samples studied are highly variable being both poorly sorted and loosely packed. Physically, the lens is 38 feet at the closest point below lens #2. Whether other clastics exist stratigraphically below is undeterminable since the stripped area terminates immediately to the south. The iron formation is completely conformable with the lens.

LENS #6

Lens #6 is in the same horizon as lens #5 being 9 feet due west. It too has a conformable relationship with the enclosing iron formation. Only one sample was obtained - its composition was CQS_A with fragments of chert and quartz in abundance. The lens is quite similar in all respects to #5.

LENS #7

This lens is barely discernable from lenses #2 and #12 and only with careful mapping was discovered. Its western end is exposed on the western edge of Richard's Cut; the eastern end is covered with rubble within the cut. An excellent cross sectional exposure can be seen on the west wall of Richard's cut while on the cut floor it can barely be traced. Where seen in contact with the iron formation,

it is conformable with the exception of a small questionable area at the western end. The composition is similar to lens #2.

LENS #8

This lens, the type lens for the CS group, is the most circular lens observed with a W/L ratio of approximately 0.6. The lower boundary is less than one foot above the large lens #7 and approximately ten feet west of lens #2. The surface is badly disrupted and covered with lichens; nevertheless, the boundaries are clearly discernible. The contact between clastic and iron formation is perfectly conformable with the above and underlying beds exhibiting pronounced arching. It appears that this arching is the result of depositional conditions. Figure 16 shows the lens as it appears in the field; notice the pronounced arching of the surrounding iron formation.

Two samples (66 and 67) were studied in detail; 66 was examined in thin section, the model analysis of which is recorded in table III. Both specimens are very homogenous. Specimen 67 exhibits in hand specimen extensive pitting caused by magnetite grains weathering out. The iron formation between lens #3 and #7 shows extensive weathering of chert and recrystallization of hematite. It is nearly identical to the rock between lenses #2 and #7 in that both exhibit good bedding and have similar percentages of clastic quartz grains.

LENS #9

Lens #9 is a small lens-shaped clastic body of the QS type. It appears to be related to #12 by an area of high density sand grains. The lens as mapped is conformable with the surrounding iron formation.



Figure 15. Close-up of Lens #2 Showing Rectangular Cobble and Numerous Pseudo-pebbles



Figure 16. Clastic Lens #3 with Center Indicated by Hammer

Figure 1
Figure 2
Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9
Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

LENS #10

This lens exhibits a typical lens shape and a conformable relationship with the enclosing iron formation. The CQS₃ lithology is readily apparent. A few well-rounded quartz grains can be seen in a predominately chert matrix. Hydrothermal quartz is prevalent in hand specimens.

LENS #11

Lens #11 is a small lens less than three feet below lens #12 and some 15 feet west of its counterpart, lens #10. As is the usual case for small lenses, the iron formation is completely conformable. This lens is a typical CQS₃ lens with good sorting, dense packing and a high homogeneity. Lens #11 is the type lens for CQS₃ sub-group.

LENS #12

The Moore Fault has cut away the entire upper portion (probably the upper half) of this lens, thus being a major factor in its resultant shape. Therefore, although the lens is similar to lens #2, there is a noticeable sparcity of CQS₃ lithology. Fragments of quartz, chert, and sericitic quartzite predominate.

The overlying iron formation is quite different from the typical underlying iron formation in that it consists mainly of chert breccia in a hematite and chert matrix. The percentage of sand grains at the contact is high but decreases rapidly. An angle of 15 degrees now exists between the top of the clastic lens and the iron formation.

Underneath, the iron formation is generally conformable with the lens although there are three zones of discrepancy. Two of these can be directly related to active joint planes; the third is more

difficult to resolve although it does lie along a possible joint plane. An interesting narrow dike of iron formation intrudes four feet into the base of this lens. It possesses bedding roughly parallel to the underlying iron formation and an above average percentage of sand grains. The western end of the lens is conformable to the iron formation being similar to the eastern end of lens #2.

LENS #13

Lens #13 is a very thin, entirely conformable clastic body lying only six to ten inches above lens #14. It is some eight feet long and only one foot wide. Due to its size and surface condition, it is hardly distinguishable from the surrounding rocks and except for its difference in composition would be easily mistaken for a part of lens #14. The composition is that of a homogeneous well sorted, cherty sericite with grains of magnetite scattered evenly throughout. All the magnetite is in late stages of altering to hematite and leucoxene. In hand specimen this is evidenced by extensive surface pitting. The surrounding iron formation is the typical banded variety with the hematite in various stages of recrystallization.

LENS #14

Lens #14, a $Q2S_D$ lens, is only four feet stratigraphically below lens #12 at the nearest point. When corrected for elevation and dip it is a very smooth, slender lens completely conformable with the enclosing iron formation. On the eastern end of the lens the composition is that of the typical $Q2S_D$ while on the western end it is similar to the fragmental variety of the $Q2S_A$ sub-group.

LENS #15

Lens #15 is located 16 feet stratigraphically below lens #14 and 5 feet above lens #19. While the iron formation is completely conformable with the lens boundaries, the area just to the west exhibits localized slumping. The lithology suggests the CQS_A sub-group. The usual fragments of chert and quartz in a matrix of sericite; chert, and sand grains is observed; the textural classification is fragmental. Of particular importance is the identification of cherty sericite fragments; this is the only lens observed containing CS fragments.

LENS #16

This lens appears to be a large semi-angular block that apparently either rolled or dropped (ice rafting) into the iron formation. It is conformable at both the top and bottom; on the sides, however, it is sharply unconformable. Compositionally it is a typical sericitic quartzite, in places it has the appearance of a good quartzite and may be a portion of the Mesnard.

LENS #16-A

Lens #16-A is a CQS_A lens similar to lenses #2, #7, and #12. The lens is conformable with the iron formation at the top and bottom but exhibits a facies gradation on the western end. The eastern end abuts against lens #16; its relation here to the iron formation is unknown.

LENS #17

This cobble lens is a rather indistinct lens lying over 50 feet stratigraphically below lens #12, it is the lowest of the cobble

lenses. The iron formation can be seen to surround the lens in a conformable manner. The one sample obtained from this lens displays a portion of a sericitic quartzite pebble.

LENS #13

Lens #18 is only seven feet above lens #17; it is an easily traced lens which, for the most part, is conformable with the iron formation. At the western end this cobble lens cuts a channel through seven feet of iron formation; this is the only true channel cut identified at the Moore Mine. Cherty sericite, sericitic quartzite, CQSp, hydrothermal quartz, and possibly granite cobbles are found in a matrix of sand grains, fine grained chert and sericite. There may be traces of primary hematite.

LENS #19

Lens #19 is the type lens of the cobble group. Figure 17 shows a portion of the lens, base is to the top left of the photograph. Except for one area on the bottom of the lens, it is completely conformable with the surrounding iron formation. On the bottom of the lens a peninsula of iron formation three feet long and two feet wide cuts into the clastic lens. Its bedding is parallel with the iron formation proper. A joint plane is present along one of the contacts. The cobbles are for the most part sericitic quartzite (QS); some granite, hydrothermal quartz, and chert cobbles are also present. A close-up of the cobble lens is shown in figure 18. The matrix is similar to the CQSp lithology.

LENS #20

Lens #20 is a very unusually shaped lens that appears to be unconformable with the iron formation. However, careful investigation



Figure 17. Cobble Lens #19 with Base to the Top and Left of Photograph

indicates that this is not true. On all sides except the east, the iron formation is conformable. The eastern side does pose a problem since it is heavily covered with moss and lichen growth. The odd shape is probably due to pronounced folding on its western side. The composition is similar to the other cobble lenses with sericitic quartzite the predominate cobble type. Two very small sand zones are found immediately below this lens.

LENS #21

This lens is a small, oddly shaped lens one foot above lens #20. On close inspection it is seen that the lens has been doubled over due also to folding and/or faulting. Except for the contact at the fault plane the iron formation is conformable to the lens. Compositionally, lens #21 is similar to #19.

LENS #22

Lens #22 is a small clastic lens west of #20. This QQS_A lens is entirely conformable with the surrounding iron formation beds. It is quite similar to lens #15.

LENS #23

This conformable lens is located midway between lens #12 and #24 just south of the Moore Fault zone. The composition is similar to lens #12. Whether this clastic body is a lens or an isolated cobble is questionable although evidence points to the former alternative.

LENS #24

Lens #24 is part of a complex of three lenses (#24, #25, and #26) brought together and confused by a branch of the Moore Fault; by which they are for the most part controlled. In particular, the

top of this lens appears to be cut by a plane parallel to the iron formation with the lens depressed nearly a foot. The lens is conformable to the iron formation at the base and both sides. On top there is evidence of a discontinuity, one sample shows the iron formation cutting at a 45° angle across the lens material. Lens #24 appears to be a normal CQ_{A2} lens, it exhibits fair to good sorting, medium packing and good homogeneity. The eastern end of the lens shows a slight influx of rounded chert grains and sericite sheafs.

LENS #25

Lens #25 is stratigraphically one to three feet below #24 being conformable on all sides with the iron formation. It is shape controlled by the Moore Fault. Samples studied place this lens in the QS group. There are a number of small chert pebbles along the bottom of this lens. The lens appears to be connected to #24 at the eastern end, but elevation-dip corrections indicate a conformable relationship. The same is indicated for the western side and lens #26.

LENS #26

Lens #26 is a CQS_A lens. On three sides the lens is conformable with the surrounding iron formation; however, at the base of the western portion the clastics grade by way of a facies change into the iron formation. The relationship to #24 and #25 is questionable, but without further study they are each considered a separate lens.

LENS #27

Lens #27 is a very slender, homogeneous, poorly defined lens whose proximity to the lens immediately above along with its



Figure 18. Close-up of Cobble Lens #19



Figure 19. Elastic Lens #28

1000

1000

1000

1000

1000

1000

1000

1000

1000

1000

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1000

1000

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1000

1000

1000

1000

1000

1000

1000

1000

similarity in composition would suggest that this clastic body is actually part of lens #25. Upon close inspecting 0.7 foot of iron formation was found to separate the two lenses. With the exception of having neither magnetite nor leucoxene this lens typifies the QS group; it possesses fair sorting and medium to dense packing. There is a faint linearity of the sand grains parallel to both the length of the lens and to the iron formation bedding.

LENS #28

Clastic body #28 on first inspection has the appearance of a boulder, but closer inspection indicates that this is actually a well formed lens. The dimensions are approximately 2 1/2 ft x 1 1/2 ft x 1 ft, the last being the length down dip which could extend many feet. Figure 19 depicts the relationship between the lens and the surrounding iron formation. The composition is that of the typical QS rock type, being very homogenous throughout. Texturally, there is no sign of the pillow-like structure found in lens #9. Leucoxene is observed throughout the lens altering from magnetite.

LENS #29

Lens #29, of Q₃S₂ lithology, is conformable to the iron formation. The contact on the western end is confused, detail field inspection defines a separation between lenses #29 and #30.

LENS #30

Lens #30 is different from all the other lenses yet described. The difference lies in the fact that its lateral ends are concave with respect to the iron formation, grading into it by means of a facies change. Otherwise, the overlying and underlying beds of

iron formation are completely conformable with the boundaries of the lens. Several inches directly above this lens the hematite layers contain large quantities of sand grains. The iron formation layers are nominally 0.13 to 0.19 mm in thickness and contain 40 to 50 percent sand.

This lens, the type lens for the QS group, has a low percentage of quartz grains. Individual sand grains float in a sericite matrix, seldom do they contact other sand grains. The overall texture is variable. The lens is extensively criss-crossed by thin hydrothermal quartz stringers. Lodged within the lens is a large boulder of chert with a cross sectional area of three square feet.

LENS #31

Lens #31 is similar to #30 which is three feet stratigraphically below. The western end of the lens grades gradually into the iron formation while the other end has a typical lens shape. Compositionally, lens #31 is quite different from lens #30. Study of this lens places it in the QQS₁ sub-group, fragmental variety. No unusual textures or mineralogy were seen with the exception of a small percentage of primary hematite.

LENS #32

Lens #32 is a very inconspicuous sericitic quartzite body some 14 feet stratigraphically above #31. No other clastic bodies were found in the horizons above, the closest lens to the east and west are 50 and 110 feet, respectively. The surrounding iron formation appears to be entirely conformable with the borders of this lens. The lens exhibits fair sorting and medium picking of sand grains.

A few milky quartz fragments are found scattered in the otherwise homogenous lens.

LENSES #33, #34, and #35

These small lenses were studied only briefly in the field. They are all conformable with the surrounding iron formation. Study of field specimens indicate that these lenses are of the CQS_A sub-group.

LENS #36

Lens #36 is identical to lens #29. Its CQS_D lithology contains fragments of quartz and chert in a fine grained matrix. The entire lens exhibits poor sorting and loose to medium packing, the composition and size of fragments is highly variable. The overlying iron formation is conformable as is the underlying eastern portion. The base at the western end of the lens cuts the iron formation at an angle of 35 degrees.

LENS #37

Lens #37 is an unusually shaped lens. From an otherwise conformable main body hang two appendages, one conformable and the other not. The unconformable appendage appears to be a clastic dike of sericitic quartzite. This lens contains other fragments of chert, quartz, and QS , typical of the CQS_A sub-group.

LENS #38

Lens #38 is one of a group of three large lenses in the western section of the Moore Mine. All of these clastic bodies are of the CQA_3 lithology; lens #38 is the type lens. The eastern extremity of this lens is offset from the main portion by over three feet. Field relationships indicate a displacement along a $N30^{\circ}W$ joint

plane. The major portion of this lens is conformable with the surrounding iron formation exhibiting the characteristic double-convex shape; the eastern edge, however, grades into the iron formation. This gradation is not a typical facies change; rather, it has a serrated appearance with a small scale tonguing or on-lap, off-lap design. This homogenous lens exhibits good sorting along with medium to dense packing.

LENS #39

The composition of this lens is typical of the CQA₃ sub-group. Physically it is similar to #38 in that it contains medium packing and fair to good sorting of its sand grains. On both top and bottom it exhibits a conformable relationship with the surrounding iron formation. On the eastern end, the lens grades by on-lap off-lap into the iron formation, while on the west the contact is normal. Like lens #38 this lens also has its eastern extremity offset by a N30°W joint plane.

Noticeably different from the other clastic lenses at the Moore Mine is the lens of iron formation within the clastic formation. This iron formation lens measures 41 by 3 feet; its bedding is parallel to the long axis of the lens and to the surrounding iron formation. The iron formation appears identical to the rest of the iron formation in the immediate area. The top and bottom are conformable with the clastics while both lateral edges merge into the clastic lens; the east, by tonguing; the west, by gradation. It is concluded that this iron formation lens was deposited during the time of clastic deposition. One sample collected from the contact

of the lens and the bottom portion of the iron formation lens displays bedding planes (layers of fine and coarse sand). Approaching the contact the bedding is cut at angles up to 80 degrees by another cherty quartzite (no bedding visible) consisting of small, angular sand grains (0.36 mm) in a cherty sericitic matrix. This lithology then passes through several broken chert layer fragments (usually parallel to bedding) and finally into the iron formation itself. The whole transformation occurs within a few inches. Aside from the obvious bedding and a few rounded chert ovals the lithology is homogeneous.

LENS #40

Lens #40 is the largest of the CQ_{A3} lenses and the most difficult to account for. Its shape appears to be structurally distorted although no definite joint or fault planes are in evidence. Portions of the enclosing iron formation are conformable while at the eastern end the iron formation grades into the clastic. The western end appears to be overlain by the iron formation. Compositionally it is similar to the lenses in the area. Texturally it differs in exhibiting poor to fair sorting and slightly less than medium packing. Lens #40 does not maintain the high degree of homogeneity of lenses #38 and #39.

LENS #41

This clastic body is a well preserved lens off-set in the middle by a N79°E striking fault. The horizontal displacement is about nine feet. The lens is a typical CQ_{A2} clastic lens. The surrounding iron formation is identical to the iron formation found to the east

of lens #2 and is entirely conformable. The contact between iron formation and lens begins at a hematite layer. The change is abrupt, sand grains are not seen protruding into the hematite layer rather sand grains line the contact. The hematite layer contains 10-20 percent sand grains in the 0.10 mm class evenly dispersed over the first few inches. The texture of the lens is semi-homogeneous, the sand grains exhibit poor to fair sorting and loose to medium packing.

G. Cobble Zone

The cobble lenses occupy a zone approximately 85 feet parallel to and 10 to 15 feet perpendicular to the strike of the iron formation along the southern boundary of the Moore Mine. This zone lies more than 25 feet stratigraphically below the main lenses of the area (#2 and #7). There are four large lenses averaging 21 feet by 3 feet along with at least one smaller cobble lens 4 feet by 2 feet. The long dimension is always parallel to the bedding.

All lenses are found to be enclosed within the iron formation although there are a few sandy zones immediately to the southeast of lens #20. There are no horizontally equivalent clastics observed at the Moore Mine or for that matter anywhere in the Palmer District. With the exception of the western portion of lens #18 and excluding obvious structural disturbances the cobble lenses are conformable with the surrounding iron formation.

The composition of the lenses is that of a typical channel deposit with cobbles composing 40 to 60 percent of the lens. Hydrothermal quartz, sericitic quartzite (QS), cherty sericite (CS), chert,

and granite cobbles lie in a matrix which is similar to that of the CQS_A lithology. The granite cobbles are highly weathered, the others are only moderately weathered. A tabulation of average cobble and matrix composition is given below:

Cobbles		%
Sericitic quartzite (QS)-	- - - - -	65
Cherty sericite (CS)-	- - - - -	18
Hydrothermal Quartz -	- - - - -	11
Chert -	- - - - -	3
Granite -	- - - - -	2
Shale (?) -	- - - - -	1

Matrix		%
Quartz grains -	- - - - -	35
Sericite-	- - - - -	45
Chert fragments -	- - - - -	6
Other fragments -	- - - - -	9
Magnetite -	- - - - -	3
Leucoxene -	- - - - -	2

A set of histograms for cobble lengths and widths is presented in figure 20. Lengths were measured between the two points furthest removed from each other on the exposed cobble face, widths were measured perpendicular to the length. Roundness and sphericity determinations were made in the field using Krumbein's visual chart from p. 81 of his text (33). Histograms for these are presented in figure 21. While cobble dimensions and shapes vary slightly from lens to lens it is evident that the cobbles in each lens are derived from the same basic population. Cobbles are well sorted and display fair roundness and poor sphericity.

The angle between cobble length and the strike of the surrounding iron formation was measured and results are shown in figure 22. All

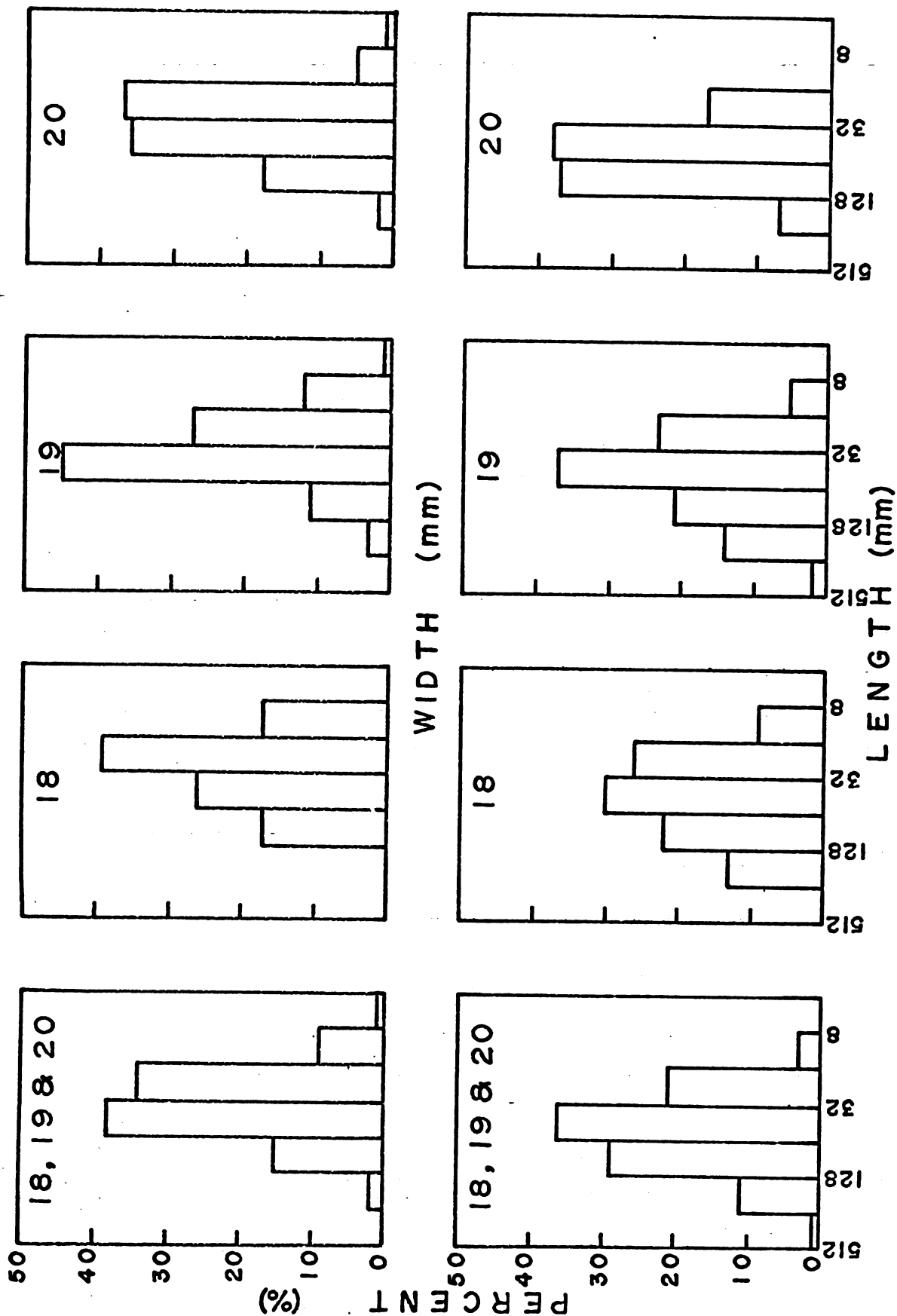


Figure 20. Cobble Lengths and Widths

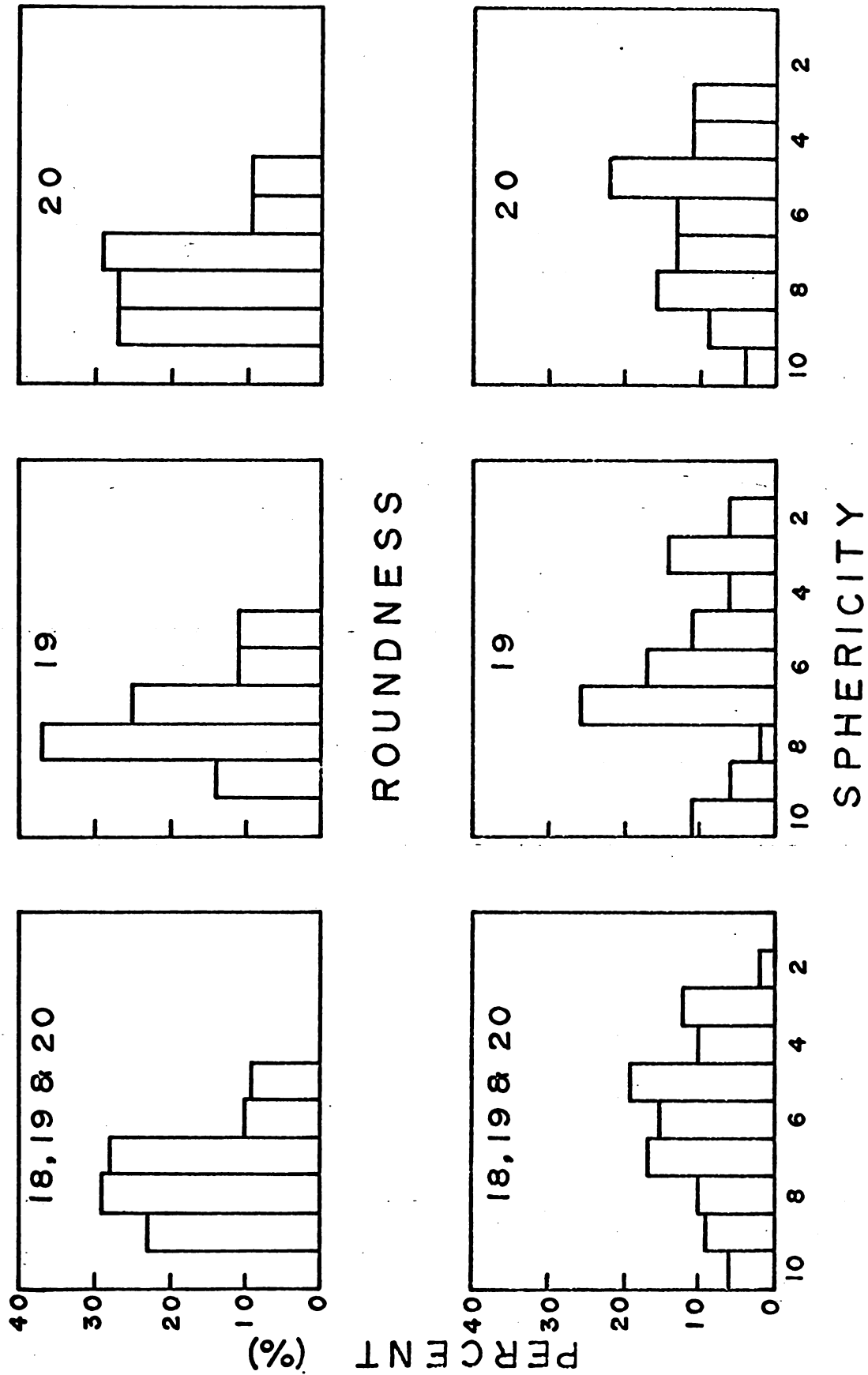


Figure 21. Cobble Roundnesses and Sphericities

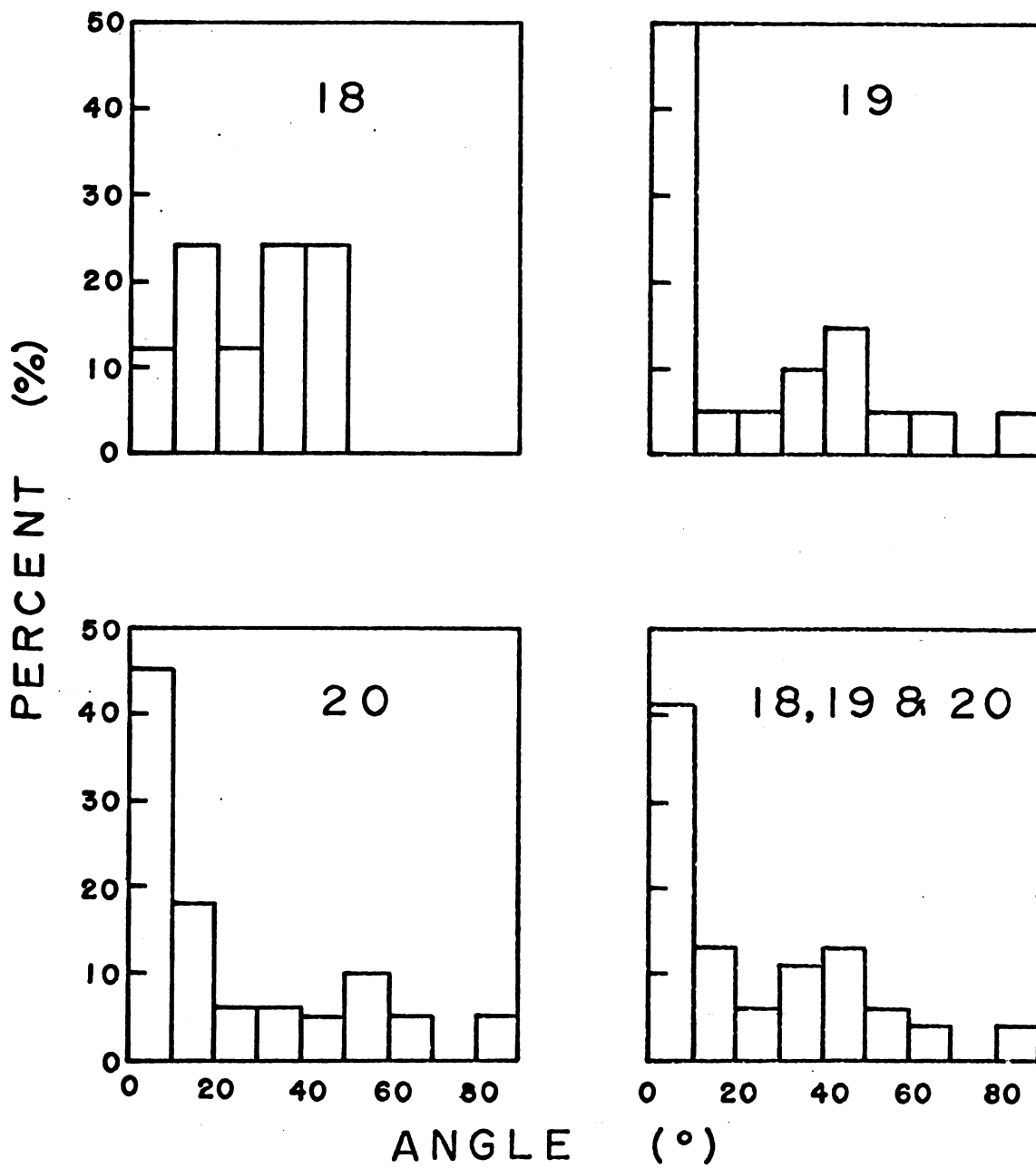


Figure 22. Inclination of Long Axes of Cobbles with Respect to Iron Formation Bedding

measurements were taken on surfaces perpendicular to the bedding, except for lens #18 where the surface dipped 30 degrees from the perpendicular.

The matrix of the cobble lenses consist primarily of sand grains in a sericite matrix with minor constituents of chert and vein quartz fragments. Magnetite and leucoxene are also present. There is no primary hematite. Analysis of the sand grains shows that they are similar to the sand grains found in the CQSA lenses with values for mean size, roundness, and sphericity of 0.31 mm, .43, and .81, respectively. The grains are between 1.0 and 10.0 mm in size and exhibit sub-angular to sub-rounded shapes.

The frequency distribution of the cobble lenses consists of four modes; the cobbles at 65.0 mm the fragments at 5.0 mm; the sand grains at 0.3 mm, and the sericite at 0.03 mm.

H. Iron Formation

Two distinct phases of the Negaunee Iron Formation are found in the Moore Mine vicinity. The typical ferruginous chert phase is predominant, occupying all but a small strip immediately beneath a portion of the pyroclastic horizon to the east of the Moore Mine entrance. This strip contains the jaspilitic phase. Both the ferruginous and jaspilitic phases are identical to those described and pictured by Van Hise and Paley in USGS Monograph 28 (2). In fact, the principal observable difference between the iron formation here and in the main syncline is the presence of large quantities of clastics.

For the most part, the iron formation exhibits relatively parallel, even bedding. In places, however, it is intricately faulted and folded on a miniature scale wherein the hematite and chert layers follow tortuous paths, see figure 23. In places the chert layers appear to be lens shaped, whether this is due to a primary mode of deposition or to post-depositional consolidation is in question. Due to the inherent brittleness of the iron formation, the dynamic action of folding and faulting has caused many portions of the rock to be extensively broken and brecciated. Thus most of the chert layers are intricately cracked, some are separated and floating in a hematite matrix forming pseudo-fragments. In places the chert has undergone partial solution with hematite filling in the resultant gaps. The hematite layers are thinned, thickened, and twisted rather than being broken; solution of the hematite layer appears probable in places. Close examination reveals that the hematite layers contain significant percentages of chert and visa versa.

The ferruginous chert phase consists of interbedded layers of hematite and chert of varying thicknesses. Bedding thickness ranges from several inches down to tenths and hundredths of a millimeter. The bedding exists as layers and lineations. The former is megascopic in size the latter microscopic in size. While the megascopic layers range down to 1 mm there is often two orders of magnitude between the layers and lineations in a given sample. For example a 1 mm layer may contain .01 mm lineations while a 10 mm layer may contain 1 mm lineations. The mean thickness of the layers range



Figure 23. Contorted Bedding in the Iron Formation

and the other side of the mountain
the other side of the mountain
the other side of the mountain
the other side of the mountain

and

the

the other side

the other side of the mountain

the other side

between 1 and 20 mm. The lineations were not studied in sufficient detail to warrant further description except to state that they are present in all samples.

The jaspilite phase is similar to the above described ferruginous chert phase except the bedding is significantly sharper and better defined. The hematite layer is metallic grey in color and the chert layer red. There is evidence to conclude that this phase is an alteration of the former.

The entire iron formation at the Moore Mine is blanketed by a noticeable quantity of sand grains. Samples studied were found to contain a minimum of 0.5 percent. These sand grains can be classified into three distinct populations. One population consists of a background of small sand grains (0.5 to 4.0%) evenly distributed throughout the iron formation. An equal number are found in both chert and hematite layers. Neither the concentration nor the properties of these sands appear to be affected directly by the proximity of larger elastic lenses, on the contrary they appear to pass up to and through the lenses. There does seem to be a general increase in percent sand grains from east to west. The range and mean of the size, roundness, and sphericity are 0.05-0.50 mm, 0.15 mm; 0.15-0.70, 0.44; and 0.23-0.74, 0.43, respectively.

Superimposed upon this background are localized lineations, beds, and small lenses of sand grains. Like the previously described population these concentrations appear unaffected by the proximity of larger elastic lenses; they are, however, found preferentially in the hematite layer. The percent concentrations cover a large

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spectrum from the background percentages up to 40.0 to 60.0 percent. The mean size, roundness, and sphericity are similar to the CQ lenses. These concentrations make up the second population and could quite probably be classified as miniature CQ_A type lenses.

The third population consists of concentrations of sand grains which can be related to particular clastic lenses. These concentrations increase gradually as a lens is approached directly from beneath; but decrease rapidly above. Parameters of population III sand grains are similar to those of population I at significant distance from the lenses and approach population II parameters when approaching a lens.

At the lateral borders of many of the lenses, especially the CQ's and CQS's there exists high density zones of sand grains. These concentrations are directly related to the lenses and appear to be an overflow of clastics from the lens basin of deposition. The iron formation beds surrounding the lateral ends wrap around and pinch out these concentrations.

I. Pyroclastic Horizon

Striking approximately N70°W from the point where the railroad track crosses the 28-29 section line to just past the Moore Mine, some 3/4 of a mile, is a conspicuous pyroclastic horizon. This horizon has been previously reported on by Tyler and Twenhofel (23), Marsden (24), Kengle (26), and others. The regional map shows the relationship between the horizon and the area geology. At the western section line a width of 160 plus feet was measured (no pyroclastic-iron formation contact found) while at its easternmost

extent a width of 70 plus feet was measured. The pyroclastic horizon can not be visibly traced east of the Moore Mine, either the clastic body quickly thins out or more likely is structurally disturbed. A superdip survey in the area northeast of the Moore Mine delineated an anomaly crossing the projected path of the pyroclastic. This anomaly can be related to a N30°E trending fault, the same fault which is prominent at the Moore Mine proper. It is thought that this fault has displaced the pyroclastic horizon to the south. No attempt was made to map the horizon west beyond the 28-29 section line, but all evidence points toward a westward extension.

About 500 feet of this pyroclastic body was mapped with a telescopic alidade north of the Moore Mine. Only four pyroclastic-iron formation contacts were found, two of these are fully exposed in the main entrance to the Moore Mine. The pyroclastic appears to be generally conformable with the iron formation as evidenced by comparison of the strikes and dips at the above mentioned contacts and by the overall trend (local exceptions probably occur). Field study of samples discloses lithological change in the iron formation above and below the pyroclastic horizon. In both cases it is the typical ferruginous chert. For the first 30 or 40 feet below the horizon, however, the iron formation is jaspilitic; but this appears to be a post-depositional phenomenon. Further, there is no indication of textural change in the iron formation above the horizon although there is a textural change in the pyroclastics.

The pyroclastic horizon is an extremely complex lithological unit. Laboratory study of selected hand specimens collected in the Moore Mine and vicinity indicate that there are at least two different rock types present, an agglomerate and a porphyritic, lithic tuff. At the Moore Mine the agglomerate occupies the bottom three to four feet grading imperceptively into the lithic tuff. In outcrop, the rock takes on a greenish color due to the chlorite-biotite in the matrix. At present the pyroclastic is moderately altered and heavily stained by hematite. An interesting outcrop at the 28-29 section line contained volcanic bombs several inches long. An interesting, fine-grained, acidic, highly-weathered dike cutting through the formation is exposed on the west wall of the entrance to the Moore Mine just 12 feet below the pyroclastic horizon. Although this dike is only two feet wide, a one-half inch thermal contact zone exists on each side. This dike cuts the dip of the iron formation at an angle of 27 degrees while the trend of the dike crosses the trend of the pyroclastic at an angle between 11 degrees. The dike has been mapped westward for 350 feet along which it maintains a constant 2 foot width, it is lost north of lenses #38 and #39.

SECTION IV

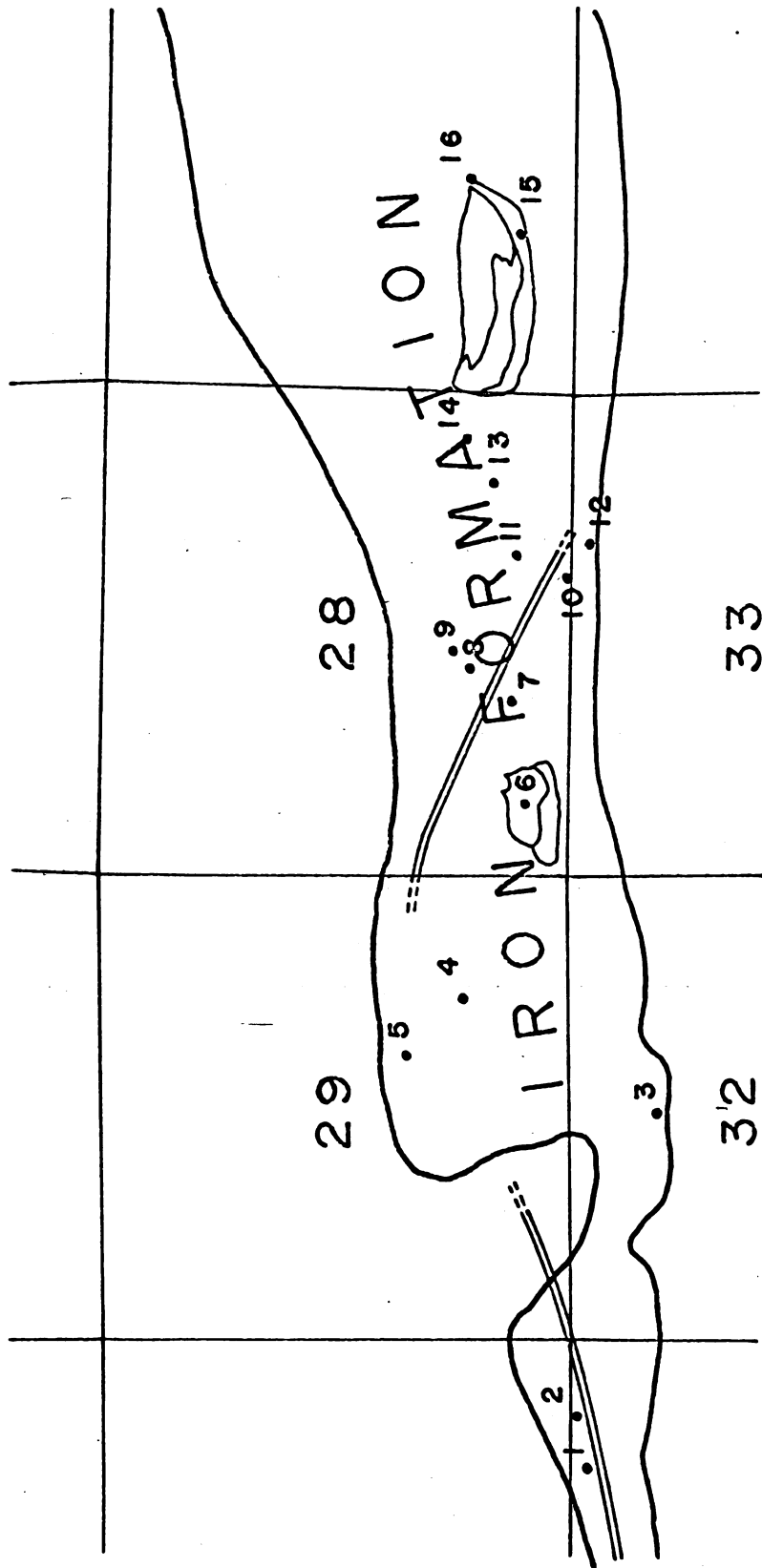
CLASTIC HORIZON

A. General

Along the entire southern portion of the Palmer District the lower strata of the Negaunee Iron Formation are well exposed. Study has revealed a significant quantity of clastics intermixed with the iron formation. Clastics range from individual particles of silt and sand to angular pebbles, cobbles, and boulders of chert, quartzite, and shale. Beds and lenses of cherty and sericitic quartzites interbedded with the iron formation are also prevalent.

Earlier workers in the area have described a few isolated occurrences; J.T. Mengel in 1956 (26) completed the first detailed survey identifying some twelve different localities. Using Mengel's work as a guide, a total of sixteen specific localities were investigated along a three mile stretch from the middle of section 31 east to the middle of section 27.

Brief descriptions of the types of clastics encountered are presented below. Each locality is numbered and identified on the Clastic Horizon Map, figure 24. All locations were visited prior to initiation of the detailed work in the Moore Mine area. Only the New Richmond Mine was revisited at a later date. Since this phase of the study was, in general, limited to the location of clastics, no detailed study of these clastics ensued. Geological field notes of a general nature were recorded, locations 10 and 15 are exceptions.



Scale: 1 in. ~ 2000 ft

.12 Clastics

Note: See map 1 for details

Figure 24. Clastic Horizon Map

B. Location Descriptions

FALLS AT WARNER CREEK

(Location 1)*

Numerous interbedded clastic lenses and hematite beds with high percentages of clastic quartz are found in the iron formation at this location. The lenses are cherty quartzites and sericitic quartzites similar to the CQ₁ and QS lithology of the Moore Mine described in Section III. Hematite appears to be primary. The size of the lenses range from microscopic up to tens of feet long; some of the larger ones contain a number of shale-like pebbles. Lens width varies from microscopic to several inches. Most lenses exhibit either a bi-convex or downward plano-convex shape. Quartz grains range from silt to coarse sand size; they do not seem to be related to the size of the lens.

Chert cobbles and pebbles are found in both clastic and iron formation layers with the roundness ranging from 0.70 down and the sphericity from 0.90 down. Generally, the cobbles and pebbles slightly depress the underlying sediments while the beds above abut against them. When the cobbles and pebbles have "sunk" far enough into the sediments, the overlying layer appears conformable.

ISABELLA HILL

(Location 2)

At Isabella Hill there are a great many beds and lenses of cherty quartzite. One lens investigated was ten feet thick while most of the others had a thickness of less than two feet. Lens length varies from

*Note: Location numbers refer to referenced numbers in Figure 24.

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

a few inches up to tens of feet. In places, chert layers are fractured and filled with cherty quartzite; in other places chert layers are seen fractured, fragmented and rotated, producing an intraformational breccia. Chert granules are seen with equal abundance in the hematite, chert, and quartzite layers.

PLATT MINE

(Location 3)

Here, cherty quartzite beds are interbedded with the iron formation closely resembling those outcrops on the western side of Isabella Hill.

STAR WEST MINE

(Location 4)

A few coarse cherty quartzite beds or lenses outcrop here on one of the pit walls and again in the immediate area. There is also a volcanic agglomerate exposed on the western edge of the pit; it is probably an erratic.

OPEN PITS NORTH OF STAR WEST MINE

(Location 5)

Numerous cherty quartzite beds (lenses) are seen outcropping on and around the various pit walls. In one pit a six-foot bed of sericitic quartzite appears to have an anomalous southern dip. Mengel believes this to be a post-depositional channel cut; it is similar to some of the sericitic quartzite lenses at the Moore Mine.

OLD RICHMOND MINE

(Location 6)

Although a nearly continuous, unbroken section is found across the iron formation, from the Ajibik to the Cookrich, clastics outcrop

27

28

29

30

31

32

33

34

35

36

37

38

39

40

only in a 100-foot wide horizon. Most of these are well sorted cherty quartzite lenses with abundant leucoxene grains present. Toward the western end of the pit there are some pebble beds with a sericite and/or chlorite matrix.

PRIEROSE PIT

(Location 7)

A few small stringers of cherty quartzite are found in the walls of the pit.

RAILROAD CROSSING

(Location 8)

Near the railroad track at the crossing of county road N.B. are exposed a series of thin bedded, very poorly sorted cherty quartzites. Angular quartz grains, biotite fragments, and a few chert fragments are in a sericite-biotite-chlorite matrix, heavily stained with iron oxide. This lithology is similar to the C₂ lithology found at the New Richmond Mine.

OUTCROPS NORTH OF RAILROAD CROSSING

(Location 9)

Fifty feet north of the railroad crossing, at the southern edge of the swamp, is a series of outcrops trending E-W. Hand samples and a thin section show the rock type to be similar to that of lens #2 at the Moore Mine. The size, shape, and contacts with the iron formation are obscured by dense covering.

MOORE MINE

(Location 10)

Here a great abundance of clastic lenses and beds, conformable and unconformable, are found intimately associated with the iron formation. Also found are numerous isolated pebbles, cobbles, and boulders. Chert, sericite, and quartz fragments make up the largest lenses; sericitic quartzites and cobble conglomerates make up the intermediate sized lenses, while cherty quartzites form the small lenses, facies zones, and numerous interbedded layers. These clastics were discussed in detail in Section III.

PYROCLASTICS

(Location 11)

The pyroclastics are mentioned here only to maintain continuity. They were treated in Section III.

LENS SOUTHEAST OF MOORE MINE

(Location 12)

This lens is 100 feet southeast of the main lens (#2) at the Moore Mine and stratigraphically 70 feet below. Iron formation appears to enclose it, whether conformable or not is difficult to discern due to heavy foliage combined with an abrupt drop-off at the edges of the lens. To the south there is a shallow 50 foot wide depression running E-W, followed by a steep rise of 65 feet. The lens is somewhat smaller than lens #2 but very similar in shape. Preliminary study indicates that it is similar in composition to the main lens at the Moore Mine although it appears to contain slightly larger fragments.

HOUSE WEST OF NEW RICHMOND PIT

(Location 13)

Outcrops of highly sheared sericitic quartzite (QS) and others closely resembling the CQS clastics at the Moore Mine occur here.

TEST PITS WEST OF NEW RICHMOND

(Location 14)

At this location impure, cherty quartzites (CQ) are found, exhibiting an interbedded relationship with the iron formation.

NEW RICHMOND SANDY REDS

(Location 15)

Cherty quartzites are exposed on all walls of the pit. On the stripped area in the south-central part of the mine there is a large area with abundant beds of cherty quartzites (CQ_{A1}) and chloritic cherty quartzites (CQ_B). The beds range from microscopic size up to several yards in length. The clastics are interbedded with layers of chert and hematite in all possible combinations, often skipping or repeating a given layer. No set ratio of width versus composition is apparent. These beds and lenses were described in more detail in Section III.

NEW RICHMOND FELDSPAR-BEARING CLASTICS

(Location 16)

In the northeastern entrance to the New Richmond Mine there is a partially exposed out showing massive green to black quartzites and graywackies grading from fine to conglomeratic. There is an identical outcrop about 300 feet to the east and a group of questionable outcrops 400-600 feet to the west, indicating a potentially

sizeable lateral extent of these clastics. There are three fragment sizes present: coarse, greater than one inch in diameter; small, less than one inch but greater than one-eighth inch in diameter; and fine (matrix), less than one-eighth inch in diameter. Fragments of white vein quartz, greenstone, and well-defined feldspar crystals (microcline) make up the coarse admixture. Some poorly sorted quartz grains compose the small size component. The matrix is mostly sericite and biotite with minor amounts of chlorite, muscovite, and leucokene. A few grains of monazite have been reported by Vickers (25).

One problem of particular importance is the location of the provenance of these parent materials. The fresh granite described by Long (23) is located directly south of here, but feldspar crystals of the magnitude found in the clastics have not been reported. Further, there has been no reported occurrence in the Southern Complex of an area capable of producing greenstone fragments. Whatever the provenance, it must not have been very far away since the constituents are all exceedingly angular and fresh.

The age of these feldspar-bearing clastics is another problem open to debate. Tyler and Twenhofel (23) and Mergle (26) believe them to be penecontemporary while Vickers (25) believes them to be younger than the iron formation - possibly a Goodrich channel filling. The problem results from the scarcity of outcrop in the immediate area. During the regional mapping of section 27 a few new outcrops of Megamoo were located, one being a little less than 1000 feet NW of the main clastic outcrop. Also, the "new" outcrops of clastic to either side of the main body indicates a horizon of feldspar-bearing

clastics rather than a more channel filling. The author believes that the above evidence points toward the clastics being contemporary with the iron formation.

C. Correlation

Using Mengel's data (26) supplemented by the author's field notes, each location is classified in terms of the lithological types as differentiated at the Moore Mine. Table X summarizes the data obtained and figure 24, the Clastic Horizon Map, presents the data plotted. The distance above the iron formation was computed using appropriate dips and assuming no structural disturbance.

Within the Clastic Horizon significant quantities of clastics are found from immediately above the iron formation base up to the 2,300-foot level. As discussed in Section III the entire area is covered by a population of sand grains (0.5-4.0%). In addition there are numerous isolated pebbles, cobbles and boulders of chert, quartzite and shale distributed throughout; while zones, lenses and beds of particular lithologies are locally concentrated.

With the exception of the CQ_A -type cherty quartzites the distribution of these clastic concentrations are restricted by lithology to particular areas of deposition. The cherty sericites (CS) and cobble lenses are found only at the Moore Mine. The cherty sericitic quartzites (CQS) are restricted laterally to the Moore Mine but are distributed vertically from the 43 to 2,300-foot level. The CQ_B -type cherty quartzites are restricted vertically to a narrow zone (1,200 to 1,700 feet) and laterally to the Moore Mine and east. The sericitic quartzites (QS), on-the-other-hand, are unrestricted vertically but occur only from the Moore Mine and west.

TABLE X
CLASTIC HORIZON DATA

Location	Distance Above Iron Formation Base (ft)	Clastic Type							
		SS ₁	SS ₂	SS	CS	SS	Cobble Lens	Pyro- clastics	Other
1	435	X		X					
2	605	X							
3	43	X							
4	1730	X						X	
5	2260	X		X					
6	693	X							
7	780	X							
8	1210		X						
9	1295					X			
10	260	X		X	X	X	X	X	
11	605							X	
12	43					X			
13	1120			X		X			
14	1295	X							
15	1780	X	X						
16	1120								X

The bulk of the clastics and the greatest variety of clastics are concentrated at the Moore Mine. Here the cobble lenses and the cherty quartzites (CQ_A) occupy the lowermost and uppermost levels respectively. The remaining clastics are found in between, with the cherty sericitic quartzites dominating in the east and the sericitic quartzites dominating in the central and west.

The inferred significance of these depositional zones is discussed in Section 7.

SECTION V

SUMMARY AND DISCUSSION

The clastic lenses, the iron formation and their unique relationships as observed and analysed in the study area are the resultant of the following four important and interrelated geologic factors: the geologic history of the region, the provenance of the sediments, the role of dispersal to the sedimentary basin, and the physical and chemical environment affecting deposition.

Post-depositional effects such as lithification, diagenesis and metamorphism is another factor which must be recognized and accounted for. The study area was selected for its simplified structure and low rank metamorphism. Aside from obvious structural modifications to some of the lenses and minor hydrothermal infiltration, post-depositional effects provide few problems in the interpretations of this thesis. Note should be made, however, that the observed clastics are the low rank metamorphic equivalents of the original clay, sand, chert and hematite sediments.

This section summarizes the evidence, both observational and analytical, obtained during this study and discusses its relevance with respect to each of the four geologic factors.

A. Geologic History

During the regional field mapping the following major formations were identified; listed in decreasing age:

1. Archean gneisses and schists
2. Palmer Complex

3. Mesnard Quartzite
4. Kona Dolomite
5. Granites
6. Ajibik Quartzite
7. Negaunee Iron Formation
8. Goodrich Quartzite
9. Keweenaw intrusives
10. Pleistocene drift

Examination of field relationships indicates the following sequence of events:

1. Deposition of Archean sediments and eruptives
2. Fluid invasion of these Archean rocks to form gneisses and schists.
3. Intrusion of hornblende schist dikes
4. Folding of the schists and gneisses
5. Introduction of the Laurentian granites forming part of the Palmer Complex
6. Deposition of the Lower Huronian Mesnard and Kona formations
7. Mild deformation during which local granite intrusions occurred followed by an erosional interval.
8. Deposition of the Middle Huronian Ajibik and Negaunee formations during which time volcanic activity resulted in local pyroclastic deposits.
9. Time and erosional unconformity
10. Deposition of the Upper Huronian Goodrich formation

11. Folding of the Huronian sediments, major faulting and intrusion by olivine diabase and related dikes
12. Time and erosional unconformity
13. Deposition of glacial till

The Volunteer Fault, a normal fault system, is the predominant factor controlling the topographic expression of the study area. The Moore Fault paralleling and probably related to the Volunteer Fault exerts considerable control on the observed iron formation - clastic relationships at the Moore Mine.

B. Provenance

Throughout Huronian time, the major source of sediments for the Palmer Basin was probably from the south. The clastics at the Moore Mine and vicinity were derived from a land mass either to the north or south as evidenced by the lithology and physical nature of the clastic lenses. The proximity to the base of the iron formation, the lithologic assemblage and the clastic textural relationships would strongly support a southern land mass as the major clastic provenance.

The hematite, chert and carbonate may have also been derived from this southern land mass but could have been derived from other land masses in or bordering the syncline. As James (34) points out, the accumulation of an iron formation is primarily dependent upon precise Eh-pH conditions of the basin waters rather than the concentration of iron or chert. It is easier to account for the iron formation-clastic relationships at the Moore Mine by submitting to a provenance for the iron formation other than that of the clastics.

The pillow lavas and other basic rocks north of the syncline offer one possibility while the pyroclastics observed at the Moore line with an indicated source to the west offers another. A third possibility would be a provenance south of the clastic provenance, but is not favored because of the source rocks available and by the fact that iron formation deposition appears to be a continuing process while clastic deposition is intermittent. There is no reason to subscribe to the same provenance for both the iron and chert.

The absence of feldspar fragments together with the overall nature of the clastics indicates a state of high maturity. Ordinarily high maturity is indicative of low relief and a warm, humid climate Pettijohn (32); this is not necessarily the case for these clastics since evidence points to a multi-cycle source. The fact that clastics are not found throughout the iron formation but concentrated in well defined zones does point to a low relief; climatic conditions cannot be so deduced.

The multi-cycle concept is substantiated by a general lack of heavy minerals, roundness of sand grains and few sand grain inclusions (igneous source) or overgrowths (metamorphic source). These observations together with the geometry of individual deposits and the broad horizontal and narrow vertical extent of the clastic horizon leads the author to propose a two-stage source. The interior provenance (first stage) provided sediments to a broad shore line (second stage) where the sediments were extensively reworked with the sands retained and the clays winnowed out. On occasion the provenance provided sediments directly to the basin.

As Negaunee time began the interior provenance consisted of the Palmer Complex overlain by the Mesnard, Kora and Ajibik formations. The principal source of the sands was the semi-consolidated Ajibik while the quartzite fragments observed in the CQ3 lenses were derived from the Mesnard. This infers that the Mesnard at that time was at least partially metamorphosed. The fresh granite pegmatite required for the large microcline and monazite crystals in the New Richmond feldspar clastics may have been the metamorphic agent. The assemblage and detrital nature of the heavy mineral suites indicates that their source, the Palmer Complex, was of minor influence although it did provide the granite cobble and clay fraction of the clastic lenses. The source of the chlorite/biotite in the CQ3 lenses may have been derived from an altered hornblende schist dike similar to that described by Long (29).

The change from cobble to sand lenses and the observed continual decrease in the clay/sand ratio of the lenses at the Moore Mine indicates that the maturity and stability of the provenance was increasing as Negaunee deposition proceeded. It is hypothesized that during this time the provenance achieved relative stability and thereafter contributed few clastics to the shore line. As the sands were transported out into the basin, the shore line reservoir was not replenished and clastic deposition ceased.

C. Dispersion

Direction of Transport - The direction of transport of the sediments from the provenance to the shore line or directly to the depositional basin is based upon previously discussed considerations. The

clastics, including the clay fractions, were transported from the south while the iron and chert were transported either from the north or west. It is hypothesized that the sands and most clays were transported to the basin shore line via streams and were reworked during an intermediate stage prior to deposition in the basin. The mechanisms required to transport the shore line sediments out into the basin are discussed in the following subsection. The cross sectional views of all elastic lenses indicate a transport acting perpendicular to the iron formation strike (perpendicular to the shore line).

Distance of Transport - Since each lens is observed at only one time interval, it is difficult to determine the distance of transport. Data indicates that the sands and possibly the cobbles are reworked sediments; therefore, size, roundness and sphericity are of little use in determining transport distances. In considering the present proximity of the Ajibik, Mesnard and Palmer complex it is reasonable to conclude that the distance from the provenance to the shore line was probably not more than a few miles.

Dispersal Reserve - Individual sand grains and the CQ₁ beds and lenses are found dispersed throughout the Negaunee. This fact combined with the similarity of these sands would indicate a shore line reservoir of sands extending along the entire basin edge. From this shore line, sands were transported either by wind (isolated sand grains) or currents (CQ lenses) perpendicularly outward.

With the exception of the isolated sand grains and the CQ₁ lithology, the clastics found in the area studied are not evenly distributed.

Noted absence of clastics is seen in both the Old and New Richmond Mines where, over a large cross sectional view, only a few isolated beds of clastics are found. Both the greatest diversity and volume of clastics is found at the Moore Mine. This diversity and areal domain of these other lithologies would indicate that a number of individual transports were involved each tapping a source area of locally different character. The fact that some lithologies appear at different time intervals suggests that their transports were not of a continuing nature.

The feldspar clastics of the New Richmond Mine are extremely fresh and give evidence of little or no transport. It is hypothesized that the source of these clastics was exposed in a rapid manner (faulting or intrusion) and transported to the basin possibly in the form of slide or rock fall with little intermediate beach working. The cherty sericitic quartzite lenses (CQS) represent an intermediate situation between lenses consisting of highly worked sediments (CQ) and those consisting of fresh unworked sediments. It is postulated that slides or turbidity currents triggered in some manner (faulting/earthquake) deposited the reworked beach sands and new, fresh sediments in a one-time operation with little sorting taking place.

D. Depositional Environment

The depositional environment can be divided into two separate but related components, the physical depositional environment and the chemical depositional environment.

Physical Depositional Environment - The physical depositional environment is a primary concern of this thesis and as discussed

here includes the various factors involved with the movement of the sediments from the basin shore line and the physical conditions under which they were deposited. Iron formation-clastic relationships are summarized followed by a discussion of each of the major clastic lithologies in terms of pertinent factors relating to their physical depositional environment.

Iron Formation - Clastic Relationships

The relationship between the clastic lenses and the surrounding iron formation was studied in some detail. The characteristics of the iron formation do not appear to change as one approaches or recedes from a given lens except for the additional influx of sand grains previously noted.

At the boundary line there is a marked border surrounding each lens consisting of broken and sheared material (mostly iron formation) now in a degenerate, crumpled state. Usually this border is less than an inch wide, but for the CQS_A lenses (#2, #7, and #12) it extends up to several feet. Examination indicates that the zone is probably the result of post-depositional effects, primarily structural disturbance along the dislocation between these two bodies.

The question arises regarding the conformity or unconformity of the clastic lenses to the enclosing iron formation. It is true that many, if not most, lenses are unconformable if one considers only a layer or two directly beneath the lenses. Study on this scale indicates that most lenses lie directly on a chert layer, it is believed that the hematite layer being quite "soft" and thus having a low erosion resistance was swept away as clastic deposition progressed. Often a

portion of a chert layer has been displaced and can be seen lodged a few feet away near the base of the lens. To the author it appears that such a case of unconformity is typical during all changes in clastic deposition and as such indicates a perfectly normal condition. In order to best utilize the relationship between iron formation and clastic, the word conformity must be defined in terms of this study. Conformity, in this study, is restricted to the gross effect, to include a zone encompassing at least several layers of chert and hematite.

Applying this definition, 38 of the 42 lenses can be classified as conformable. There are three types of conformable relationships found at the Moore Mine. The most common is where the clastic material forms a "lens shape" deposit and where the surrounding iron formation completely conforms. Usually the iron formation below the lens is depressed slightly, rarely is the overlying iron formation arched significantly. A number of lenses exhibit a gradation with the iron formation at their lateral ends, while on top and bottom they are conformable; lens 16-A is a good example. Three of the CQ_{A3} lenses exhibit an unusual lateral contact with the iron formation, each exhibiting serrated edges giving the appearance of miniature on-lap, off-lap.

A number of apparent unconformities can be explained by post-depositional structural movement, jointing, folding, and faulting. Ten lenses are at least in part structurally controlled. Lenses #20 and #21 provide examples where folding played an important role in the lens shape, both having been doubled over.

Four lenses exhibit definite unconformable relationships with the iron formation. The western portion of lens #18 is a good example of a channel cut into the underlying iron formation. Several feet to the east lies lens #16, a large quartzite block which has been emplaced within the iron formation. The iron formation abuts against the block on three sides, only on the top is there a conformable relationship. Two other lenses, #26 and #36, demonstrate an unusual type of unconformity. On the base of each lens the clastics cut obliquely across the iron formation, resembling a deltaic deposit rather than an erosional surface.

Each lens at the Moore Mine can be placed within the following iron formation-clastic classification:

1. Conformable

- (a) Normal: all lenses except 1-b, c and 3
- (b) Gradation: lenses 3, 4, 16-A, 30, and 31
- (c) On-lap, off-lap: lenses 38, 39, and 40

2. Structurally Unconformable

- (a) Jointing: lenses 2, 12 and 19
- (b) Folding: lenses 20, 21 and 37
- (c) Faulting: lenses 2, 12, 24, 25, 26 and 41

3. Unconformable

- (a) Channel cut: lens 18
- (b) Oblique cut: lenses 26 and 36
- (c) Abutment: lens 16

Figure 25 presents idealized sketches of selected clastic lens types.

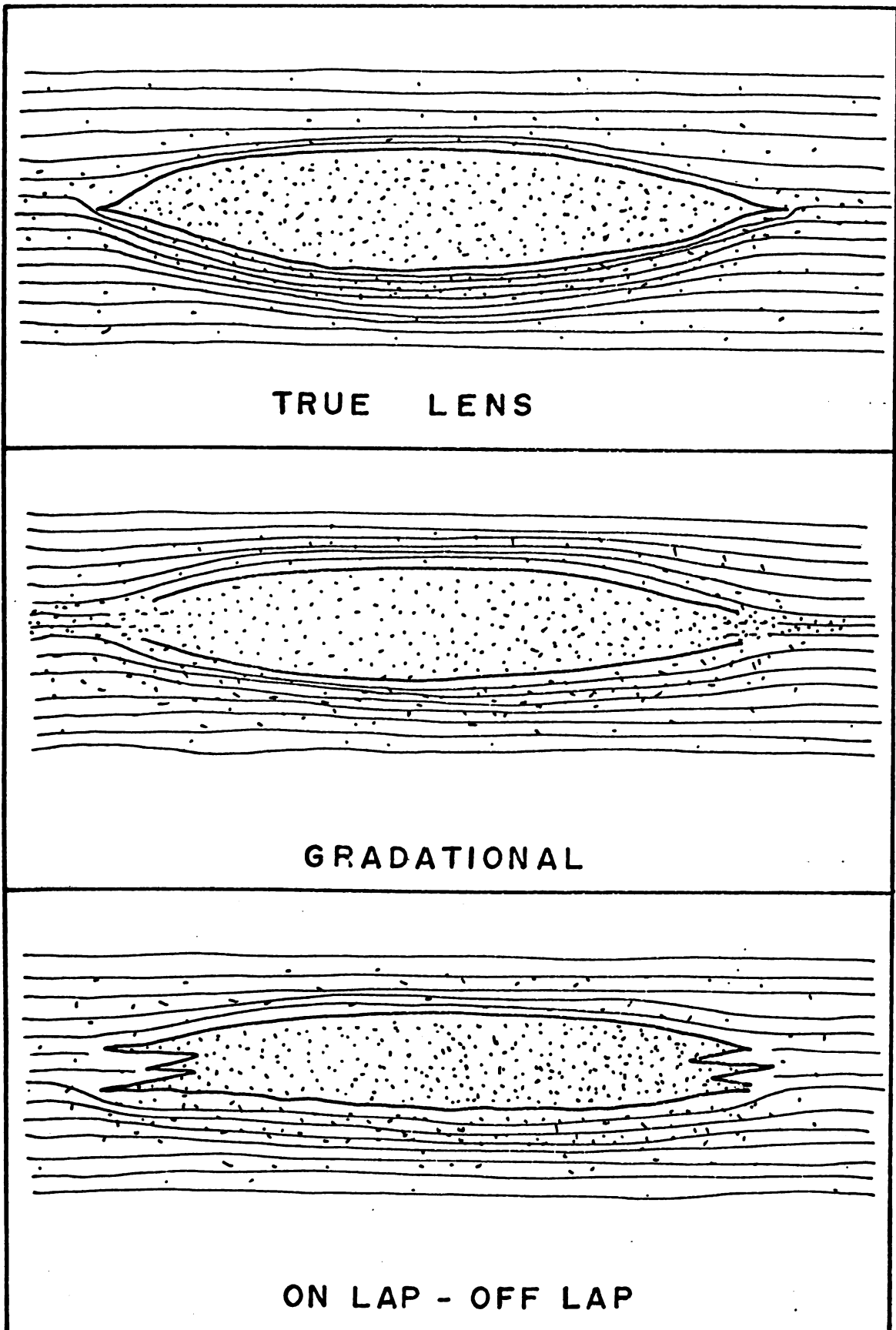


Figure 25. Idealized Sketches of Clastic Lenses

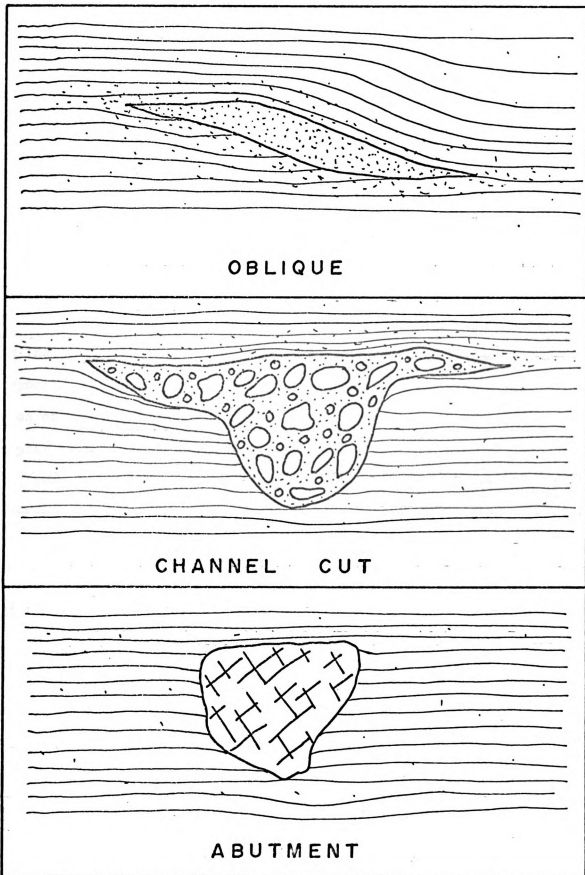


Figure 25. Idealized Sketches of Clastic Lenses (cont'd)

Clastic Lithologies

Cobble Deposits: The cobble zone deposits can be classified as protoquartzitic conglomerates. They appear to be typical river or stream deposits as evidenced by their size distribution and shape characteristics. It is believed that these cobble lenses represent a branching river or stream deposit whose open voids were later filled in by the matrix sediments. The cobbles themselves are well sorted indicating a high velocity, shallow water deposit, possibly at a time when the iron formation was above wave base. The matrix, on the other hand, is poorly sorted indicating a deeper water deposit. The cross section of the lenses indicate that the direction of transport was north, while the long axis of the cobbles appear to be oriented perpendicular to that direction.

The numerous isolated cobbles found throughout the clastic horizon are thought to have reached their present positions by rolling down slope along the bottom of the basin. Deposition of the large quartzite block (lens 16-A) is an enigma, rolling or less likely ice rafting is called upon. The absence of broken rounds places an upper bound on the transport velocity.

Chert-Clay-Sand Deposits: The CQS_A-CQS_C lenses represent a rapid deposition as evidenced by the turbulent textures found at the base of the lenses, by the angular fragments and by the poor sorting. The transport medium must have been of high density since coarse and fines are intimately mixed. It is believed that for the most part these lenses are the result of turbidity currents and/or slides. For some of the lenses it appears that at least half of

the material was deposited during one occurrence with the larger fragments settling to the bottom. This may explain the gradual decrease in the fragment size from the bottom to the middle of the lens. From the middle up, the fragments become larger, indicating possibly a new influx of material. The broken chert layers along the bottom indicates that the transport medium possessed a current velocity of considerable strength. The CQS_B lithology represents a similar deposit but with lower transport velocity. The CQS_D lithology is probably the result of current deposits; fragment size and lack of primary hematite indicate that the current velocity was strong. The transport medium was not as "clean" as in the case of the CQ's but, on the other hand, was not as dense as that indicated for the CQS_A's.

Clay-Sand Deposits: The sericitic quartzites (QS) are believed to have been deposited by currents where the velocity was sufficient to orient many sand grains with long axis parallel to the strike. Since this is the only lens deposit not containing chert it is suggested that deposition occurred above wave base. The roundness and sphericity of the sand grains are significantly different from those of other lenses possibly indicating a source outside the basin area.

Clay-Chert Deposits: The origin of the sericitic chert (CS) lenses is unknown. One hypothesis is that they represent deposition within a naturally formed depression below wave base. The reason for the absence of hematite and the formation of chert globules is unknown; but is probably related to the chemical environment.

Sand-Hematite-Chert Deposits: The cherty quartzite (CQ) lenses represent off-shore current deposits flowing essentially perpendicularly away from the shore line. The roundness, sphericity and sorting of the sand grains and the complete lack of clays are indicative of reworked sediments, probably Ajibik and/or Mesnard derivatives. While the sand grains were being transported from the reservoir of beach sands and deposited along the current path, hematite and chert were being chemically precipitated. That the sand, chert and hematite were deposited concurrently is evidenced by the uniform distribution of sand grains in the hematite-chert matrix and by the homogeneity of the lenses.

Each particular subgroup retains the above general characteristics but differ in one or more specifics. The CQ_{A_1} and CQ_{A_2} subgroups exhibit a high percentage of primary hematite indicating that current velocities were quite weak. The CQ_{A_3} and CQ_B subgroups, on the other hand, exhibit a lower percentage of primary hematite and a greater percentage of sand grains indicating a stronger current velocity.

The intermittency, thinness, and lateral extent of the cherty quartzite beds in the New Richmond Mine area are indicative of currents which are less persistent and more varying in velocity and direction than those to the west.

Sands: The percentage of sand grains evenly distributed throughout the iron formation, population I, are believed to represent wind blown sands from the basin edge. The local, small sandy lenses and zones, population II, are the result of isolated currents.

Table XI presents a relative transport velocity index which has been worked out for the Moore Mine area. It is based upon a combination of textural and compositional characteristics of the clastic deposits and their relationship with the iron formation. It is significant to note that while there is a continuous grade between indices, a particular lithology usually can be indexed within a very narrow range.

When viewed in its entirety, the clastics at the Moore Mine are found to form a steady progression toward normal iron formation depositional conditions as one proceeds upward from the base of the Negaunee. With increasing distance from the base of the Negaunee, the velocity index, sand and clay content and quantity of fresh unworked sediments decreases while the degree of sorting, homogeneity and general maturity of the clastics increases.

Chemical Depositional Environment: It was not the primary intent of this thesis to evaluate the chemical environment. However, in the course of this study certain interesting factors which bear upon the chemical environment have emerged and are discussed below.

Considering the total deposition in the Palmer Basin, it is obvious that the chemical environment was the major controlling factor in the deposition of the hematite and chert during Negaunee time. It is hypothesized that a sufficient quantity of iron and chert were continually supplied to the basin with their deposition being precisely controlled by the Eh and pH conditions locally present, see Garrells (35). This continuing, cyclic deposition

Table XI

TRANSPORT VELOCITY INDEX FOR CLASTICS AT THE MOORE MINE

INDEX	STRENGTH	DESCRIPTION	EXAMPLE
1	Nil	Iron formation bedding undisturbed, sand grain content less than 5%.	Majority of the iron formation
2	Very weak	Iron formation bedding essentially undisturbed, sand grain content up to 15% for population II and up to 45% for population III.	Iron formation with sands
3	Weak	Iron formation bedding absent, localized small pockets of hematite, chert and sands.	Very small lenses and sandy zones
4	Very Mild	No iron formation bedding, sand, hematite and chert deposited together.	CQA ₂ lenses
5	Mild	Homogenous mixture of sand, little primary hematite and chert.	CQA ₃ lenses
6	Normal	Non-homogenous mixture of sand, little primary hematite and chert, with scattered fragments.	CQS _D lenses
7	Moderately Strong	Sand grains are oriented with long axis down dip.	QS lenses
8	Strong	Long axis of cobbles are oriented down dip.	Cobble lenses
9	Very Strong	Immediate underlying beds are eroded away, clastics include unsorted material.	CQSA lenses
10	Extreme	Channel cuts through significant thickness of iron formation.	Cobble lens #18

of hematite and chert was locally modified from time to time by the influx of clastics. The clastics altered the Eh-pH balance, temporarily ceasing the deposition of hematite (CQ lenses excepted). It is interesting and important to note that deposition of chert was usually not terminated during clastic influx. Chert is found as a component of the matrix of all but the QS clastics. It would appear, therefore, that while deposition of hematite was sensitive to the Eh-pH condition, chert was not.

It should be noted that the deposit of a clastic lens was restricted laterally and did not appear to influence the iron formation deposition on either side of a lens area. Disconformities were not observed in the iron formation on horizons contemporaneous with a clastic lens.

The general nature of the clastics and their relationship with the iron formation would indicate that the Negaunee at the Moore Mine represents a shallow water, near shore deposit. This together with the primary hematite in the cherty quartzite lenses provides evidence that the area is the equivalent to James' oxidation zone (34).

Study of the iron formation-clastic contact indicates that the chert layers became hard soon after deposition while the hematite layers did not. Where the iron formation-clastic contact can be clearly examined, the chert layers are found to usually provide the base. In addition, there are numerous examples of chert fragments deposited in the lenses; few hematite fragments have been found.

SECTION VI

CONCLUSIONS

Following are the more significant conclusions reached during this research:

1. The Negaunee Iron Formation, along the southern edge of the Palmer Basin, represents a shallow water environment within the oxidation zone where the chert and hematite were both deposited in a primary state. Deposition of the hematite was sensitive to the Eh and pH conditions of the water; deposition of the chert was not.

2. The various clastics interbedded with the iron formation represent normal depositional conditions. These clastics were deposited in the basin both during iron formation deposition and during intervals when portions of the basin were above wave base or even above water level. During these latter periods the hematite and chert layers previously deposited were re-worked; the hematite being washed out into the basin, the chert worked by waves and currents and re-deposited.

3. The provenance of clastic sediments was a low lying land mass located a few miles south of the Negaunee Basin. Within this provenance the major source of the sands was the semi-consolidated Ajibik, the Mesnard provided the quartzite fractions while the Palmer Complex and Kona contributed the granite and shale fractions together with the heavy mineral suites.

4. Lower Huronian Mesnard and Kona formations were metamorphosed prior to Middle Huronian Ajibik and Negaunee deposition.

5. Material was transported from the provenance to a broad shore line bordering the Negaunee Basin where the sediments were extensively reworked, with the sands retained and the clays winnowed out. On occasion the provenance provided sediments directly to the basin.

6. Clastics were moved from the shore line into the basin by one of five basic transport mechanisms depending upon the particular lithology: winds, off-shore currents, streams, traction and slides and/or turbidity currents.

7. As Negaunee time progressed maturity and stability of the provenance increased. As sediments were transported out into the basin, the shore line reservoir was not replenished and clastic deposition ceased.

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APPENDIX A

CHEMICAL TESTS

A. Introduction

This appendix presents a report on the chemical tests performed in the development of a technique for disaggregating some of the metamorphosed clastics from the study area. Documented are the step by step results obtained, substantiating that the developed disaggregation process is valid and when properly performed will yield sands statistically similar to the original sands in the outcrop.

Analysis of these disaggregated samples provides an important key to the origin of the iron formation clastic. See Section III-D for a discussion of the analysis. To the author's best knowledge such a disaggregation process has not been reported on previously.

B. Summary

The first disaggregation method tried (Experiment 1) consisted of alternately freezing and thawing clastic samples saturated with various solutions. This method is dependent upon the degree of permeability of the specimen, which for the samples tested was very low. After 288 hours of alternating the two conditions, no disaggregation was observed in any of the samples.

It was found that due to the extensive hematitic staining it was impossible to sufficiently analyze the specimens either in polished section or in thin section. Krumbine and Pettijohn (30) suggest the use of hydrochloric acid and stannous chloride to remove iron oxide. This process was adapted with a slight modification (Experiment 2)

wherein hydrochloric acid was used in a concentrated form (36.5%) and only enough stannous chloride added to maintain the iron in a soluble state. The HCl-SnCl_2 solution worked quite well in de-staining the clastic samples; in fact, it was noticed that samples left in the solution for a few hours began to deteriorate. The next experiment (Experiment 3) was performed to determine if this deterioration effect could be increased to a point where a partial or even complete disaggregation of the sample would occur. Using the procedure described, all samples were completely disaggregated after 16 days of immersion. The residue consisted of sand grains encased in a chert cement. Experiment 4 documents the use of potassium hydroxide solutions for dissolving this chert cement; normally accomplished after five hours of boiling.

Once a disaggregation process had been developed, it became necessary to determine what effect the HCl-SnCl_2 and KOH solutions had upon the quartz grains. Experiment 5 provides evidence that the HCl-SnCl_2 solutions, acting for periods up to 36 days, had no measureable adverse effect on quartz crystals or sand grains. Quartz crystals were used for surface texture study. The sixth and seventh experiments dealt with the effect of boiling KOH solutions on quartz crystals and sand grains. It was found that a moderate KOH solution with a boiling time of less than six hours provided adequate "cleaning action" while limiting the percent weight loss of the quartz grains to less than 0.8%. Experiment 8 showed that quartz crystals were unaffected by immersion in standing solutions of KOH for periods up to two months. Experiment 9 was conducted to determine the optimum

solution strength and boiling time needed to yield the cleanest sand grains within the formulated safety limits (solution strength 80-20* and boiling time ~ 6 hrs). Only an 80-20 strength solution boiling between 3 and 6 hours produced a final residue of well cleaned sand grains. It appears that a 90-10 solution boiling for 8 to 10 hours may produce similar results. Finally, the entire disaggregation process of HCl-SnCl_2 solution and the 80-20 KOH solution were tested on a typical beach sand (clear surface texture) with roundness, sphericity, and sieve analyses serving as test criteria.

It can be stated with considerable confidence that the developed disaggregation process produces no measurable effect on the resultant sand grains.

C. Tests

EXPERIMENT 1

FREEZING AND THAWING

Objective: To determine whether a process of alternate freezing and thawing will produce disaggregation in the clastic samples.

Procedure: Six specimens of a cherty quartzite (CQ_{A_1}) from the New Richmond Mine were divided into three groups containing two samples each. Two groups were subjected to a solution of concentrated hydrochloric acid for one week, one was further subjected to a boiling KOH solution for two hours. The remaining group was not treated. One sample from each group was placed in a container of distilled

*80% by volume H_2O and 20% by volume KOH.

water, the other in a container of hypo-solution. The six samples were then alternately frozen and thawed - 24 hours at -10°C , 24 hours at 70°C , 24 hours at -10°C etc.

Results: No disaggregation was observed in any of the samples after six complete cycles of 48 hours each.

EXPERIMENT 2

DE-STAINING

Objective: To determine the optimum procedure for removing iron oxide stain from semi-polished sample surfaces and thin sections using an HCl-SnCl_2 solution.* Evaluation of the effect of such a solution on jaspilite is a second objective.

Procedure: Portions of two different cherty quartzites (CQ_{A2}) and a jaspilite from the Moore Mine were placed in an HCl-SnCl_2 solution for three hours. Samples were washed and examined under a binocular microscope at fifteen minute intervals. A similar test was run using a boiling solution of HCl-SnCl_2 . Finally, a thin section of a cherty quartzite (CQ_{A2}) from the Moore Mine was subjected to the above tests.

Results: Optimum destaining was obtained by soaking the samples in the HCl-SnCl_2 solution for a time interval between fifteen and thirty minutes. Subjection for times greater than thirty minutes led to surface deterioration;

* HCl-SnCl_2 solution consisted of hydrochloric acid of 36.5% concentration with enough stannous chloride to maintain the iron in solution.

with longer subsection times the samples began to disaggregate. It was found sufficient and desirable to place only that portion of the samples to be destained in contact with the solution. The above procedure was not applicable for thin sections due to a chemical reaction between the solution and cement. Even after seventy-five hours of boiling in the HCl-SnCl_2 solution the jaspilite sample was only "cleaned up"; little, if any, removal of the red coloring from the chert bands or disaggregation of the sample was observed.

EXPERIMENT 3

DISAGGREGATION (1)

Objective: To determine whether the clastic samples can be completely disaggregated with the HCl-SnCl_2 solution, to determine the rate of disaggregation, and to analyze the residues.

Procedure: Three cherty quartzite (CQ_{A_2}) samples from the Moore Mine and one cherty quartzite (CQ_{A_1}) sample from the New Richmond Mine were washed, dried, weighed, examined and placed in 250 ml beakers containing 200 ml of HCl-SnCl_2 solution. A 100 ml of fresh HCl was added every four days. At the finish of the experiment the residues were again carefully washed, dried, weighed and examined.

Data:

Sample	Type	Location	Sample Wt. (grams)	Residue Wt. (grams)	% Loss
#173	CQA ₂	Moore Mine	30.2	20.9	30.8
#173	CQA ₂	Moore Mine	54.9	37.3	32.1
#173	CQA ₂	Moore Mine	27.3	18.6	31.7
#302	CQA ₁	New Richmond Mine	61.2	48.8	20.3

Results: After 16 days all samples were completely disaggregated. Analysis of the residues showed that the samples had been broken down into small clusters consisting of several sand grains bound together by a white crystalline substance identified as chert. No traces of hematite were observed.

EXPERIMENT 4

DISAGGREGATION (2)

Objective: To determine whether the chert portion of the clastic sample residue can be dissolved with a solution of potassium hydroxide.

Procedure: The residues from the third experiment were examined, washed, dried, weighed and placed in 250 ml beakers containing 200 ml of potassium hydroxide solution. Each preparation was boiled for five hours. At the end of five hours the residues were again carefully washed, dried, weighed, and examined.

Data:

Sample	Type	Location	Sample Wt. (grams)	Residue Wt. (grams)	% Loss
#173	CQA ₂	Moore Mine	20.9	14.7	29.7
#173	CQA ₂	Moore Mine	37.3	25.6	31.4
#173	CQA ₂	Moore Mine	18.6	12.9	30.8
#302	CQA ₁	New Richmond Mine	48.8	35.5	27.2

Results: After five hours of continuous boiling most of the fine chert had been dissolved. All sand grains were singular - none being bound in aggregates by the chert cement.

EXPERIMENT 5

HYDROCHLORIC ACID AND QUARTZ

Objective: To determine the effect of concentrated hydrochloric acid on sand grains, quartz crystals, and quartzite fragments.

Procedure: Samples prepared for testing were examined under a binocular microscope prior to washing and drying at 70°C for 24 hours. Particular emphasis was placed on the surface condition of the specimens. A control specimen identical to the test specimen was kept for post-test comparison. Once weighed, specimens were placed in 250 ml beakers containing 200 ml of concentrated HCl (36.5%). Enough stannous chloride was added throughout the experiment to keep the iron in solution; 100 ml of fresh HCl was added to the beakers every four days. Duration of the test was 36 days. At the end of the experiment specimens were thoroughly washed in distilled water, dried at 70°C for 24 hours, and weighed. All specimens were then re-examined.

Data:

Sample	Sample Wt. (grams)	Residue Wt. (grams)	% Wt. Loss
Indian River Beach Sand	50.52	49.48	2.06
Mesnard Quartzite	44.82	44.76	0.13
Clear Quartz Crystals	19.20	19.19	0.05
Milky Quartz Crystals	17.17	17.16	0.06
High Quality Clear Quartz Crystals	20.81	20.78	0.14

Results: None of the samples exhibited a significant weight loss with the exception of the Indian River Beach sand. The Indian River Beach sand contained approximately 2% carbonate. Re-examination of the surfaces and comparison with the control samples showed that the tested specimens suffered no surface textural damage due to the HCl-SnCl_2 solutions. It is concluded that the HCl-SnCl_2 solution had no effect on the specimens tested.

EXPERIMENT 6

KOH BOILING - QUARTZ

Objective: To determine the effect of boiling potassium hydroxide solutions of varying strengths and boiling times on the percent weight loss and surface texture of quartz crystals.

Procedure: Five KOH solutions of the following strengths were prepared: 60-40, 70-30, 80-20, 90-10, and 95-5. The notation 60-40 represents a solution containing 60% by volume of H_2O and 40% by volume of KOH. Such a solution is

prepared by adding KOH pellets to 60 ml of distilled water until the meniscus is raised to the 100 ml mark. Two sets of matched pairs of quartz crystals were used for each solution; one pair being a milky variety of quartz; the other, a clear variety. These quartz crystals were of high quality with shiny faces and sharp edges. Long diameters varied from 15 mm to 35 mm, while the weights varied from 2 gm to 7 gm. A total of 24 crystals were used. From each group of four crystals, one milky and one clear quartz crystal was placed in each solution; the other two were held as controls for post-test comparisons. All crystals were examined under a binocular microscope and their textural characteristics recorded. The crystals were first placed in an oven at 70°C for 24 hours, cooled, weighed, and placed in their respective solutions. Total boiling times varied between four and six hours with each sample being weighed at each hour time period. After boiling the samples were rinsed in hydrochloric acid, thoroughly washed in water, dried, and weighed. Textural characteristics were compared to the initial data. Finally, a control set of quartz crystals were processed in the above described manner in 100% distilled water in order to ascertain the effect of tumbling in a boiling solution.

Results: A graph of percent weight loss of the crystals as a function of time is presented in figure 26. It appears

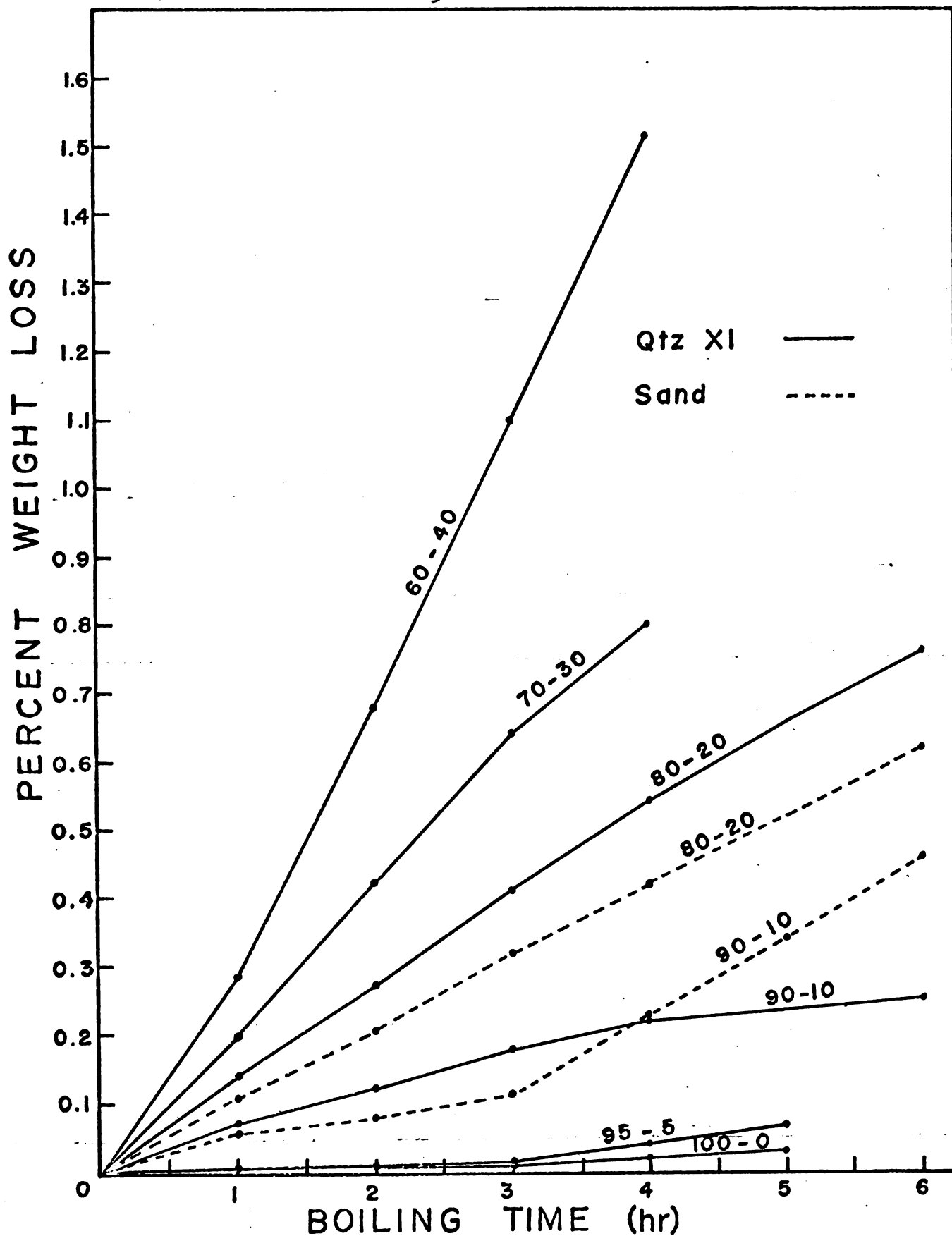


Figure 26. Percent Weight Loss for Various KOH Solutions as a Function of Boiling Time

that the percent weight loss of quartz crystals is insignificant for KOH solutions of 80-20 strength and less with boiling times not longer than six hours. It is, however, fully realized that the strengths reported are initial strengths and that these strengths are increased due to water vapor escaping during boiling. In fact, the solutions became so strong that testing had to be run in intervals because the pyrex beakers would last only a few hours before dissolving. Further, the percent weight data represents a maximum loss due to mechanisms such as chipping and spallation of the crystals and removal of foreign particles. One must be careful that all the KOH is removed from the crystal prior to weighing. During the early part of this experiment it was found that by not rinsing the crystals first in concentrated HCl a quantity of KOH would remain on the crystal surfaces. Upon comparison of pretest and post-test specimen surfaces, a noticeable degree of chipping of edges, striation of faces, etc., was found to occur. Since the crystals from the 100% water solution also exhibited such wear, it is concluded that such surface markings were the result of physical contact with each other and the surfaces of the beaker. In support of this hypothesis, beakers as well as samples were often observed to be cracked. The dullness of the tested specimens is likewise thought to be due to specimen-specimen and specimen-beaker contact. In summary, it is

felt that although there is finite dissolving of quartz by the concentrated potassium hydroxide solution, strengths of 80-20 and below do not produce appreciable damage over periods of up to six hours of boiling.

EXPERIMENT 7

KOH BOILING - SAND

Objective: To determine the effect of boiling KOH solutions on sand grains by studying the percent weight loss and surface textures.

Procedure: Two HCl treated (2% carbonate removed) samples of Indian River sand were placed in 80-20 and 90-10 KOH solutions and boiled for six hours. The testing procedure was identical to experiment 6. Indian River sand was chosen because of its fresh texture (no frosting, few stiration marks, etc.).

Results: A graph of percent weight loss versus boiling time is presented in figure 26. These percent weight loss values are subject to the same conditions as described in Experiment 6. Comparison of pretest and post-test sand grains revealed no frosting, stirations, cracking, or other similar effects. The lack of surface markings was probably due to the small mass of the individual grains - thereby reducing the force of collision with the beaker and other grains. It is concluded that if the sand grains have been partially dissolved by the KOH solution, the percentage loss is not quantitatively

significant. The surface textures are unaffected by the KOH solutions tested.

EXPERIMENT 8

KOH STANDING - QUARTZ

- Objective:** To determine the long term effect of room temperature potassium hydroxide solutions on quartz crystals.
- Procedure:** The preparation procedure was identical to that used in experiment 6. Twenty-four new quartz crystals were used in solution strengths of 60-40, 70-30, 80-20, 90-10, and 95-5. Test time was two months.
- Results:** In all cases the percent weight loss was less than 0.05%. Inspection of the post-test specimens revealed that the surface textures were unaltered during the period of testing.

EXPERIMENT 9

KOH TIME DURATION

- Objective:** To determine the time required for 90-10 and 80-20 strength potassium hydroxide solutions to remove sufficient chert cement from the sand grains to permit valid sieve analysis.
- Procedure:** Nine identical portions of the residue from the HCl-SnCl₂ treated sample #332 (CQ_{A1} - New Richmond Mine) were boiled for time intervals of one, two and one-half, three, and six hours. Each sample was microscopically examined at the end of its respective time period.

Results: A data table is presented below.

Aggregation			
Many	Some	Few	None
90-10: A ₁₀	B ₁₀ C ₁₀	D ₁₀	
80-20:	A ₂₀	B ₂₀ C ₂₀	D ₂₀

Samples A were tested for one hour; samples B, for two and one-half; etc. Sample D₂₀ (boiled in 80-20 KOH solution for six hours) contained no aggregates while the individual quartz grains were found to be essentially free of the chert cement. Samples D₁₀ and C₂₀ were found to contain a few aggregates and a small amount of chert cement.

EXPERIMENT 10

HCl and KOH - SAND

Objective: To determine the effect of the entire disaggregation process, HCl-SnCl₂ and 80-20 KOH boiling solution, on sand grains using roundness, sphericity, and sieve analysis as criteria.

Procedure: Roundness and sphericity measurements were made on Indian River Beach and Ferndale sands prior to being placed in concentrated hydrochloric acid for 30 days. At the end of 30 days samples were washed, dried, and measured for roundness and sphericity. Samples were then placed in 80-20 solutions of boiling KOH for six hours, at which time samples were washed, dried, and

measured again. Roundness and sphericity measurements were made by mounting 300 or more grains on a slide, projecting on a screen, and tracing at a magnification of approximately 30X. The roundness equation used was $R = \frac{\sum (r_i/R)}{N}$; where r_i is the radius of the individual corners; R , the radius of the maximum inscribed circle; and N , the number of corners measured. The sphericity equation used was $S = R/R_c$; where R is again the maximum inscribed circle; and R_c , the minimum circumscribed circle. Measurements were made with a celluloid scribed in millimeters. Sieve analyses were made on the Indian River Beach and Ferndale sands before and after boiling in the KOH solution. A set of four-inch diameter Tyler sieves of meshes 10, 20, 40, 60, 80, 100, 120, 150, and 200 were used. Samples were sieved in a Tyler Automatic Ro-Tap shaker for 15 minutes.

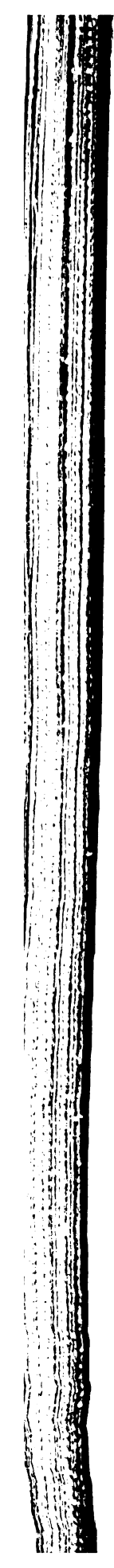
Results: Below is presented a table of the test results. It is obvious that all the percent changes are well within the error of measurement. Furthermore, as stated previously, there is no observable difference in surface textures.

Table XII

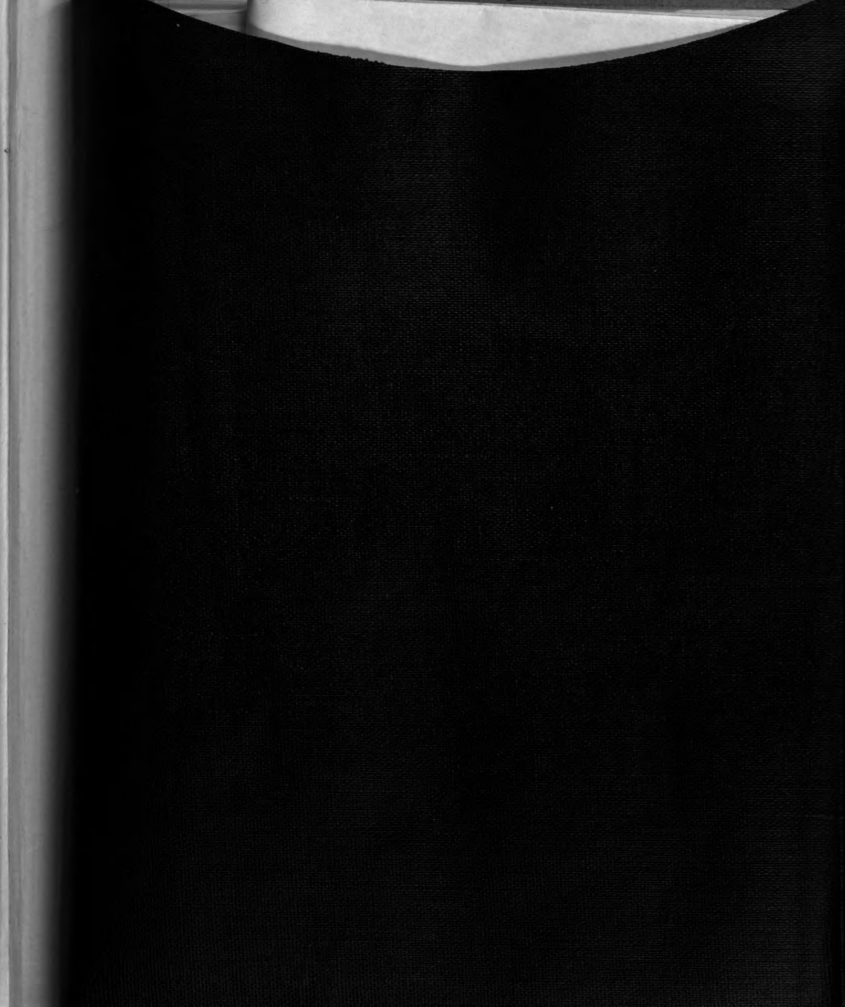
TEST RESULTS - EFFECT OF HCl AND KOH SOLUTIONS ON SAND

Sample	Test*	Control	After HCl	% Change	After KOH	% Change	Total % Change
Indian River Beach	Roundness	0.476	0.458	3.78	0.462	0.86	2.94
	Sphericity	0.818	0.813	0.61	0.804	1.10	1.71
	Median size	0.205	0.203	0.97	0.202	0.49	1.46
	Sorting	0.867	0.863	0.46	0.860	0.35	0.81
Ferndale	Roundness	0.440	0.433	1.59	0.398	8.08	9.54
	Sphericity	0.809	0.802	0.86	0.824	2.67	1.81
	Median Size	0.210	0.208	0.95	0.206	0.96	1.90
	Sorting	0.837	0.826	1.31	0.835	1.08	0.24

*Median size in mm, others dimensionless.



Pocket has:
4 maps



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