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1. ABSTRACT

Petrological and mineralogical investigations of Upper Keweenawan age rocks associated with the Midcontinent Rift System (MRS) suggest that two distinct sequences can be recognized.

Overlying the Middle Keweenawan volcanics is a sequence of volcanogenic sediments, in which the volcanic component decreases upwards. Several formations, including the Copper Harbor Conglomerate, the Nonesuch Shale, the Freda Sandstone, and the Solor Church Formation have been recognized and mapped in Wisconsin, Michigan, and Minnesota, where these rocks occur at or near the surface.

Overlying these rocks is a sequence of clastic sedimentary rocks primarily consisting of arkoses, subarkoses, and minor siltstone and shale. Again several formations, including the Orienta Sandstone, the Devils Island Sandstone, the Cheqaumegon Sandstone, the Fond du Lac Formation, and the Hinckley Sandstone have been recognized in outcrop in Wisconsin, Michigan, and Minnesota.

Examination of surface samples, drill hole cuttings and some core from wells located along the trend of the MRS, it appears that some of these units can possibly be traced southward into the subsurface of Iowa, Nebraska, and Kansas. The Precambrian sedimentary rocks in Nebraska and Kansas have traditionally been referred to as the Red Clastics and the Rice Formation respectively. It has been possible to tentatively correlate some of these rocks with known formations in the outcrop belt. We found that petrographic analysis of the rock materials is an excellent tool to define and correlate the various units.

2. INTRODUCTION.

This study is part of the U.S.G.S Midcontinent Strategic and Critical Minerals Program that was initiated in 1985. The principal goal of this multi-year program was to study available cores and cuttings from drill holes, and outcrop samples from the exposed portion of the rift, to better characterize the nature of the rocks and to aid in an attempt to carry the recognized stratigraphy southward along the buried portion of the rift into Kansas.

During the first years of this study (1985 and 1986) the samples from surface exposures in Michigan, Minnesota and Wisconsin were collected and described. Limited samples were also collected from subsurface penetrations of Precambrian rocks in Minnesota, Iowa, Nebraska and Kansas. These preliminary studies have already been reported by Anderson et al. (1987). The descriptive logs of more than 60 drill holes from Minnesota, Iowa, Nebraska, and Kansas were examined and interpreted. Additional subsurface samples were collected in 1986, 1987 and 1988 from southern Nebraska and northeastern Kansas. For comparative studies, a small number of surface Cambrian samples were collected in Iowa, Wisconsin and Minnesota. These materials have been examined at the Kansas Geological Survey.

The studies include:

1) Microscopic analysis of 130 thin sections. Of these, 65 were from surface exposures, 45 from drill hole cuttings, and 20 from cores. Because many of the rocks were quite friable, 77 samples, including all cuttings from drill holes, had to be treated with epoxy resin. Fifty thin sections were point counted and 30 were stained to estimate their porosity. All these studies were conducted using an Olympus BH-2 polarizing microscope.

2) Cuttings from more than 40 drill holes were described and evaluated with the aid of a binocular microscope. Thin sections were made of appropriate intervals and the more important descriptions are included in this report.

3) Twenty seven samples were disaggregated and heavy minerals were separated.using bromoform (specific weight—2.85g/ccm). All heavy mineral separates were point counted.

4) Over 50 x-ray analysis were conducted on different samples including clay mineral samples (separated by decantation), to determine the clay mineralogy.

5) More than 400 color microphotographs were taken from the most interesting fragments of thin sections.

6) A limited amount of chemical, AA and EPR analysis were conducted to determine the composition of mineral phases.that were microscopically difficult to recognize

The last two years (1988 and 1989) were dedicated to literature studies and evaluation of the results of the Texaco #1 Poersch drill hole which penetrated approximately 8500 feet of Precambrian rift-related sedimentary and igneous rock (Berendsen et al., 1988).

This report details the results of laboratory studies and discusses the nature of the clastic rocks examined. We have tried to correlate the various rock types along the length of the rift and describe the structural setting of the rocks.

3. PURPOSE OF THE STUDY.

The main purpose of this study is to compare the volcanogenic sedimentary and arkosic Precambrian rocks associated with the MRS in order to extend the stratigraphy from surface exposures in Minnesota and Michigan southward into the subsurface. Our knowledge of the paleontologically barren sediments is based on outcrop information from the Lake Superior area, a limited number of drill holes, and from geophysical modeling and extrapolations. Geological data collected so far allow us to compare stratigraphic sections of Precambrian sediments between adjacent states, as for example between Michigan and Wisconsin, Minnesota and Iowa, and to some extend between Iowa, Nebraska and Kansas (Morey and Ojakangas 1982, Dickas 1986, Adler 1987). The comparative lithostratigraphy of Precambrian sediments along the entire extension of MRS has still many gaps and needs much more work. The main methods employed in this study are petrographical and mineralogical examinations of surface and subsurface materials. Such an approach offers many positive aspects, but also has its limitations. There are major questions to be answered concerning the structural development of MRS, and its subsequent tectonic history. This and other questions as well as favorable factors will be discussed in following chapter.

3.1. QUESTIONS AND CONSTRAINTS.

The major questions and constraints may be organized as follows:

3.1.1. The Time Factor.

The nominal age of basalts associated with the MRS in the Lake Superior area and Minnesota is about 1.100+10Ma (Van Schmus et al. 1982). This age is confirmed by rubidium-strontium determinations of the Nonesuch Shale overlying the basalts in Wisconsin and Minnesota (Barghoorn et al., 1965). Only a few reliable dates for the age of the volcanic rocks in the subsurface of the southern extension of the rift have been reported. Younger ages have been reported from some localities, such as the basalt from the Williams #1 Radenslaben drill hole in Saunders County, Nebraska Lidiak, (1972), and from the Texaco #1 Poersch drill hole in Washington County, Kansas (Berendsen et al., 1988). All of these ages were arrived at using the K/Ar age-dating technique, and as such only give a minimum age for the rocks in question. A Rb/Sr age similar to those reported for mafic rocks in the Lake Superior region has recently been determined (Van Schmus, personal communication) for the roughly 300-foot thick gabbro topping the Precambrian section in the Texaco #1 Poersch drill hole. Several much younger K/Ar ages for the same gabbro were obtained by Texaco and reported by Berendsen, and others (1988). Although the section penetrated in the Poersch #1 drill hole may have been faulted (Woelck, 1989), the rocks in Kansas are roughly of the same age as those in the Lake Superior region.

It has been suggested (Mc Swiggen et al., 1987) that the MRS may have had a different evolutionary history in its northern part relative to its southern part. The recently obtained age for the gabbro does not support this view. Direct comparison of the Poersch #1 stratigraphic succession with rocks of the same age in the better known and exposed portion of the rift is not possible. The post-rifting structural development of the rift, including substantial repeated vertical movement along rift bounding faults, and considerable erosion in the time span between roughly 1,000 m.y. and 500 m.y., presents great difficulties trying to correlate between various drill holes that penetrate the Precambrian basement rocks. It is also possible that considerable thicknesses of rocks are Late Proterozoic reworked equivalents of Keweenawan age sequences.

3.1.2. Ratio of MRS Extension, Subsidence and Sediment Deposition.

The most prevailing concept (Chase and Gilmer 1973), of the MRS is that of an aborted continental rift, which if continued, might have resulted in the formation of an ocean basin. Different ratios of crustal extension and basin subsidence in various segments of the MRS are highly probable. This inference is supported by the geological record of active rift zones and by the change in width and depth of the MRS. Chandler (1983) estimated that there must have been at least 60 km of spreading along the northern segment of the rift, while Serpa et al. (1984) suggests only 29 km of extension for its southern end. It seems that the width and the depth of different MRS segments show a relationship to the position of major NW-trending accommodation zones, some of which have been referred to as transform faults.

Therefore, different rates of sedimentation as well as different environments of deposition are likely to occur along the trend of the MRS. Narrow, deep basins have a different structural architecture, higher ratio of deposition and a different set of associated sediments, compared to wider basins. The wider basins in the northern part of the MRS resulted in synrift rocks that are composed and derived mainly from volcanic sources. Synrift deposits in the southern and narrower portion of the rift may contain larger contributions from the rift shoulders.

3.1.3. Model of MRS Development.

A widely accepted tectonic model for the formation of the MRS includes three stages. The first or volcanic stage begins with the opening of the rift accompanied by extrusion of mostly mafic, massive volcanic suites and minor associated amounts of igneous rocks. The second stage includes consequent slow divergent movement of the rifting plates, subsidence of its flattened bottom and development of a volcano-clastic sequence. The third stage is marked by cessation of rifting, tectonic inversion, and formation of horst structures flanked by basins that are later filled by first- or second cycle clastics derived from both inside and outside the rift.

3.1.4. Climatic Changes.

The time span between the processes that mark the beginning of the MRS and transgression of the Cambrian sea is about 600 m.y., thus more than all of the Phanerozoic. During this time, climatic changes occurred over short time spans and regions of varying climatic regimes might have been in close proximity (Chumakov and Elston, 1989). This may also have affected the environments of deposition along the MRS. Three periods of glaciation (two Rhaetian and one Vendian) occurred during this time. At least two of them are recorded from Proterozoic rifting environments in Utah and Idaho (Crittendon et al., 1983), and in southwestern Virginia (Miller 1989).

The red color of Proterozoic sedimentary rocks associated with the MRS is generally interpreted to result from dry, and occasionally semi-dry, climates. However, it is possible that some of these rocks, especially the older volcanogenic sedimentary rocks, were formed in a different type of environment.

Their present-day color may be the result of repeated periods of secondary weathering or intraformational oxidation. The red color of younger, mostly quartz-arenitic and subarkosic rocks may be of syndiagenetic origin, related to a prolonged period of crustal stability.

3.1.5. Geological Material.

The quality of the geological materials available for study varies widely from drill hole to drill hole. With the exception of a few, most drill holes penetrating the Precambrian surface reach total depth (T.D.) within a limited number of feet. Samples presumed to be of the older units.(e.g., Solor Church equivalent rocks) are not available. The petrographic character of these rocks is mostly taken from the literature. The small amounts of core material available did not allow sampling in a systematic manner. The available descriptions of sections based on cuttings often contain mistakes and confusing terminology. For example, volcanic rocks from the Winkler #1 and Kratchovil #1 drill holes in Kansas were described as metamorphic schists. Samples of St. Peter Sandstone from the Koutney #1 drill hole in Nebraska were interpreted to be of Precambrian age. In addition, cavings from up-hole contaminate the samples to varying degrees, often making it impossible to interpret the lithology with much confidence. The lack of, or in many cases the poor condition of electric logs, especially for the older drill holes, complicates the task of interpreting the geology encountered in the drill hole.

3.2. FAVORABLE FACTORS

To assist in our interpretation of the Precambrian sediments and their lithostratigraphic correlations an understanding of the geotectonic development of the Midcontinent area and adjacent Canadian Shield is of essence. Even though they are subject to many constraints, all major geotectonic events can be recognized throughout large portions of the continent. There is general agreement that no major movements occurred within the Midcontinent in the time span between the cessation of rifting and the encroachment of the Cambrian sea. Therefore, the uppermost clastic rocks associated with the MRS, composed mostly of more mature sediments, lend themselves best to lithostratigraphic studies.

As recorded by the occurrence of quartz arenites on Devils Island, Wisconsin, and the Hinckley Sandstone in Minnesota a period of long lasting tectonic crustal stability occurred during the sedimentation of uppermost Keweenawan clastic rocks. Similarly, a long lasting period of mature, quartz arenite deposition took place on the Canadian Shield (Donaldson, 1989). The presence of similar, corresponding rocks in Iowa, Nebraska or Kansas may be a key point in the correlation of the entire clastic package. Geophysical evidence (Dickas, 1986; Serpa et al., 1984) suggests that the MRS was less developed towards the south.

The composition of Cambrian sediments and the extend of the transgressing Cambrian sea are generally well defined. Therefore, the specific petrographic character of the Cambrian rocks may be worked out to help us define lithologically the upper boundary of the paleontologically barren rocks.

Other, mostly petrographic methods of study, that may be utilized in helping to decipher the lithostratigraphy include: 1) modal analysis of psammitic rocks, 2) heavy mineral analysis, 3) provenance and composition of various rock fragments, 4) the specific mineralogic character of the major mineral components, for example quartz, feldspars and phyllosilicates, and their suggested origin, 5) types of cement, 6) authigenic minerals, 7) the general maturity of the rocks, 8) depositional structures and textures.

4. PETROGRAPHIC INVESTIGATIONS.

4.1. PETROGRAPHIC CHARACTERISTICS OF SURFACE VOLCANOGENIC SEDIMENTARY AND CLASTIC ROCKS ASSOCIATED WITH THE NORTHERN PART OF THE MRS.

4.1.1. Chequamegon Sandstones.

Samples: 10a, 10b—Washburn, WI
13, 13a—Big Rock Wayside Park, near Washburn, WI

The rocks are fine to medium grained , clayey-ferruginous subarkoses (10a and 10b), and medium to coarse grained, clayey-ferruginous sublitharenites (13 and 13a). The rocks are mostly made up of quartz, with amounts ranging from 52.6 to 57.7% by volume. Most quartz grains are angular and have very sharp edges with corrosive bays and inclusions of devitrified volcanic glass. These features indicate a volcanic origin for part of the quartz grains. The remainder of the quartz grains have abraded rims that show secondary overgrowth and may suggest at least two cycles of sedimentation. Feldspars (12.1 to 16.0%) consist mainly of relatively fresh microcline with a few altered microcline, orthoclase and perthite grains.

Rock fragments are very rare in the subarkoses (0.8%), but are common in the sublitharenites , up to 15.8 %. They consist primarily of metamorphic rocks fragments (9.6%) such as quartzites, cataclasites, quartz-graphite, quartz-sericite and quartz-muscovite schists, quartz-ferruginous rocks (Iron Formation), and minor less metamorphosed quartz-sericite mudstones. Volcanic rock fragments (4.1%) consist of altered basalts having an ophitic and micro-ophitic texture. Few fragments of rhyolites and diabases with an unusual granophyric texture have been also found. Sedimentary rock fragments, such as chert and agate make up only 2.1% of the rock volume. No mica and chlorite have been found in Chequamegon sandstones.

The porosity of these rocks varies from 6.1 to 10.5%. Sample 10b contains relicts of primary matrix (9.6%). The heavy mineral fraction in the subarkoses consists of very resistant minerals, such as zircon and opaque minerals, with lesser amount of tourmaline, epidote, and hornblende. The heavy minerals in the sublitharenites are dominated by opaque minerals, but other heavy minerals similar to those found in the subarkoses are present. X-ray analysis of sample (10a) confirms the presence of quartz and microcline.

4.1.2. Hinckley Sandstone.

Samples: 2—Quarries at Robinson Park, Hinckley, MN
3a—East bank of Kettle River at Hwy. 123, Hinckley, MN
3b—Roadcut along Hwy. 23, near Askow, MN

The rocks are fine to medium grained, quartz-clay cemented, quartz arenites. Quartz, often with thick, secondary overgrowth and abundant corrosive features, makes up more than 60% of the rock by volume. Rock fragments are very rare (0.9%), and are represented by chert and fine grained quartzites. Weak cement makes up to 9.0%, and pores up to 14.8% of the rock by volume. The sandstones contain also variable amounts of clayey- muddy intraclasts, up to 5.9%. Heavy minerals consist of opaques, zircon, tourmaline, hornblende, with minor rutile, kyanite and pyroxene. Sample 2 contains 3.4% of secondary xenotime and pyrochlore. A single thin ferruginous streak, about 1 cm thick (sample 3b), could be traced for several hundred feet along the outcrop. X-ray analysis of the rock (sample 3a) shows the presence of chlorite, which is probably associated with the muddy intraclasts.

4.1.3. Devils Island Sandstone.

Sample: 11—Siskiwitt Falls, Cornucopia, WI

The rock is a medium grained quartz arenite with quartz-clay cement. Highly recrystallized quartz with abraded secondary overgrowth makes up 71.3% of the rock volume. The rock is weakly cemented with pores up to 10.5% by volume. Feldspars (1.4%) are highly altered and replaced by sericite and kaolinite. Rock fragments (1.9%) consist of very resistant chert, quartzite, and schist. Minor chlorites appear to be of secondary origin.

The heavy mineral fraction is dominated by phyllosilicates associated with minor resistant minerals. Tourmaline is more abundant than zircon.

4.1.4. Fond du Lac Formation.

Samples: 6a, 6b, and 6 c—along Mission Creek, Duluth, MN
7a, 7b, 7c, 7d, and 7e—Fond du Lac Park, Duluth, MN
8b, 8c and 8d—Jay Cook State Park, Little River, MN

The rocks are fine to medium grained subarkoses (6b, 6c, 7a, and 7e), fine to medium grained lithic arkoses (6a and 7b), coarse to very coarse, conglomeratic sublitharenites (7c and 7d), and basal conglomerates (8b, 8c, and 8d). On a triangular Q-F-R diagram.(Fig. 1), the points project close to each other , indicating that the composition of these rocks is very similar, as far as the main detrital components are concerned (quartz, feldspar and rock fragments).

In contrast to the detrital mineral composition, the content and composition of the cement in the Fond du Lac sandstones is variable. The composition of the cement determines to a large degree the color of the rock. In brown and reddish rocks the cement consists mostly of ferrugenous minerals intermixed with clay minerals(7b), dolomite (6a), dolomite, clay minerals, barite and fine grained quartz (7a). Greenish gray rocks have a clay cement with variable amounts of other minerals, fine grained quartz (8b and 8d) quartz and dolomite (6c), or pyrite (8c). The samples studied show relicts of a primary matrix ranging from 0.4 to 3.9% by volume. The variability in the composition of the cement is probably a function of several factors, including a difference in the primary environment of deposition, and a complicated history of diagenesis of the Fond du Lac sandstones.

Quartz is the main component of these rocks with its content ranging from 37.8 to 53.3% of the rock volume. Quartz grains are well rounded in coarse grained and conglomeratic sandstones. They are poorly rounded and angular in fine to medium grained sandstones,which may partly be attributed to quartz recrystallization under the influence of stress. At least part of these angular, sharp edged quartz grains may be related to their pyroclastic origin. Only a few quartz grains have abraded thin secondary overgrowth rims. Feldspars (from 9.2 to 18.6%) consist mainly of fresh microcline with minor altered microcline, perthite and orthoclase grains. Plagioclases have been not found in the Fond du Lac sandstones examined.

Rock fragments (from 8.1 to 13.7% by volume) consist mainly by metamorphic rocks, such as quartz mica, quartz-sericite schists, fine grained quartzites, and quartz-ferruginous rocks, probably derived from iron formations. A lesser amount consist of sedimentary rock fragments of chert and clay intraclasts. Basaltic, diabasic, and devitrified volcanic rock fragments are of minor importance. The same is true for igneous rocks fragments. Only several grains of granitic and gneissic origin have been found. Samples 6c and 7b are characterized by an increased amount of large clay and mudstone intraclasts, some of which have laminae up to 2 cm long and 0.5 cm wide.

Phyllosilicates (from 2.9 to 3.7%) consist mostly of secondary chlorite with minor muscovite, and fresh and altered biotite. Nearly all phyllosilicate flakes are strongly deformed. The porosity of Fond du Lac sandstones varies from 3.5 to 8.3%. X- ray analysis of samples 6b and 6c confirms the presence of quartz, microcline, chlorite and dolomite. The heavy mineral fraction is dominated by opaque minerals. Other heavy minerals consist of detrital zircon, tourmaline, garnet, epidote, hornblende and apatite, as well as authigenic epidote, tourmaline and apatite.

The most characteristic features of the Fond du Lac sandstones are: the low rank of maturity of nearly all the rock components, the high content of microcline and rock fragments (metamorphic and sedimentary), the low content of pyroclastic material, the occurrence of muddy-clayey intraclasts, the deformed mica flakes, quartz grains recrystallized in preferred directions, the complex composition of the cement, and the high content of authigenic minerals.

4.1.5. Orienta Sandstone.

Samples: 12a, 12b and 12c—Iron River, Port Wing, WI
29a and 29b—Amnicon Falls State Park, WI
30a and 30b—Pattison Falls State Park, WI

The rocks are fine to medium grained subarkoses (12a, 12b, 12c, 30a and 30b) and coarse to very coarse grained, conglomeratic sublitharenites (29a and 29b). The cement in the lighter colored rocks (white, light gray) is composed of quartz and clay minerals (12a, 29b and 30b), in darker colored rocks (brown, reddish and pink) the cement consists of quartz and clay minerals impregnated with disseminated iron oxides. The presumed primary matrix is also present (samples 12a, 29a and 30a). Sample 29a contains locally secondary zeolite cement.

Recrystallized, deformed, flattened and corroded quartz grains make up from 46.7 to 61.7% of the rock by volume. Quartz grains are well rounded in the coarser grained rocks , but poorly rounded in finer grained rocks, which might be interpreted as an indication of pyroclastic origin. Some of the quartz grains commonly show other signs of pyroclastic origin, such as corrosive bays, increased elongation and inclusions of devitrified glass. Other quartz grains have been involved in several sedimentary cycles, with grain edges being several times abraded and recrystallized. Some of quartz grains contain abundant needle like rutile intergrowths. This feature has been also observed in samples from other locations, as for example in sample No. 86/14 from the Livingood #1 drill hole in Kansas.

Feldspars (from 9.0 to 14.2%) are composed mainly of relatively fresh microcline together with a few altered microcline, perthite and orthoclase grains. Some microcline grains show signs of deformation with curved and disrupted twinning lamellae. The amount of rock fragments varies from 4.0 to 11.3%, and their composition seems to be very similar to those found in the Fond du Lac formation. Metamorphic rock fragments: quartzites, cataclasites, quartz-mica, quartz-sericite, guartz-chlorite and quartz-graphite schists are dominant in the Orienta Sandstone. Chert chalcedonite, and volcanic rocks fragments are of minor importance. However, samples 12a and 29a are enriched both in sedimentary rock fragments, muddy-clayey intraclasts and volcanic rocks, consisting of basalt clasts having a felsitic and micro-ophitic texture and diabase clasts having ophitic, granophyric, and graphic textures.

Highly deformed mica and chlorite flakes account for 0.8 to 2.8% of the rock volume. The rock porosity ranges between 5.0 to 8.9%. X-ray analysis of sample (29a) confirms the presence of quartz and microcline. Heavy minerals are dominated by highly resistant opaques, zircon, tourmaline, garnet, and hornblende. Some apatite and epidote grains are authigenic.

The most characteristic features of the Orienta Sandstone are the low rank of mineralogical maturity, the high content of microcline and metamorphic rock fragments, the presence of muddy-clayey intraclasts as well as pyroclastic material,the deformation of mineral species, the high content of authigenic minerals, and the common occurrence of recrystallized quartz.

4.1.6. Jacobsville Sandstone.

Samples: 22a and 22b - Keweenaw Bay at Gay, MI
23a, 23b, 23c and 23d - Keweenaw Bay at Baraga, MI

The rocks are fine to medium grained subarkoses (22a and 22b), fine to medium to coarse grained sublitharenites (13a, 23b and 23c) and very coarse grained conglomeratic litharenites (23d). The cement (from 16.9 to 17.7%) consists mainly of clay, locally with additional quartz (22a), iron oxides (22b and 23c) and with calcite-dolomite (23a, 23b and 23d). Quartz grains make up from 42.8 to 43.5%. They are poorly rounded, except for the larger grains and pebbles, which are well rounded. Some of the quartz grains have rims of secondary overgrowth. Feldspars (from 12.7 to 13.5%) consist mainly of relatively fresh microcline with minor altered microcline, orthoclase and perthite. In sample 22a several grains of altered plagioclase have been found.

Rock fragments (from 6.8 to 16.8%) are mainly of metamorphic origin, and consist of various schist fragments and quartz-ferruginous rocks (iron formation). Minor sedimentary and volcanic rock fragments were also found. They are composed of chert, chalcedony, mudstone, clay intraclasts, basalt, rhyolite, trachyte, ignimbrite, tuff and granophyre. Muscovite, biotite and chlorite are altered and deformed to varying degrees. The variable pattern of biotite alteration seems to be the main factor determining the color of the rock. In samples 23b and 23c some parts of the section have a brown-reddish color due to biotite alteration into iron oxides. The grayish-white or greenish color of other parts of the same formation results from biotite alteration into chlorite. The same alteration pattern was also observed on a smaller scale in other Jacobsville Sandstone localities.

The porosity of the Jacobsville Sandstone varies from 4.9 to 9.2% by rock volume. X-ray analysis of sample (23a) confirmed the presence of quartz, microcline and phyllosilicates. The heavy mineral fraction is composed of opaque and resistant minerals such as zircon, tourmaline, garnet, hornblende, rutile, epidote, and apatite.

The Jacobsville Sandstone can be recognized by its high content of secondary xenotime and pyrochlore in the heavy mineral fraction, with sample 22a having the highest content of these minerals of all samples.examined

4.1.7. Freda Sandstone.

Samples: 14a, 14b and 14c—White River, south of Ashland, WI
26a—Presque Isle inlet, Porcupine Mt. State park, MI
28—Copper Falls State Park, Mellen, WI

All the rocks studied are poorly sorted and poorly rounded, tuffacaeous litharenites with a high content of volcanic rock fragments. The grain size varies greatly within the formation. Sample 26a is a very fine to fine grained litharenite, sample 28 is a medium to coarse grained tuffite, while samples 14a, 14b and 14c are coarse to very coarse grained, often brecciated, conglomeratic litharenites. The average grain size of these litharenites is about 2.0 mm, but grains up to 4.0 mm are also common. Cement (12.7 to 19.1%) is composed mainly of clay minerals impregnated with iron oxides derived from altered volcanic ash. Sample 14c also contains up to 14.7% secondary calcite cement, while sample 28 is recognized by its unusually high content of zeolites in the calcite cement.

The quartz content of the rocks is relatively low and ranges from 6.9 to 12.4% by volume. Quartz is typically of volcanic origin with characteristic angularity, corrosive bays and abundant inclusions of volcanic glass. Feldspars consist mainly of relatively fresh microcline with some altered microcline, perthite, and orthoclase. The amount of K-feldspar varies from 5.7 to 15.1%. In contrast to the above described sandstones of the Jacobsville Sandstone and equivalent rocks, the Freda Sandstone also contains albite (from 0.7 to 3.3%). Albite is a product of albitization of Ca-rich plagioclases from basic volcanic rocks. Both detrital and secondary biotite and chlorite are altered and deformed to varying degrees. Muscovite flakes are very rare in the Freda Sandstone.

Among the rock fragments (40.1 to 62.6%) volcanic rocks account for 29.2 to 48.6% by volume. They consist mostly of altered basalt having felsitic and micro-ophitic textures and diabase showing ophitic and sometimes graphic textures. Altered rhyolite is also common, while trachyte, trachybasalt, tuff, and tuffites are of minor importance. A few grains of serpentinite and metavolcanic diabase, rich in epidote, have also been found. Sedimentary rock fragments (5.0 to 6.5%) consist of ferruginous shale, mudstone, siltstone, and fine grained micaceous sandstone, that often shows parallel bedding or laminae. Less common is chert and chalcedony. Among the metamorphic rocks (from 5.0 to 6.5%) quartzite and quartz-ferruginous rocks, associated with minor quartz-mica-sericite schist and cataclasite, are dominant. Granitoids (from 1.0 to 2.1%) occur only in the coarser grained sandstones.

The porosity makes up from 3.2 to 5.2% of the rock by volume. X-ray analysis confirm the presence of quartz, microcline, albite, calcite, and chlorite. Heavy minerals are abundant in the Freda Sandstone and constitute from 0.7 to 3.0% of the rock volume. They are mostly opaque minerals and secondary euhedral epidote, which is probably derived by alteration of Ca-rich plagioclase. Apatite and pyrochlore are also considered to be epigenetic. Detrital garnet, zircon, and rutile are very rare.

The characteristic features of the Freda Sandstone are the extremely low mineralogical maturity, the relatively high content of feldspar, including plagioclases, the variable provenance of the rock fragments together with a high content of volcanic rocks, the low quartz content, and the elevated content of authigenic epidotes.

4.1.8. Nonesuch Shale.

Samples: 16a, 16b, and 16c—Potato River Falls, Gurney, WI
24a and 245b—Silver City, MI
26b—Presque Isle inlet, Porcupine Mt. State Park, MI

The rocks are fine to medium grained litharenites (28), medium to coarse grained litharenites (16a) fine to very fine grained arkosic arenites (16b and 16c), and laminated, clay shales (24a) or laminated, muddy-clayey-ferruginous shales (24b). The cement is composed mainly of clay minerals impregnated with varying amounts of iron oxides and hydroxyl oxides. Samples 16a, 16b and 16c contain in places relatively large amounts (15.2 to 23.2%) of an unusual ferruginous-zeolitic-chloritic cement. The cement in sample 16c contains in addition chalcedony. Zeolites, chlorites and chalcedony are believed to be of secondary origin, as a replacement of pyroclastic material.

Angular quartz (from 10.9 to 27.3%) with corrosive bays and inclusions of devitrified glass also indicates a pyroclastic origin. Rims of secondary overgrowth, and other signs of quartz grain recrystallization, are very rare. The feldspars (11.0 to 21.3%) are similar to those in the Freda Sandstone. They consist of abundant fresh microcline associated with lesser amounts of plagioclase and minor altered microcline, perthite and orthoclase. One of the most important features of the Nonesuch Shale is a high content of deformed phyllosilicates. They are dominated by chlorites accounting for 4.3 to 20.1 of the rock volume. Two types of chlorites are recognized. The first one after detrital biotite, the second one as the result of metasomatic replacement of volcanic glass. Brown, or green, highly altered biotites and muscovites are accessory.

Among rock fragments (11.7 to 30.6%), quartz-mica-sericite-graphite-epidote schists, quartzite, quartz-ferruginous rocks and cataclasites are most abundant. A lesser amount of sedimentary rocks such as: chert, chalcedony and clayey-, or clayey-ferruginous shales are present. Volcanic rock fragments consisting of basalt and diabase are quite rare. The porosity of the Nonesuch Shale is very low and ranges from 2.2 to 2.5% of the rock volume. X-ray analysis of sample (16c) indicate the presence of quartz, microcline, calcite, chlorite, and laumontite.

The rocks of the Nonesuch Shale contain an increased amount of epidote (pistacite and clinozoisite). The high epidote content is probably related to the observed extensive alteration of Ca-rich plagioclases. The heavy mineral fraction is dominated by opaque minerals and epidote. Other heavy minerals, such as garnet, apatite, rutile, zircon, are quite rare.

The most important features of the Nonesuch Shale are the small grain size and large amount of shale in the section, the low rank of mineralogical maturity, the high content of feldspar and metamorphic rock fragments, and the extensive metasomatic alteration (laumontite, epidote and sericite).

4.1.9. Copper Harbor Conglomerate.

Samples: 18a and 18b—Eagle City, MI
19—North shore of Keweenaw Penninsula, south of Copper Harbor, MI

The rocks are very coarse grained conglomeratic, volcanic sandstones (18a and 18b), and very coarse grained, sandy volcanic conglomerates (19). The sandy matrix in samples 18a and 18b is composed of calcite (9.4%), iron minerals (2.8%), aleuritic quartz (2.0%), and zeolites (2.0%). Sample 19 has a similar sandy matrix cemented by iron minerals (25.6%) and zeolites (7.2%). Iron minerals are thought to be products of volcanic glass alteration.

Quartz, mostly with abraded secondary overgrowth rims, makes up from 2.6 to 5.4% of the rock volume. Feldspars (5.7 to 12.6%) consist of slightly to intensely altered microcline associated with minor altered plagioclase (albite), orthoclase, and perthite. Chlorites and other phyllosilicates are very rare.

Rock fragments (47.2 to 59.8%) are represented mainly by volcanic rocks (43.0 to 54.6%). In samples 18a and 18b the two principal types of volcanic rocks are rhyolites and basalts/diabases. Both rock types are intensely altered. The ferruginous groundmass in the basalts and rhyolites is mainly micro-ophitic and rarely intersertal or felsitic. Diabases with relicts of ophitic texture and locally graphic intergrowths of quartz and feldspar have also been found. The latter are believed to be of secondary origin. The composition of the rock fragments in sample 19 differs from those described above. Trachyte fragments with fluidal texture and K-feldspar phenocrysts predominate, with basalt and diabase fragments occurring in smaller amounts. A few andesite fragments with fluidal texture, rich in secondary albite laths, have been also found. The largest rock fragment in sample 19 is a basaltic, lithoclastic tuff with voids filled with zeolites and adularia.

Sedimentary rocks in the Copper Harbor Conglomerate (2%) are mostly chert, shale, ferruginous mudstone, and sandstone. Metamorphic rocks (1.8 to 2.2%) consist of fine grained quartzite, various types of schist, quartz ferruginous rock, and cataclasites. The pores make up from 2.6 to 3.7%. X-ray analysis of sample (18a) confirms the presence of adularia, quartz, calcite, hematite, magnetite, and chlorite. Heavy minerals are opaques, together with small amounts of apatite, zircon, epidote, rutile and sillimanite.

The most important features of the Copper Harbor Conglomerate are its very low rank of mineralogical maturity, its high content of variable volcanic rock fragments, its elevated content of altered microcline, the occurrence of zeolites, and its lack of micas.

4.2. PETROGRAPHIC CHARACTERISTICS OF SUBSURFACE VOLCANOGENIC SEDIMENTARY AND CLASTIC PRECAMBRIAN ROCKS ASSOCIATED WITH THE MRS

4.2.1. Minnesota.

4.2.1.1. Lonsdale 65-1, Rice County, NW SW SW section14, T112N, R21W.

Description of core samples:

Lo-1 (900'). Thin section

The rock is a medium to coarse grained , weakly cemented, clayey, quartz arenite. It is mainly composed of quartz (90%) that shows very quiet, straight extinction patterns, and only seldom has abraded secondary overgrowth rims. Other constituents are: orthoclase, kaolinitized muscovite, and carbonate nodules. Rock fragments are very rare. When present they consist of quarzite and chalcedony.

Lo-2 (918'). Thin section.

The rock is a fine to medium grained, weakly cemented, clayey, subarkose with a bimodal grain size distribution. The fine grained angular quartz is associated with the clayey matrix, while the medium grained quartz grains occur in the very porous primary matrix (secondary porosity up to 22.8%). Other minerals identified are: feldspar (mainly euhedral, authigenic microcline), altered muscovite, and a few rock fragments consisting of quartzite, gneiss and chert. Heavy minerals are rare, but zircon, tourmaline and epidote have been identified.

Lo-3 (934'). Thin section.

The rock is a coarse grained, calcite cemented quartz arenite. The rock is mostly made up of mosaic, undulose quartz associated with a calcitic, poikilitic, partly ferruginous cement, that constitutes up to 30% by volume. No heavy minerals are found.

Lo-4 (947'). Thin section.

The rock is a ferruginous shale with interbedded or intermixed mudstone laminae. The illite groundmass, with some chlorite, is impregnated with iron oxides and hydroxyl oxides. The mudstones are enriched in detrital quartz and altered K-feldspars.

Lo-5 (1279'). Thin section.

The rock is a laminated dark green, green, red shale with irregular intercalations of mudstone. Some of the shale laminae are noticeably enriched in iron oxides, some with very fine, aleuritic quartz, while others are micaceous. The mudstone intercalations can petrographically be classified as very fine grained arkoses and arkosic wackes with elevated amounts of highly altered feldspar (up to 20%), muscovite and chlorite (up to 20%), and a clay cement (up to 35%). The heavy mineral fraction is dominated by opaque minerals, with minor zircon, epidote, tourmaline and glauconite.

Lo-6 (1310'). Thin section.

The rock is a very fine grained, laminated, cross-bedded lithic arenite. It is slightly cemented with a porous clay cement. Main component is angular quartz, with the angularity partly due to secondary overgrowth. Feldspar (up to 20%), is mainly fresh microcline with minor kaolinitized plagioclase. Rock fragments (up to 20%), are mainly metamorphic: quartz-mica-, quartz-chlorite schists, and minor volcanic basalts. This rock is particularly enriched in the phyllosilicates muscovite, biotite (both of which are altered) and detrital or authigenic chlorite. Heavy minerals are very rare. Authigenic epidote dominates over zircon, tourmaline, and garnet.

Lo-7 (2507'). Thin section.

The rock is a laminated, cross-bedded, greenish shale with minor siltstone and mudstone partings. The clay material consists mainly of illite associated with muscovite, altered biotite, aleuritic quartz and organic matter. Locally it is impregnated with calcite. In the coarser grained parts, microcline, poorly rounded quartz, and chlorite dominate. Heavy minerals are mainly opaques, together with a lesser amount of epidote, zircon, and glauconite.

Lo-8 (2524'). Thin section.

The rock is a cross-bedded, laminated, calcareous siltstone and mudstone. The aleuritic fraction is composed of angular quartz (up to 20%), feldspar (up to 10%), micas (up to 15%) and chlorite. The rock has a high content of organic matter. The heavy mineral fraction consists of opaques, semiopaques, zircon, rutile, epidote and tourmaline.

Lo-9 (2774'). Thin section.

The rock is a dark gray, black, pelitic siltstone. The aleuritic fraction is composed of quartz (up to 30%), fresh and altered K-feldspar and plagioclase (up to 10%), micas (up to 10%), chlorite (up to10%), and opaque minerals (up to 10%) cemented by clay matrix. The heavy mineral fraction consists of zircon, epidote, sphene, rutile and tourmaline. The rock has a high content of organic matter.

4.2.2. Iowa.

4.2.2.1. B. Lehman #1, Dallas County, SW NW NW section18, T79N, R27W.

Description of core samples.

Lm-1 (2922'). Thin section.

The rock is a medium to coarse grained, very poorly sorted subarkose. The rock is highly compacted, with recrystallized quartz (up to 80%) having common secondary overgrowth rims. Quartz has partly straight, partly undulose extinction. Feldspars, both microcline and perthite (up to 20%) have regeneration rims. A few rock fragments of chert and quartz-sericite schist are present. The cement is clay-silica. Heavy minerals are zircon and epidote.

Lm-2 (2922'). Thin section.

Fine grained subarkose with clay-silica cement. The composition of the rock is as above.

Lm-3 (2947'). Thin section.

The rock is a fine grained subarkose intermixed with brown shale, greenish mudstone and conglomeratic sandstone. The various sedimentary units differ in composition. Quartz, from 20 to 40% by volume forms the main component of the rock. Feldspars (from 10 to 20%) consist of microcline with associated perthite and minor orthoclase. Kaolinitization and sericitization is common. Micas and chlorite (up to 10%) are present. Clayey-ferruginous-chloritic cement makes up from 5 to 35% of the rock volume. Rock fragments in the conglomeratic part of the section consist of quartzite, gneiss, and ferruginous shale intraclasts. Heavy minerals are zircon, tourmaline, epidote and glauconite.

Lm-4 (2956.5'). Thin section.

Red siltstone interbedded with greenish siltstone. The pelitic groundmass is composed of illite, chlorite, iron oxides and pelitic quartz. Quartz (up to 30%), feldspars (microcline, orthoclase, up to 10%), and the phyllosilicates, muscovite, biotite and detrital chlorite make up to 30% of the rock volume

4.2.2.2. McCallum A-1, Dallas County, NW NW SW section 5, T79N, R27W.

Description of core samples.

M-1 (2967'). Thin section.

The rock texture varies from pelitic to psammitic. It consists of about equal amounts of shale interlaminated with siltstone and fine grained arkose. The pelitic components of the rock are illite, iron oxides, organic matter, and micas. The psammitic fraction consists of quartz, feldspar, including fresh microcline and altered orthoclase, muscovite, biotite, and detrital and authigenic chlorite. Only a few zircon, tourmaline and epidote grains are present.

M-2 (2990'). Thin section.

The rock is medium to coarse grained, locally very coarse grained subarkose. Quartz (up to 80%), is recrystallized with abraded secondary overgrowth rims. It shows partly straight, partly undulose extinction patterns. Feldspar (up to 6%) grains are much smaller than quartz grains and composed of equal amounts of microcline and orthoclase. Only few mica and chlorite particles were found. The rock shows secondary porosity. Zircon is the only heavy mineral.

M-3 (3008.5'). Thin section.

The rock is a coarse to very coarse grained, locally conglomeratic subarkose. The rock is mostly composed of recrystallized quartz (up to 80%), showing abraded secondary overgrowths. Feldspar grains (up to 10%) show symptoms of secondary growth. Secondary quartz forms much of the cement. A few metamorphic rocks fragments (quartzite) are present.

M-4 (3012.5'). Thin section.

The rock is a medium grained subarkose with ferruginous clay cement. Otherwise the rock is much like M-3

M-5 (3014'). Thin section.

The rock is a fine grained subarkose to arkose, laminated with subarkosic wacke or mudstone. The main component is quartz (up to 72%) showing metamorphic characteristics. Feldspars consist of relatively fresh microcline (up to 24%) with minor altered plagioclase (up to 3%). An increased content of phyllosilicates (up to 10%) are preferentially accumulated along bedding planes. Rock fragments consist of clay intraclasts that occur mainly in the more muddy laminae. Only a few zircon and tourmaline grains are present.

4.2.2.3. Fitzgerald #1, Mills County, W section 21, T71N, R41W.

Description of cuttings:

Fi-1 (2595-2600'). Thin section.

The cuttings are fine to medium grained arkoses with a clay cement. Quartz (up to 70%) is slightly recrystallized, and shows mostly straight extinction patterns. Feldspars (up to 20%) consist of microcline and orthoclase with a few albite grains. High content of opaque minerals, up to 5%. Minor rock fragments consist of claystone, dolomite cataclasites and a glassy groundmass altered to varying degrees

Fi-2 (2600-2605'). Thin section.

The cuttings are dominated by medium to coarse grained arkoses with a texture and composition as in Fi-1. In addition basalt with a micro-ophitic or intersertal texture can be recognized. They have a partly chloritized groundmass impregnated with iron oxides. The plagioclase laths are also altered to a mixture of kaolinite and sericite. The cuttings contain also minor basaltic tuffs and tuffites.

4.2.3. Nebraska.

4.2.3.1. Koutney #1, Saunders County, SE SE NW section11, T15N,R7E.

Description of cuttings.

Ko-86/5 (1690-1700'). Thin section.

The cuttings consist mainly of coarse grained lithic arkose. Quartz (up to 40%) with mostly undulose, mosaic extinction patterns and abundant inclusions of zircon, tourmaline, and rutile needles forms the main component of the rock. A minor amount of quartz grains show volcanogenic features. Feldspar (up to 20%) consists of fresh or altered microcline with minor orthoclase. Rock fragments in the lithic arkose (up to 30%) are made up of various sedimentary rocks, calcite cemented arkoses, sublitharenites, clay quartz arenites, different carbonate rocks, spherulitic siderite, claystone and a few altered basalts.

Ko-86/11 (1730-1740'). Thin section.

Cuttings of different rock types are present. Sandy dolomite and dolomites associated with fine grained subarkoses are dominant, together with lesser amounts of medium grained quartz arenite and ferruginous rock. The heavy mineral fraction is mostly pyrite and pyritic siltstone.

Ko-86/6 (1790-1800'). Thin section.

Shale, siltstone and mudstone dominate (up to 75%). They are associated with dolomite, dolomitic sandstone and quartz arenite similar to the rocks in Ko 86/11. Claystones consist mainly of illite.

Ko-86/8 (1890-1895'). Thin section.

Cuttings are dominated by oolitic ironstones, showing a concentric structure. They are composed of hydroxyl iron oxides.

Ko-86/7 (2260-2270'). Thin section.

The cuttings consist mainly of ferruginous claye shale, and siderite (with spherulitic texture) that is partially replaced by iron oxides.

Ko-86/9 (2300-2310'). Thin section.

Among the cuttings, quartz arenite with a clay cement is dominant. The rock consists mainly of quartz (up to 90%) exhibiting straight extinction patterns. All quartz grains have secondary overgrowths. Other cuttings are ferruginous rocks composed of a goethitic groundmass with quartz grains and calcitic pseudomorphs after feldspar.

Ko-86/12 (2570-2580'). Thin section.

Illitic/sericitic, and calcareous shale with abundant organic matter debris makes up the cuttings.

Ko-86/10 (2650-2660'). Thin section.

Three types of cuttings are recognized. The most common are illitic shale with a variable amount of organic matter. They are associated with dolomitic limestone, limestone with phosphoritic pebbles and pyrite crystals disseminated throughout the rock. Minor ironstones were also found.

4.2.3.2. Schroeder (Amerada) #1, Cass County, E section 26, T11N, R12E.

Description of cuttings.

Sch-86/4 (1570-1575'). Thin section.

The cuttings are dominated by very fine grained arkose with a clay/calcite, porous, contact cement. Quartz (up to 40%) appears to be volcanogenic. Feldspars, up to 40% by volume, are mainly microcline, microcline perthite, and orthoclase. They are sericitized, carbonatized and kaolinitized to varying degrees. A few altered plagioclase grains are present. Minor volcanic rock fragments consist of basalt, altered volcanic glass and tuff.

Sch-86/4A (1575'). Thin section.

Fine grained calcitic arkose. Quartz (up to 50%) with volcanic characteristics is dominant. Quartz grains are corroded by carbonate cement. Feldspars (up to 30%) consist of microcline, altered plagioclase and a few authigenic albite crystals. Rock fragments in the arkoses are very rare. A few basalt and diabase grains have been identified. The rock has a high content of heavy minerals, up to 10%. Most abundant are epidote (pistacite, clinozoisite), and opaque minerals, together with minor rutile, zircon, and hornblende.

4.2.3.3. Idhe #1, Seward County, SE NW section14, T10N, R4E.

Description of cuttings.

Id-1 (2830').

Sandstone with pink spots, red hematitic shale, and several fragments of granite-gneiss.

4.2.3.4. Sullivan #1, Lancaster County, NW NW NW.section 36, T9E, R5E.

Description of cuttings.

Su-1 (2310-2319').]

Granite wash. Orange to pink broken feldspar, partially kaolinitized. Medium to coarse grained, well rounded, some broken quartz grains.

4.2.4. Kansas.

4.2.4.1. Livingood #1 (Lumingood), Dickinson County, SE SE NW.section 13, T13S, R2E. (Precambrian, penetrated from 3039-4854 feet, is overlain by the Arbuckle)

Description of cuttings.

Livingood (3260-3810').

The section consists of vari-colored sandstones ranging from white to yellow to pink. The rock is probably weakly cemented, as cuttings consist nearly entirely of medium to fine grained disaggregated quartz grains with a variable amount of feldspar and minor mica. The proportions of these minerals suggest that we are mainly dealing with quartz arenites, subarkoses and rarely arkoses. Locally an increased amount of heavy minerals is observed.

Li-3 (3810-3820'). Thin section.

Various rock types as well as separate minerals were recognized. Dominant are quartz grains (up to 40%), that are poorly rounded, medium grained, and have straight or undulose extinction. Feldspars (up to 20%) consist of microcline, orthoclase, and perthite, that are altered to varying degrees. Among the rock fragments present, red, green, and black (organic) shales are most common, followed by ferruginous subarkoses and lithic arkoses. Minor phosphate replacement after faunal debris is observed.

Li-4 (3820-3828'). Thin section.

The composition of cuttings is similar to those in Li-3, except for a higher content of semiopaque ferruginous rock fragments.

Livingood (3828-4781').

The section is dominated by light colored sandstones. They are generally quarz arenites and rarely subarkoses because the amount of feldspar seems to be very low. The sandstones appear to be interbedded with mudstones of similar composition, as well as a few beds of gray-greenish shale.

Li-86/15 (4781-4783'). Thin section.

The rock is an arkose. Quartz, which makes up to 50% of the rock volume shows abundant secondary overgrowths, and intergrowth of rutile are common. Feldspars (up to 30%) consist of altered orthoclase and microcline. However, some fresh microcline grains with polisynthetic twinning occur. A few fresh plagioclase (oligoclase) grains are present. Rock fragments consisting of quartzite and chert are of minor importance. Fragments of illitic shales and ferruginous sandstones make up to 20% of cuttings.

Li-86/13 (4798-4804'). Thin section.

The composition of the cuttings is similar to Li-86/15. However, the rock becomes more miceaceous. Muscovite flakes make up to 10% of the rock.

Li-86/14 (4810-4820'). Thin section.

The cuttings have the same composition as in samples Li-86/13 and Li-86/14. The secondary quartz cement is locally enriched in iron oxides. Secondary porosity is developed.

4.2.4.2. Finn #1 (Catherine), Marshall County, NE NE NE.section 4, T4S, R7E, (Precambrian, penetrated from 2245-3900 feet, is overlain by the St. Peter Sandstone).

Description of cuttings.

Finn (2245-3900').

The section consist mainly of brown, brown-pink, yellowish-pink, pink-gray arkoses with a variable amount of clay-ferruginous cement. The psammitic fraction of the cuttings consist of medium to fine grained quartz and feldspar in variable proportions. In some samples the feldspar content is larger than quartz. The arkoses are probably not well cemented, because in the cuttings the mineral grains are disaggregated.

FC-10 (2718-2720'). Thin section.

Ferruginous shales with a high content of iron oxides (up to 70%), predominate. Locally, they are interbedded with laminae enriched in detrital psammitic material that contains quartz (up to 20%), feldspar (up to 5%), and mica (up to 5%). the shales are associated with clay mudstones of similar composition in which phosphatic pellets occur.

FC-9 (2910-2912'). Thin section.

The cuttings consist of siltstone, mudstone and claystone, with minor fine grained sandstone. All these rocks are quite ferruginous,limiting their study.In the psammitic fraction, individual, coarse grained, well rounded quartz grains, and minor feldspar and dolomite grains are observed.

FC 5/6.(3225-3228') Heavy mineral concentrate.

FC-8 (3800'). Thin section.

Volcanic rock fragments dominate the sample. They are mainly altered basalts, with plagioclase replaced by calcite, and iron oxides impregnating the dark groundmass. Voids in the basalt are filled with prehnite.

4.2.4.3. Ireland #1, Marshall County, SE NE NE.section 8, T5S, R7E, (Granite wash, penetrated from 2295-2360 feet, is overlain by the St. Peter Sandstone).

Description of cuttings.

Ireland (2295-2360').

In the upper part of the section the cuttings are dominated by cavings from the overlying Paleozoic section, consisting of light gray siltstone, pyritic siltstone, reddish shale and white gray dolomitic sandstone/limestone. Farther down the cuttings are mainly composed of medium to coarse grained, sometimes broken, quartz grains with a variable but relatively high amount of feldspars (20 to 40%). The rock is probably a weakly cemented arkose.

I-1 and I-2 (2350-2355'). Thin sections.

The composition of the cuttings is quite variable. Probably, a large part of the cuttings are cavings. Among the fragments that are thought to be derived from approximately this depth, coarse grained arkose and quartzitic arkose, together with a smaller amount of fine grained subarkose and quartz arenite make up the bulk of the rock. Separate quartz and feldspar grains account for 30 to 40% of the cuttings. Feldspar consist of relatively fresh microcline, together with a lesser amount of altered orhoclase and perthite.

4.2.4.4. Beach #1, Marshall County, NW NW SW section 3, T4S, R8E, (Pre-cambrian sediments, penetrated from 1454-2164 feet, overlain by the St. Peter Sandstone).

Description of cuttings.

Beach (1454-2164').

The section is composed of white-pinkish to dark-reddish sandstone, interbedded or intermixed with light or dark reddish and black shales. The sandstone is probably better cemented than in the other drill holes described above, because sandstone fragments predominate over individual quartz and feldspar grains. The proportion of quartz and feldspar suggests that the rock is an arkose or subarkose.

B-1 (1580-1590'). Thin section.

Various types of shale: illite-chlorite, ferruginous-illite, illite-chlorite with aleuritic quartz and illite with organic matter dominates over sandstone. Among the sandstone cuttings, fine-grained arkoses and arkosic wackes prevail over coarse grained arkoses. Quartz grains and quartz-clay cement are recrystallized. Quartz is mainly of metamorphic origin. Carbonate rock fragments with micritic organic remnants are common.

B-3 (2090-2100'). Thin section.

In this sample arkose and arkosic wacke (often with calcitic cement) predominate over various shale types. A high content of secondary epidote, together with smaller amounts of zircon, tourmaline and pyrite. The arkosic wackes are often micaceous.

4.2.4.5. Blaney #1, Marshall County, NE SW SW.section 3, T5S, R7E, (Precambrian, penetrated from 2420-2570 feet, is overlain by the St. Peter Sandstone).

Description of cuttings.

Blaney (2420-2570').

Due to poor fluid circulation and bad caving, the cuttings cannot provide reasonable information about the rocks penetrated. They contain geologic material from several hundreds or more feet.

Bl-1 (2435-2440'). Thin section.

A large part of the cuttings can confidently be correlated with the overlying Paleozoic rocks. They include organic-rich limestones, finely crystalline dolomites, dark organic-rich shales, and pyritiferous and clay mudstones. Rocks believed to Precambrian include fine grained calcitic subarkose rich in heavy minerals (tourmaline, opaques, and glauconite), and medium grained subarkose with illite cement.

Bl-2 (2460-2470') Thin section.

Three major rock types occur in the cuttings. They are arkosic and ferruginous siltstone, different types of shale, and various carbonate rocks. In the psammitic fraction, broken quartz and feldspar grains occur in equal amounts. The feldspar grains are sericitized. A few broken granitic rock fragments are also present.

4.2.4.6 Reese #1, Rice County, NE NE NE section 22, T19S., R.9W. (Precambrian sediments, penetrated from 3645-3820 feet, are overlain by the St. Peter Sandstone).

Description of cuttings.

Reese (3645-3820').

The sediments in this section consist of variously colored, weakly cemented subarkoses and arkoses interbedded with siltstones and mudstones of similar composition. The cuttings are contaminated.

Re-3 (3775-3780'). Thin section.

Three rock types are recognized in the cuttings. They are ferruginous, illitic-organic-rich calcareous shales, fine to medium crystalline carbonates,and fine to medium grained arkoses. The psammitic fraction is dominated by coarse grained, well rounded quartz grains, and often broken, smaller fresh microcline, perthite and orthoclase (up to 30%).

4.2.4.7. Hodgson #3A, Ellsworth County, C SE.section 32, T16S R8W (Precambrian sediments, Penetrated from 3773-3905 feet, are overlain by the Reagan Sandstone).

Hodgson (3773-3905').

The section is composed of light to dark reddish arkoses, having in part a clay or carbonate cement.

Ho-2 (3900-3905'). Thin section.

Many different types of rocks and minerals were recognized. Carbonate rocks, shales and ferruginous rocks are thought to be derived from the overlying lithology. The Precambrian sediments are believed to be represented by fine to medium grained arkoses, fine grained subarkoses and mudstones. The cement of arkosic rocks is clay or carbonate. In some of the arkoses the cement content increases to such a degree that the rock may be considered an arkosic wacke.

4.2.4.8. Neal #1, Marshall County, SW SE NE.section 5, T4S R8E (Precambrian sediments, penetrated from 1623-1715 feet, are overlain by the St. Peter Sandstone).

Neal (1623-1715').

The section is most likely composed of white, pinkish, yellow arkosic sandstone with alternating beds of minor siltstone having the same composition.

N-2 (1715'). Thin section.

Fine to medium grained arkose fragments dominate. They consist of quartz and feldspars that are poor to medium rounded, and well sorted. Fine grained arkose grades into an arkosic mudstone. Quartz grains are half plutonic, half metamorphic in origin. Other rock fragments present consist of shale, carbonates and cataclasites. Common heavy minerals are mainly zircon, epidote, tourmaline and opaques.

4.2.4.9. Crawford #1 (Wood), Clay County, SE SE SE.section 1, T7S R3E. (Precambrian sediments, penetrated from 3162-3255 feet, are overlain by the Arbuckle).

Crawford (3162-3255').

Very little geologic material is available for examination consisting mostly of quartz and feldspar grains, and some.black crystalline rock fragments.

WD-1 (3175-3180'). Thin section.

The rock fragments consist of shales, carbonates and ferruginous rocks. Minor quartz and feldspar grains. In addition variously altered fragments of diabase and microgabbro, having an ophitic and intersertal texture, are present. The mafic minerals in these fragments are altered to chlorite or serpentine.

WD-2 (3245-3250'). Thin section.

The rock fragments consist nearly entirely of volcanic rocks. They are diabases and microgabbros, or dolerites. They are relatively fresh. Plagioclase in the microgabbro is believed to be Ca-rich bytownite and anorthite. The basalts contain large augite crystals and also chlorite-serpentine pseudomorphs after olivine.

4.2.4.10. Sedlacek #1, Marshall County, SE SE NE.section 31, T4S R8E. (Granite Wash, penetrated from 1920-2264 feet; overlain by St. Peter Sandstone).

Sedlacek (1920-2264').

Cuttings are badly contaminated with cavings. The upper part of section probably consists mostly of sandstone, while some shales and mudstones appear to be interbedded in the lower part of the section.

Se-1 (2030-2035'). Thin section.

The cuttings consist of about equal amounts of various types of shale, carbonates and ironstone of probable Paleozoic origin, and arkosic sandstone and mudstone. The subarkoses are medium to coarse grained, with a highly recrystalized cement and abundant secondary overgrowths. The feldspar grains are much smaller than the quartz grains and consist exclusively of microcline. The finer grained sandstones and mudstones are rich in muscovite, biotite and chlorite.

Se-2 (2205-2210'). Thin section.

Cavings predominate. Among the sandstones that are thought to be Precambrian, sublitharenites are new to the section. The rock fragments are chert, chalcedony, quartzite, and basalt with a micro-ophitic texture. The arkoses have either a silica-clay, or carbonate cement.

4.2.4.11. Sugget #1, Marshall County, NW SW NW section 34, T2S R8E (Precambrian sediments, penetrated from 1780-2372 feet, are overlain by Pennsylvanian (Lansing) sediments).

Sugget (1780-2372').

In the cuttings two main rock types can be recognized occurring in variable proportions. The first are dark-gray or reddish-brown shales and siltstones (cavings). The second are partly broken quartz and feldspar grains. Limestone fragments occur in lesser amounts. Pyrite and chalcopyrite grains are common. The section is mostly composed of arkosic sandstones. In the lower part of the section quartz arenites with some alternating beds of mudstone and claystone appear to be quite common.

Su-3 (2300-2305'). Thin section.

Very fine grained clayey ferruginous subarkoses, quartz arenites and arkosic mudstones dominate. Other rock types, believed to be cavings, consist of black organic-rich shales, micritic limestone with organic remnants, dolomite stained with iron oxides. Separate mineral grains are: well rounded, coarse grained quartz, microcline and minor altered plagioclase.

4.2.4.12. Seneca #1 (Mayers) Nemaha County, NW NW NW.section 19, T3S R11E. (Sediments, penetrated from 750-3256 feet, are overlain by Pennsylvanian (Lansing) sediments).

Seneca (750-3256').

The section is dominated by two rock types occurring in the cuttings in variable proportions. The first are light-gray, gray, reddish, red to brown.colored dolomites and sandy dolomites. The second are red, light brown colored, poorly to well-cemented sandstones. The dolomites generally predominate over the sandstones.

SM-1 (2210'). Thin section.

The dominant component of the cuttings is broken granitic rock fragments together with separate quartz and feldspar grains. The granite (aplite) consists of quartz, microcline, orthoclase, kaolinitized plagioclase and green to brown biotite. Also present are ferruginous arkoses and feldspathic mudstones with an iron-rich cement. Minor rhyolites with a porphyritic texture, carbonates and shales were also noted.

4.2.4.13. Fagerberg #1, Pottawatomie County, SE SE NE.section 31, T6S R8E (Precambrian sediments, penetrated from 2114-2150 feet, are overlain by the St. Peter Sandstone).

Fagerberg (2114-2150)

The section is dominated by medium to coarse grained arkosic sandstone with minor volcanic rock fragments.

Fa-1 (2130-2140'). Thin section.

The dominant components are fine to medium grained arkoses to subarkoses and coarse grained quarzites with sutured textures. Quartz in the arkoses is mainly of plutonic origin with straight extinction and common inclusions of zircon, tourmaline and rutile. Feldspars consist of both fresh and variably altered microcline, perthite and orthoclase. Other rock types in the cuttings include: quartz arenites, phosphatic subarkoses and few shale and micritic limestone fragments.

4.2.4.14. Sherman #1, Washington County, SW SW NE section 13, T5S R3E Sandstone).

Sherman (3140-3264').

Cavings dominate the cuttings. The upper part of the section probably consists of pink-red, medium grained, polymictic sandstone. In the lower part of the section volcanic rock fragments become prominent.

SH-1 (3240-3245'). Thin section.

The cuttings consist mostly of fragments of fine grained subarkoses, mudstones and feldspathic shales. The rocks are impregnated-with iron oxides and contain: quartz, volcanic glass fragments, and minor feldspars and mica. The second important component of the cuttings are large fragments of basalts and diabases having a micro-ophitic texture, and a groundmass impregnated with abundant iron oxides. Minor micritic, organic limestones were also found.

4.2.4.15. Winkler #1, Riley County, C SE NE section 8, T6S R6E (Precambrian, penetrated from 2585-2728 feet, is overlain by the St.Peter Sandstone).

Winkler (2585-2728').

The rocks have previously been desribed as schists. However, the cuttings consist of finely crystalline, black volcanic rocks with gray-greenish spots. The matrix of these rocks is carbonatized.

Wi-1 (2580-2585'). Thin section.

The dominant rock type in the cuttings are microgabbros and diabases with an ophitic or micro-ophitic texture. The plagioclases are kaolinitized, sericitized, and carbonatized with the rock interstices filled with chlorite, opaque minerals and serpentine. In addition to the highly altered rock fgragments a few pieces of fresh dolerite were found. Other rock fragments, probably cavings, consist of shale, mudstone, quartz arenite, phosphatic mudstone and phosphoritic faunal debris (trilobites ?).

4.2.4.16. Beck #1A, Nemaha County, SW SE SE.section 14, T5S R12E (Precambrian, penetrated from 2710-2745 feet, is overlain by the St. Peter Sandstone).

Beck (2710-2745').

The cuttings consist of granite fragments with white to pink quartz and feldspar, and black and reddish shales.

Bk-1 (2705-2710'). Thin section.

Granitic rock fragments and broken quartz grains are the dominant rock type. The granite consists of quartz, microcline, plagioclase (oligoclase) and biotite. Plagioclase and microcline are kaolinitized to varying degrees. Shales, quartz arenites, subarkoses, siltstones, and phosphatic, pyritiferous, fine grained sandstones, occurring in about equal amounts, make up the rest of the cuttings..

4.2.4.17. Weakly #1, Marshall County, NW NW NE section 26, T5S R7E (Precambrian, penetrated from 2015-2030 feet, is overlain by the St. Peter Sandstone).

Weakly (2015-2030').

Well rounded, broken quartz grains, and white, pink feldspar dominate the Precambrian cuttings. Large amount of cavings are present.

W-1 (2015-2030'). Thin section.

Only a few quartz and feldspar grains are present. High content of Fe-Ti oxides. Fragments of sandstones, mudstones, and dolomitic sandstones, believed to be Paleozoic in origin, are present.

4.2.4.18. Kratochvil #1, Marshall County, SE SE SE.section 30, T5- S R7E (Precambrian, penetrated from 2500-2526 feet, is overlain by the St. Peter Sandstone).

Kratchovil (2500-2526').

The cuttings have been described as schists. However, no schist fragments were identified. Fragments of shales, carbonates, ferruginous rocks and cryptocrystalline volcanics are present.

Kr-1 (2510-2515'). Thin section.

Besides cuttings of probable Paleozoic origin, only a few Precambrian fragments, consisting of a volcanic groundmass highly impregnated with iron oxides, were identified.

4.3. PETROGRAPHIC CHARACTERISTICS OF CLASTIC CÁMBRIAN ROCKS ASSOCIATED WITH THE NORTHERN PART OF THE MRS (Surface Samples).

4.3.1. Low Rock Formation (Reno Member).

Sample 1/86. Collected near Lansing,Iowa

The rock is fine to medium grained arkose with a clay cement, that is locally dissolved. The main rock components are quartz (up to 40%), feldspar (up to 20%), glauconite (up to 20%), micas (up to 5%), and phosphorite (up to 5%). Quartz and feldspar grains are elongated, with common regeneration rims. Phosphates are mainly replacements after faunal debris (trilobites ?).

4.3.2. Ironton Formation.

Samples: 2a/86 and 2b/86. Collected near Galesville, Wisconsin.

Sample 2a/86 is a ferruginous, medium grained, quartz arenite with a clay cement. Quartz grains (up to 80%) are well rounded, moderately sorted and often coated with a thin film of iron oxides. Other rock components are microcline (less than 5%) and collophane replacements after faunal debris. A few zircon grains are present.

Sample 2b/86 is a fine grained, slightly laminated arkose with a clay cement, that is partially dissolved. Main component of the rock are poorly rounded quartz (up to 30%), microcline (up to 20%), glauconite (up to 20%), phosphorite (up to 20%), and minor biotite and muscovite.

4.3.3. Eau Clair Formation.

Sample 3a/86. Collected near Whitehall, Wisconsin.

The rock is a fine grained, highly recrystallized subarkose with a clay-phosphorite cement. Individual grains are elongated,giving rise to a slightly parallel texture. Also some parallel interbeds of trilobite-rich shales occur. The rocks consist of quartz (up to 50%), recrystallized euhedral microcline, orthoclase, and perthite (up to 20%), and phosphoritic faunal debris (up to 20%). The rock contains abundant heavy minerals, up to 3% by volume. The most common are: zircon, tourmaline, rutile, epidote, glauconite and opaques.

4.3.4. Mt. Simon Sandstone.

Samples: 4a/86 and 4b/86. Collected near Eau Clair, Wisconsin.

The rocks are fine to medium grained quartz arenites (4b/86) and fine grained subarkoses (4a/86). The rocks show a bimodal grain size distribution of fine grained angular, and medium grained, medium to well rounded quartz. The rocks consist of quartz (70 to 80%) with abundant liquid and stable inclusions (rutile, zircon), microcline (5 to 10%), and minor muscovite and biotite. A few rock fragments of cataclasite, chert and quarzite are present. Heavy minerals are rare, and include zircon and tourmaline.

4.3.5. Cambrian Rocks at the Contact with Basalts

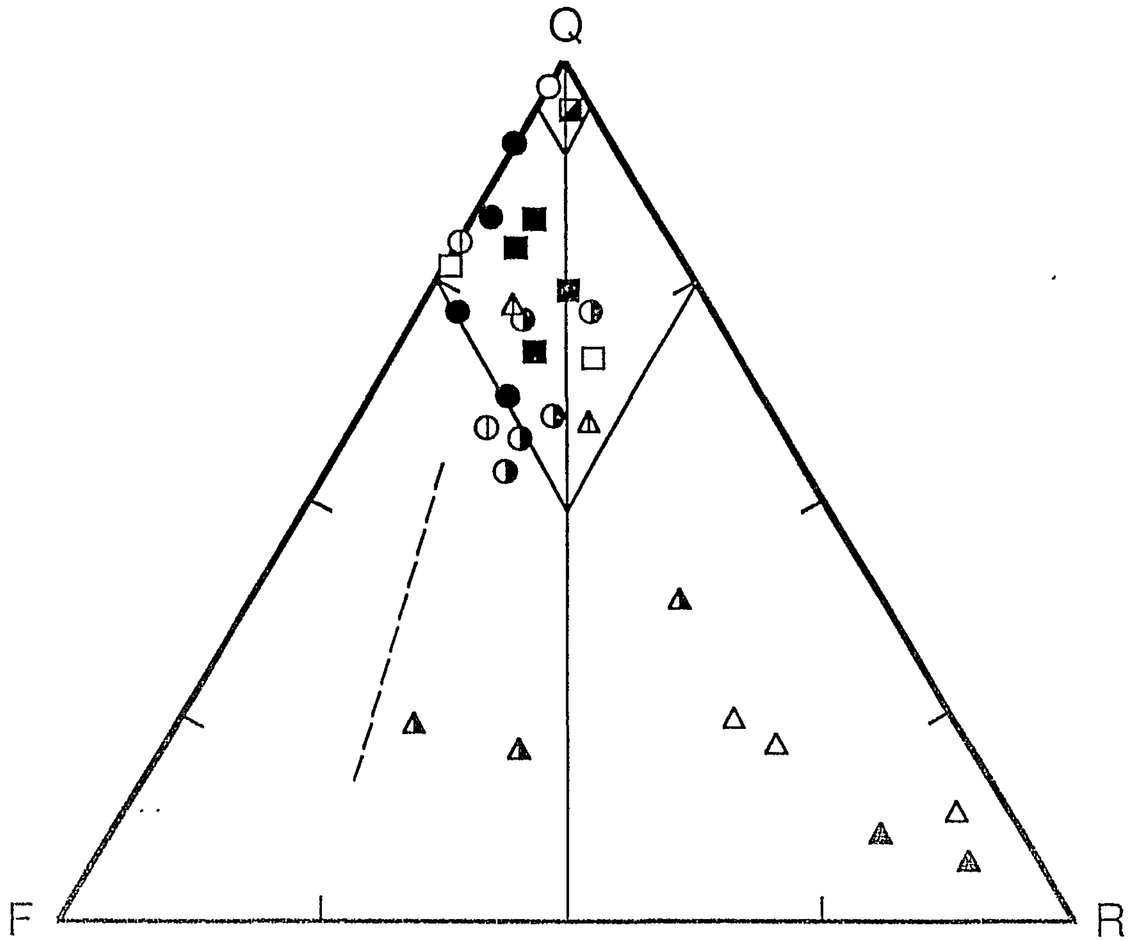
Sample 5a/86. 3 miles SW from St. Croix Falls, Minnesota.

The rock is a very fine grained, clayey subarkose alternating with feldspathic mudstone. The rock is predominantly composed of poorly rounded, tightly packed quartz (70%), and euhedral, recrystallized microcline (up to 20%), together with a few orthoclase grains. Fragments of the underlying basalts are common. The heavy mineral fraction is dominated by opaque minerals with a smaller amount of zircon, tourmaline, epidote, rutile and glauconite.

4.4. MODAL ANALYSIS.

The results of modal analysis of Precambrian sedimentary rocks associated with the central and northern portion (Michigan, Wisconsin, Minnesota and in part Iowa) of the MRS are shown in table 1. The thin sections that were made from well cuttings in the southern part of the MRS consist of relatively small rock fragments that may not be representative of the formation being penetrated by the drill. Thus the modal analysis of these rocks can only be considered to be semiquantitative in nature. Only the main rock components, without additional subdivisions, were considered. These results can not be compared statistically with the results obtained for the northern and central part of the MRS, and thus were not included in table 1. When available, they are mentioned in the description of the particular drill holes.

The results of the analysis show that major petrographic differences exist between the arkosic and volcanogenic sedimentary rocks of the MRS (figure 1). The psammitic volcanogenic sedimentary rocks are exclusively litharenites and lithic arkoses, while the arkosic rocks are mainly subarkoses, sublitharenites and rarely quartz arenites and lithic arkoses. On Pettijohn's et al. (1972) classification diagram the clastic rocks pretty well occupy the upper quartzose rocks corner (figure 1). Moreover, the majority of the rocks (about 80%) plot in the left or arkosic



Minnesota

- ○ Hinckley Sandstone
- ◑ Fond du Lac Formation
- ⦶ Well - Lonsdale 65-1

Michigan - Wisconsin

- △ Jacobsville Sandstone
- △ Freda Sandstone
- ▲ Nonesuch Shale
- ▲ Copper Harbor Conglomerate

Wisconsin

- □ Chequamegon Sandstone
- ◪ Devils Island Sandstone
- ▦ Orienta Sandstone

Iowa

- ● Wells - Lehman #1, McCallum #A-1 "Red Clastics" Precambrian

Figure 1. Petrographic composition of Precambrian sedimentary rocks of the northern portion of the MRS.

TABLE 1

	Formation Drill Hole Identification	Sample Symbol	QUARTZ (Q)			FELDSPAR (F)			ROCK FRAGMENTS (R)					Fe-Aggregates	Fe-muddy-clayey Lithoclasts	MICA AND CHLORITE				CEMENT (C)						MATRIX	PORES	OTHERS
			Quartz	Vein (Q)	Total (Q)	K-Feldspar	Plagioclase	Total (F)	Sedimentary	Igneous	Volcanic	Metamorphic	Total (R)			Muscovite	Biotite	Chlorite	Total Micas	Iron	Clayey	Quartz	Carbonate	Other	Total (C)			
CLASTICS	Chequamegon Ss	10b	43.3	14.4	57.7	16 0	-	16 0	0 2	-	-	0 6	0 8	-	-		-	-	-	3 8	0.4	1.0	-	-	5.2	9.6	10.5	0 2
CLASTICS	Chequamegon Ss	13	35.6	17.0	52.6	12.1	-	12.1	2.1	-	4.1	9 6	15.8	-	-	0 2	-	-	0.2	9.5	2.3	0.4	-	-	12.2	-	6.1	1 0
CLASTICS	Hinckley Isl.	2	59.6	2.4	62.0	-	-	-	0.2	-	-	0 7	0 9	-	5 9	-	-	-	-	-	9.0	7.2	-	-	16.2	-	14.8	0.2
CLASTICS	Devils Isl.	11	62.9	8.4	71.3	1 4	-	1.4	0.6	-	-	1 9	2 5	-	-	-	-	1 9	1.9	5 5	2 5	4.4	-	-	12 4	-	10 5	-
CLASTICS	Jacobsville Ss	22a	39.8	8.5	48.3	13.5	0 2	13.3	1.9	-	1.4	3 5	6.8	0.2	-	0 5	1 2	-	1.7	1.4	16.1	0.2	-	-	17.7	2.4	9 2	0 2
CLASTICS	Jacobsville Ss	23a	27.9	14.9	42.8	12.7	-	12.7	2.8	-	3 6	10 2	16 6	1 5	-	1 5	0 6	1.9	4.0	-	12.7	-	4.2	-	16.9	-	4.9	0.6
CLASTICS	Fond du Lac Fm	6a	36.4	4.8	41.2	18.0	-	18.0	3.4	0.2	0.5	8.9	13 0	-	-	1 6	1 4	0 7	3.7	17 1	-	-	2.0	-	19 1	-	3.6	1.4
CLASTICS	Fond du Lac Fm	6c	38.7	4.5	43.2	15 5	-	15.5	3.7	0 2	1 4	8 4	13 7	-	4 9	1 2	0 2	1.8	3.2	-	-	2.0	8.0	-	10 0	2 5	6.4	0 6
CLASTICS	Fond du Lac Fm	7a	39.1	14.2	53.3	15.7	-	15 7	2.1	0.2	1 7	4.1	8.1	-	-	0 8	0 8	1.3	2.9	6 7	2.1	0.8	0.2	1 3	11.1	2 4	5.6	0 9
CLASTICS	Fond du Lac Fm	7b	23.0	14.8	37.8	18.6	-	18.6	3.2	-	2.5	6 7	12 4	-	0 7	0 7	1 4	1.1	3.2	4 6	7 8	0.2	-	-	12.6	3 9	8.3	2 5
CLASTICS	Fond du Lac Fm	7c	40.3	13.0	53.3	9 2	-	9.2	6.5	0.2	2.8	2 8	12 3	-	-	0 2	0 4	2.6	3.2	2 2	9.8	-	5.0	-	17 0	0.4	3.5	1 1
CLASTICS	Orienta Ss	12a	52.6	9.1	61.7	9.0	-	9.0	1.8	-	0 6	1.6	4.0	-		1 0	1.6	0 2	2.8	-	10 7	-	-	-	10.7	3.6	8.0	0.2
CLASTICS	Orienta Ss	12b	43.5	9.8	53.3	9.8	-	9.8	1.5	-	0.4	2 2	4.1	-	5.4	0 2	0.4	0.2	0.8	15 0	2.8	0.2	-	-	18.0	-	7.8	0.8
CLASTICS	Orienta Ss	29a	31.0	24.3	55.3	10 7	-	10.7	-	-	6.8	4 5	11 3	-	1 0	-	-	-	-	10.4	3.5	1.6	-	-	15.5	1.2	5.0	-
CLASTICS	Orienta Ss	30a	32.7	14.0	46.7	14.2	-	14.2	2 3	-	1.2	6.1	9.6	1.4	-	0 5	0 5	-	1.0	8.9	7 2	1.4	-	-	17.5	0.5	8.9	0.2
VOLCANOGENIC SEDIMENTS	Freda Ss	14a	2.5	9.9	12.4	15 1	2.0	17.1	5.0	1.0	30.8	5.7	42.5	5 9	-	-	0 2	0.5	0.7	12 2	0 5	-	-	-	12 7	0 5	5 2	3 0
VOLCANOGENIC SEDIMENTS	Freda Ss	14c	2.1	4.8	6.9	5.7	0.7	6.4	5.3	2.1	48 6	6 6	62 6	2 8	-	-	-	-	-	2 3	0 2	0 2	14.7	-	17 4	-	3.2	0 7
VOLCANOGENIC SEDIMENTS	Freda Ss	28	5.8	4.6	10.4	10.9	3 3	14 2	6 5	-	29.2	4 4	40.1	6 5	-	-	0 2	2.8	3.0	5.8	-	-	2 3	11.0	19.1	-	3.7	3 0
VOLCANOGENIC SEDIMENTS	Nonesuch Shale	16a	10.6	16.7	27.3	10.8	0 2	11.0	10.2	-	4.7	15 7	30 6	4 9	-	0 4	0 4	3 5	4.3	1.6	0.4	-	-	13.2	15.2	-	2 4	4.3
VOLCANOGENIC SEDIMENTS	Nonesuch Shale	16b	3.2	7.8	11.0	14.3	4 3	18.6	1.7	-	1 3	14 1	17.1	10 2	-	0 9	2.6	12.4	15.9	0.9	12 8	-	0.2	7.6	21.5	-	2 2	3.5
VOLCANOGENIC SEDIMENTS	Nonesuch Shale	16c	3.7	7.2	10.9	16 6	4 7	21.3	1 4	-	1 0	9 3	11.7	7 4	-	2 1	6 2	11 8	20.1	2 3	11.4	0 8	-	8.7	23 2	-	2 5	2 9
VOLCANOGENIC SEDIMENTS	Copper Harbor Cgl	18a	4.0	1.4	5.4	11 2	1.4	12.6	2.2	0 8	54.6	2 2	59.8	3.0		-	-	0 4	0.4	2 8	-	2 0	9.4	2.0	16 2	-	2.6	-
VOLCANOGENIC SEDIMENTS	Copper Harbor Cgl	19	2.2	0.4	2 6	4 7	1 0	5 7	2.2	0 2	43 0	1 8	47.2	3.3	-	-	-	0.4	0.4	25 6	-	-	-	7 2	32.8	-	3.7	4 3
DRILL HOLES	Lonsdale (MN)	Lo-2	49.4	6.7	56.1	13 5	-	13.5	-		-	0 2	0 2	-	5 3	-	0 5	0.2	0.7	-	0.7	0.5	-	-	1 2	-	22.8	0 2
DRILL HOLES	Lonsdale (MN)	Lo-6	26.9	10.8	37.7	16.1	1 1	17.2	2 2	0 2	0 9	6.3	9.6	5 4	-	3 2	0 9	0 6	4.7	17 9	0.2	1.3	0.6	0 2	20 2	-	2.2	3.0
DRILL HOLES	Lehman (IA)	Lm-1	53.6	14.6	68.2	12 2	-	12.2	0 2	-		1 0	1 2	-	-	-	-	-	-	-	1.2	7.3	-	-	8 5	-	9.7	0 2
DRILL HOLES	Lehman (IA)	Lm-3	14.6	5 4	20.0	7.8	-	7 8	0 4	0 4	0 2	2.7	3 7	2.5	27 1	1 6	1 6	1.6	4.8	19 5	2.5	0.2	-	-	22 2	8 0	2.9	-
DRILL HOLES	McCallum (IA)	M-2	60.5	6.9	67.4	5 8	-	5.8	-	-	-	0.3	0.3	-	-	0 8	-	-	0.8	0 6	12 4	4 1	-	-	17 1	-	8 3	0 3
DRILL HOLES	McCallum (IA)	M-5	23.8	6.3	30.1	10 1	-	10.1	-	-	0 2	1 2	1 4	0.8	12 3	2 2	4 8	2.2	9 2	-	10.5	-	-	-	10 5	12.3	8 1	0 2

Table 1. Petrographic composition of volcanoclastic and clastic sedimentary rocks associated with the MRS.

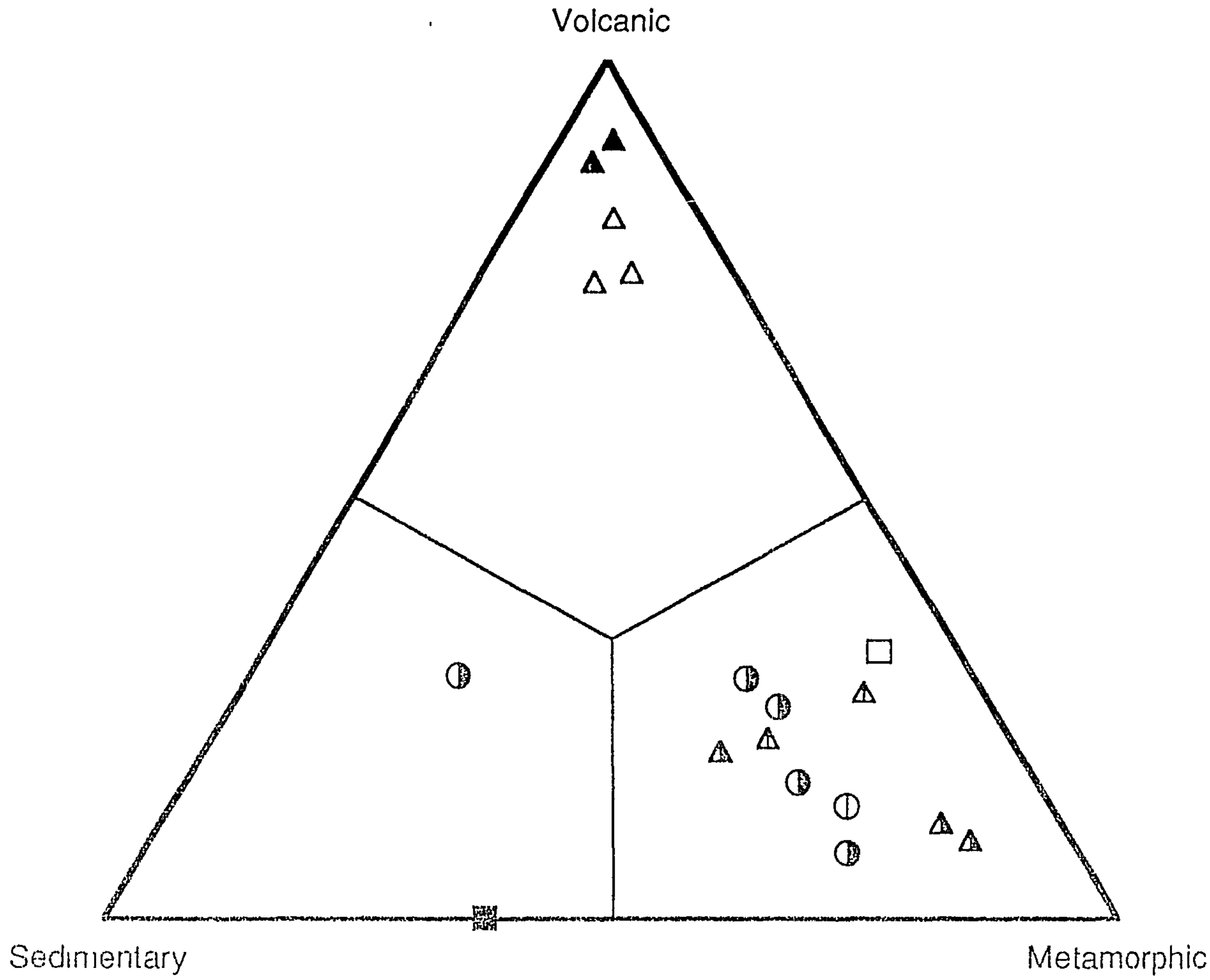
portion of the quartz-rich corner. The rocks that are transitional between arkosic and volcanogenic sedimentary rocks, such as the well samples from the Fond du Lac formation, plot in intermediate positions on the classification diagram (figure 1). In addition, they are also slightly enriched in volcanic and sedimentary rock fragments (figure 2).

An attempt was also made to contrast the petrographical character of the rocks deposited in the center (horst) and on the flanks (graben) of the rift. With the available data no differentiation could be discerned. Classifying the rocks according to the composition of the rock fragments shows very similar trends as the petrographic classification (figure 2). The volcanogenic sedimentary rocks are mostly volcanic arenites, while the arkosic rocks containing metamorphic fragments.are classified as phylarenites (only rocks that contain >5% rocks fragments were included). The samples of the Nonesuch Shale form an exception. Their position on the plot results from the pelitic to aleuritic character of the Nonesuch Shale. The fine grained volcanic rock fragments of the Nonesuch Shale have already been kaolinized, zeolitized and chloritized and this accounts for a large portion of the cement and the chlorite content. Additionally, both the quartz and iron content of these rocks are mainly of volcanogenic origin. Using Krinine's (1948) classification based on rock fragments the rocks of the Nonesuch Shale will plot as volcanic arenites.

Thus it appears that the metamorphic rocks are quite important components of the arkosic rocks examined. This can partially be attributed to the fact that the texture and composition of these rocks is such that in the weathering process they survive longer. They consist almost exclusively of fine grained, compacted, and recrystallized fragments. The plutonic rocks on the other hand are coarser grained, less hard and consequently contribute mostly to the mineral fraction of the newly formed rocks. The characteristic features of the quartz and feldspar grains of the upper part of arkosic sequence suggests that the material is mostly derived from granitic rocks.

As far as mineral components are concerned, the feldspar content of the volcanogenic sedimentary and arkosic rocks is low to medium, and does not show any significant or noticeable changes. Excluding the quartz arenites of the Hinckley Sandstone and the Devils Island Sandstone the feldspar content ranges from 5.7 to 21.3%, with an average of about 10 to 15% by volume. Significant amounts of plagioclase occur only in volcanogenic sedimentary rocks. These rocks are also characterized by their low quartz content, ranging from about 2.6 to 12.4% (only in sample 16a it is up to 27.3%). The quartz content of arkosic rocks is markedly higher, ranging from 37.8 to 71.3%. The differences in the quartz content of the rocks in this group can be related to their depositional environment. The lower quartz content is mainly compensated for by a higher content of pelitic and aleuritic material.

The important components of the volcanogenic sedimentary rocks are Fe-aggregates of magmatic or metamorphic origin, while the ferruginous arkosic rocks contain mainly muddy and clayey ferruginous intraclasts. The elevated amount of metamorphic ferruginous rocks in the Jacobsville Sandstone may be related to the



Minnesota

- ○ Hinckley Sandstone
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- ▩ Orienta Sandstone

Iowa

- ● Wells - Lehman #1, McCallum #A-1 "Red Clastics" Precambrian

Figure 2. Petrographic classification of Precambrian sedimentary rocks based upon the composition of their rock fragment content.

spatially associated Iron Formation. The amount of phyllosilicates is generally higher in the arkosic rocks. The exception is the Nonesuch Shale, which is enriched in both micas and secondary chlorites. Its depositional environment as well as extensive secondary metasomatic alteration are contributing factors. The composition and the amount of cement varies greatly in the rocks that were examined. The amount of zeolites can vary quite a bit and is high in some samples. These variations are believed to be controlled mainly by local conditions in the depositional environment, and as such are of minor significance for comparative studies.

The porosity increases with the maturity of the rocks and reaches its maximum in the quartz arenites of the Hinckley Sandstone and the Devils Island Sandstone formations.

The content of authigenic and accessory minerals such as,epidote, pyrochlore, apatite and xenotime is on the average two times higher in the volcanogenic sedimentary rocks.

4.5. HEAVY MINERAL ANALYSIS.

Analysis of heavy minerals is a proven and excellent method in.lithostratigraphic comparative studies. Thus, this method was employed to study the samples collected from outcrops in Michigan, Wisconsin and Minnesota (table 2). The composition of the heavy mineral fraction was also analyzed in Precambrian rocks derived from various drillhole penetrations (table 3). Table 3 also includes the results of heavy mineral determinations in rocks from Cambrian formations in Iowa, Wisconsin and Minnesota, that were collected for comparative purposes .

The heavy mineral analysis show some persistent trends that may be interpreted with respect to possible tectonic events.

There is a noticeable difference in the heavy mineral composition between volcanogenic sedimentary rocks (Oronto Group), and progressively more arkosic rocks containing lesser and lesser amounts of volcanic material (Bayfield Group). The volcanogenic sedimentary rocks, such as the Nonesuch Shale and the Freda Sandstone, generally have increased amounts of heavy minerals (up to 3% by volume). However, the bulk of the heavy minerals in these rocks consist of opaque and semiopaque minerals (ferroan metamorphic rocks, iron titanium oxides and in some cases sulphides), together with a small amount of mostly authigenic epidote. In contrast to the arkosic rocks, the epidote group minerals consist not only of pistacite and normal epidote but also of clinozoisite. The volcanogenic sedimentary rocks contain small amounts of zircon, garnet, and rutile and are completely devoid of tourmaline. Also, the amount of minerals generally associated with metamorphic rocks is very low.

The arkosic, relative to the volcanogenic sedimentary rocks, are characterized by an increased amount of zircon, tourmaline, garnet, rutile, and hornblende. These minerals constitute a larger fraction of the total amount of

TABLE 2

Formation	Sample Number	Location	Rock Type	Opaques	Semi-opaques	Muscovite	Biotite & Chlorite	Carbonates	Phosphate	Glauconite	Zircon	Tourmaline	Garnet	Epidote	Rutile	Apatite	Hornblende	Kyanite	Staurolite	Sphene & Anatase	Sillimanite & Andalusite	Pyroxene & Monazite	Spinel & others	Xenotime	Pyrochlore
Hinckley Ss	2	MN	Quartz Arenite	14.0	12.0	1 5	1 5	0.2	-	0.2	47 7	5 7	-	6 9	0.8	0 3	2 8	0.2	0.2	-	-	0.4	0 2	2.9	0.5
	3a			83.8	4 0	0.1	0.2	-	-	-	7.5	2 5	-	1 5	0 1	-	-	-	0 2	-	-	0 1	-	-	-
Chequa-magon Ss	10a	WI	Subarkose	20.8	11.8	0.7	0.9	-	-	-	53.6	5 6	0 2	3 5	0 3	0 2	2.2	-	-	-	-	-	0 2	-	-
	10b		Subarkose	46.6	9.0	0 4	0.9	-	-	-	33 4	6 7	-	1 9	0 4	0.1	0 5	-	-	-	-	0.1	-	-	-
	13a		Sublitharenite	80.0	6.4	0.1	1.4	-	-	-	5 8	4.1	0.1	0 7	0 5	-	0 7	0 1	-	-	-	0.1	-	-	-
Devils Isl.Ss	11	WI	Quartz Arenite	8.7	5.7	74.8	1.9	-	-	-	1.9	3.8	0.1	0 8	0 3	0 1	0 5	-	-	-	0.1	0.1	-	0 9	0.3
Jacobs-ville Ss	22a	WI	Subarkose	14 8	11.3	3 0	6 2	-	-	0 1	16 6	14 7	8 7	2 0	4 3	0 4	3 8	-	-	-	-	-	-	12.1	2 0
	23a		Sublitharenite	24.5	29 2	4 0	7.9	4.6	-	-	2 2	3.7	6 6	2 3	0 8	7.0	2 0	0 1	0.2	-	-	-	-	4.1	0.8
Orienta Ss	12a	WI	Subarkose	5.1	6 7	16 9	39.2	-	0 3	0 1	9 6	4.1	-	0 8	1 1	12.1	0.9	0.2	0 2	-	-	-	-	2.6	0.1
	12b		Subarkose	1.8	1.1	55 6	32.9	-	-	-	2.5	1.1	-	0 3	0 3	3.4	0.7	-	0 1	-	-	-	-	0.1	0.1
	29a		Sublitharenite	50.7	34 5	2 6	0 5	-	-	-	1.4	1.6	3.4	1 2	0 4	1 8	0.9	-	-	-	-	-	-	0.8	0.2
	30a		Subarkose	56.2	22.7	1.5	2.9	-	-	0 1	5 3	2.9	0.1	0 7	1 1	4 5	0 6	-	-	-	-	-	-	1.3	0.1
	30b		Subarkose	26 1	24 0	2 3	15 3	0 2	-	-	7 6	3 5	0 2	1 5	0 7	10 0	0 3	-	-	0 9	0.1	-	-	5.8	0.5
Fond du Lac Fm	6a	MN	Subarkose	1.3	79 8	3 5	7 6	-	0 1	-	0 8	1 1	0.2	0 5	0 2	4 1	0 4	-	-	-	0 1	-	-	0.2	0.1
	7b		Lithic arkose	22 5	54.6	5 5	7 6	-	-	-	1.4	2 1	0.1	0 3	0 2	4 7	0.3	-	-	0 2	0.1	-	0 1	0 2	0 1
	7c		Lithic arkose	23.7	22.0	1 5	2 3	29 5	0 1	0 4	2 5	2 6	1 1	0 7	0 5	4 9	0 3	1.0	-	0.3	-	0.1	-	0.1	6.5
Freda Ss	14b	WI	Litharenite	50 0	27 1	-	0.5	2.1	-	-	0.4	-	0 8	14 5	0 2	2 3	-	-	-	-	-	-	-	-	2.1
	14c		Litharenite	19.1	27.6	0 2	0.8	18.1	-	0 1	0 2	-	0 2	28 5	0 2	0 3	-	-	-	-	-	-	-	-	4.7
	28		Litharenite	23 8	53 6	0 6	8.1	2 1	-	0 1	0 1	-	2 1	8 6	-	1.1	0.1	-	-	-	0 1	-	-	-	-
Nonesuch Shale	16c	WI	Lithic arkose	14.6	50.1	2.7	19.9	-	-	0 3	0.1	0 1	0 7	10 1	0 2	0 7	0.1	0 1	-	-	-	-	-	-	0.3
Copper Harbor Cgl.	18a	MN	Conglomerate	49 2	47 2	0 3	0.1	0.9	-	0 1	0 4	-	-	0 3	0 2	1 2	-	-	-	-	0 1	-	-	-	-

Table 2. Heavy mineral composition of volcanoclastic and clastic sedimentary rocks associated with the MRS (outcrop samples).

TABLE 3

Formation Drill Hole Identification	Sample Number	Location	Rock Type	Opaques	Semi-opaques	Muscovite	Biotite & Chlorite	Carbonates	Phosphate	Glauconite	Zircon	Tourmaline	Garnet	Epidote	Rutile	Apatite	Hornblende	Kyanite	Staurolite	Sphene & Anatase	Sillimanite & Andalusite	Pyroxene & Monazite	Spinel & others	Xenotime	Pyrochlore
McCallum A-1	M-2	IA	Subarkose	16.5	35.3	9.4	0.4	-	-	-	19 8	1.5	0 7	1 7	0 3	-	0.1	-	-	-	-	0.1	-	1 3	12 9
	M-4	IA	Subarkose	45.1	21.2	7 2	4.5	4.8	-	-	11.1	2 7	0 1	0 7	0 5	-	0 3	-	-	-	-	-	-	1 5	0.3
	M-5	IA	Subarkose	12.5	18.2	12.5	20.4	-	0 4	1.1	14 7	1.9	0 1	2 0	1 8	8.6	0 1	-	-	-	-	-	-	4 5	1.2
Lonsdale 65-1	Lo-6	MN	Lithic arkose	31.5	43.2	2.7	2.0	-	-	-	2.1	0.4	1 5	12 7	0.4	3 0	-	-	-	0.1	-	-	-	0.4	-
Lehman #1	Lm-2	IA	Subarkose	8.0	9.0	16.5	45.0	-	0.1	0.9	5.2	2.3	-	0 9	1 0	8.3	0 3	-	-	-	-	-	-	2.4	0.1
	Lm-3	IA	Sublitharkose	37.0	39 3	2.0	7 8	0.2	-	0.2	3 8	1.7	0 1	1 1	0 5	4 6	0 3	-	-	-	-	-	-	1.3	0.1
Schuette #1	S-1	MN	Subarkose	52.5	26.2	0.6	0.5	1 2	-	-	1.2	1 0	1 7	0 4	0.6	3 7	0.1	-	-	0.1	-	-	0.1	9.8	0.3
Finn #1	FC 5/6	KS	Arkose	47 4	26.6	0.7	1.2	5.4	-	0.1	5.9	0.8	0 8	1 5	1 3	6.0	0.1	-	-	-	-	-	-	2.0	0.2
Koutney #1	86/9	NE	Quartz Arenite	64.5	8.3	-	0.1	23.5	-	-	1.5	1.0	0 5	0 3	-	0.1	0.1	-	-	-	-	-	-	0.1	-
Eau Clair Fm	3a/86	WI	Subarkose	9.8	7.1	1.6	0.6	-	17.9	0.3	29.5	27 5	0 6	4 8	-	-	0.3	-	-	-	-	-	-	-	-
Low Rock Fm	1/86	IA	Sublitharkose	0.3	0.5	5.5	0.5	50.5	17.0	12 0	2.7	2 8	7 0	0 2	0 6	-	-	-	-	0 1	-	-	-	0.3	-
Ironton Fm	2a/86	WI	Quartz Arenite	0 7	0.6	0.2	-	0.1	93.4	-	1.1	0 7	3 1	-	0 1	-	-	-	-	-	-	-	-	-	-
Mt. Simon Ss	4a/86	WI	Subarkose	38 8	7.8	4.2	2.5	-	-	-	26.2	10.5	3 1	3 1	0 8	-	1 7	-	-	0 2	0 2	-	-	0 8	0.1
	4b/86		Quartz Arenite	55 0	2.0	3 6	-	-	-	-	16.7	8 3	6 4	4 0	0 6	-	-	-	0.1	-	-	-	-	1.0	0.3
St. Croix Falls	5a/86	MN	Subarkosic Wacke	52.2	10 0	2.6	0.2	-	1 7	1 0	15.3	11.2	2 1	1 5	1 3	-	0.1	-	-	-	-	0 1	-	0.7	-

Table 3. Heavy mineral composition of Precambrian and Cambrian outcrop samples and drill hole cuttings associated with the MRS.

heavy minerals in the more mature rocks. The rocks of the transitional Orienta Sandstone and Fond du Lac Formations are characterized by elevated amounts of partly authigenic apatite. Some inconsistencies in the make-up of the heavy mineral composition of the arkosic rocks may be attributable to differences in the local environment of deposition. For example, the very fine grained quartz arenite (sample No. 11) of the Devils Island Sandstone was deposited in a low energy, lacustrine environment, resulting in an extremely high muscovite content and a lower heavy mineral content.

The amount of opaque and semiopaque minerals (rock fragments) in the heavy mineral fractions varies from about 3 to 90%, but exceeds in most cases 40%. Since the individual minerals or components of this group could not be recognized using the methods employed in this study, they could not be used for comparative studies. In some samples (e.g. 3a and 13a) the content of the opaque minerals is extremely high. Further investigations (polished section examinations) are necessary to determine the composition and possible provenance of the opaque and semiopaque minerals.

The variations in the amount of biotite and muscovite present in the rocks, is thought to be a function of the conditions in the local depositional environment. However a persistent trend towards a lower content of these minerals seems to be characteristic of older volcanogenic sedimentary rocks. The amount of phosphorite and glauconite in all Precambrian rocks examined is generally low.

The heavy mineral composition of core samples is characterized by elevated amounts of zircon and tourmaline and low contents of epidote (except in sample Lo-6), corresponding to the heavy mineral composition of the upper clastic rocks. They also show increased amounts of apatite characteristic of the Orienta Sandstone and the Fond du Lac Formations.

The heavy mineral fractions of the Cambrian formations are characterized by their generally high content of zircon, tourmaline and garnet. The garnet content in the Cambrian formations is larger than in all the Precambrian rocks examined. Another very important feature of the heavy mineral composition (excluding lower Mt. Simon) of the Cambrian relative to the Precambrian rocks is the high content of phosphorite faunal debris and glauconite.

5. COMPARATIVE PETROLOGY VERSUS STRUCTURAL DEVELOPEMENT

The results of the petrographic and lithostratigraphic studies suggest that the sequence of Precambrian volcanic and sedimentary rocks correlate well with major geotectonic events that affected the MRS. The initial opening of the rift gave rise to the eruption of a series of mafic volcanic flows, and emplacement of shallow mafic intrusives during a relatively short time span of up to 100 m.y. During the extensional phase, the basins that formed were initially filled with sedimentary materials mostly derived from the mafic rocks within the rift. With the waning of the extensional phase and the change to a compressional tectonic environment the basins were being filled up with materials that were increasingly derived from areas surrounding the rift. Vertical movement on faults, giving rise to the formation of horsts and grabens, had a great influence upon the topography. This in turn resulted in erosion and weathering of sedimentary rocks within the rift, and subsequent deposition of second-cycle sediments. These factors determined to a large extend the nature of the rocks found within the rift zone.

Our initial studies seem to indicate that the general succession of rock types characteristic of the stage of development of the rift system can be recognized in a gross sense. The geology of the Precambrian subcrop does vary widely from place to place. This can be attributed to tectonic processes and events that affected the area during the Precambrian and even as late as the Early Mississippian. High angle normal and reverse faults, and overthrusting may have juxtaposed rocks of different kinds and of widely different ages. One example is the 1195 m.y. old gabbro in the Poersch # 1 drill hole in Washington County, Kansas. It is exposed at the Precambrian basement surface and overlies an 8000 feet section of volcanic and sedimentary rocks, some of which are believed to be younger than the gabbro.

The general succession of rocks consisting of mafic volcanics overlain by volcanogenic sediments and still younger arkosic rocks can be recognized in the materials studied from along the length of the rift. The sedimentary rocks will be discussed in more detail in the following sections.

5.1. VOLCANOGENIC SEDIMENTARY ROCKS.

The volcanogenic sediments of the Oronto Group and equivalent Solor Church formation represent a depositional system that developed in basins during the final stages, and directly after cessation, of volcanic activity. The lowest unit of the Oronto Group is the Copper Harbor Conglomerate, which conformably overlies the Middle Keweenewan lavas and locally interfingers with them. It, in turn, interfingers with and passes gradationally into the overlying Nonesuch Shale, which is probably conformably overlain by the upper unit of the Oronto Group, the Freda Sandstone (Myers 1971; Daniels,1982). This depositional sequence suggests that no major geotectonic activity occurred within the MRS during sedimentation of entire Oronto Group.

The petrographic composition and depositional structures of the Copper Harbor Conglomerate and associated sandstones suggest that their material was derived mostly from nearby associated volcanic rocks, and was deposited in a prograding alluvial fan environment (conglomerates) and shallow water, fluvial fan environments (Daniels 1982).

Deposition of the Nonesuch Shale (Jost 1968, Ehrlich and Vogel 1971, Hubbard 1975) occurred in a changing depositional environment. The rocks were deposited in a generally shallow water, lacustrine environment of rift-flanking basins, that were created by tectonic and/or volcanic activity disrupting and modifying existing drainages. Thus it is quite likely that volcanic activity was still active during the deposition of the Nonesuch Shale both in close proximity and farther away. Activity farther away resulted in the contribution of a large share of the intermediate and acid pyroclastic material in the Nonesuch Shale. The nearby quite similar. The other important feature of the Solor Church rocks encountered in the Lonsdale 65-1 drill hole is the occurrence of organic rich bituminous shale. This may be of importance for base metal prospecting in areas of the MRS south from the White Pine deposit.

Equivalent rocks of the Oronto Group/Solor Church formation have not been recognized in any of the drill holes in Iowa, Nebraska and Kansas. Some problems exist with the interpretation of certain drill hole cuttings in Kansas that contain fragments of organic-rich black shales. In most cases they can confidently be recognized as cavings from the overlying, shale-rich, Paleozoic units overlying the Precambrian. In the Beach #1 sequence, the composition of the cuttings and the high epidote content may be indicative of Solor Church Group equivalent rocks. However, interpretation of the geophysical log argues against such a correlation.

5.2. CLASTIC ROCKS.

The clastic rocks show more structural, textural, petrographical and spatial diversity than the underlying volcanogenic sedimentary rocks. The rocks of the Bayfield Group and equivalent formations could have been deposited at any time after cessation of rifting and the onset of marine Late Cambrian (Croaxian) sedimentation. The generally uncomformable contact between the volcanogenic sedimentary rocks and the overlying clastic rocks, marked by a basal conglomerate, coincides roughly with the change from an extensional to a compressional tectonic regime. The deposition of clastic rocks occurred in basins bounded by high-angle normal and reverse faults that show considerable displacement.

The lithology of the Bayfield Group in Wisconsin, consisting of 99% sandstone and only 1% shale (Thiel 1956), is relatively uniform in composition. The sedimentary sequence of the Jacobsville Sandstone in Michigan, and the Fond du Lac Formation and Hinckley Sandstone in Minnesota is similar compared to the Bayfield Group of rocks in Wisconsin. In Iowa (Anderson et al., 1987) shale predominates over sandstone and siltstone in the Fond du Lac Formation. The results of the materials studied for this report suggest that even more pronounced differences in lithology occur in presumed equivalent rocks in southern Nebraska and Kansas. We believe that some of these differences can be attributed to differences in the local depositional environment.

Some of the factors that influence, determine, or modify the environment are the overall geometry of the sedimentary basins, including their depth, width, length, and the vertical gradients along the edges of the basin, the presence of paleohighs, tectonic activity, and the composition of the crystalline basement. The composition and the age of the crystalline source rocks changes along the length of the rift. The basement rocks associated with the southern part of the rift are thought to be younger than those with the northern portion (Van Schmus and Bickford 1989). Significant vertical displacements and erosion of Precambrian strata is believed to be responsible for the variable lithologies encountered in northern Kansas.

The homotaxial petrographic parameters of the Bayfield Group of rocks and related formations in Michigan and Minnesota show that these arkosic rocks have similar characteristics. The lithostratigraphic composition of these rocks can be contrasted with the volcanogenic sedimentary rocks of the Oronto Group. The most important differences include: 1) the composition of the heavy mineral suites; notably the large share of minerals such as zircon, tourmaline, garnet, rutile and hornblende, derived from plutonic and metamorphic sources, in the arkosic rocks. 2) the petrographic composition of the arkosic rocks, including the higher content of quartz with its variable provenance, the lack of plagioclases, the lower content and different composition of rock fragments, different types of cement, the larger porosity, and the increasing maturity of the sediments.

The petrographical parameters may be used to correlate clastic rocks along the MRS extension to the south, or to assign Precambrian arkosic sediments to the lower or upper part of the clastic sequence.

The composition and lithology of the Orienta Sandstone and the Fond du Lac Formation, consisting of conglomerates, sandstones and siltstones that generally occur in repetitive upward fining sequences, suggest that the material was derived from two different sources. The first source of sediments are exposed volcanic rocks and immature Oronto Group sediments. Secondly, and of equal importance, are metamorphic, plutonic and sedimentary rocks exposed along the shoulders of the rift. These materials were deposited in a fluvial, lacustrine to alluvial fan environment (Tryhorn and Ojakangas 1972). Thus the Orienta Sandstone and the Fond du Lac Formation, when contrasted with the overlying lithologies, have an equal amount of volcanic and other rocks fragments, a lower petrographic maturity, a higher amount of authigenic minerals such as apatite and chlorite, and a different cement composition.

The petrology of the Hinckley and Devils Island sandstones suggests that they were deposited during a period of prolonged crustal stability. The area associated with the rift probably consisted of an extensive peneplain and the sediments consist mostly of reworked older sedimentary units. These units can be characterized as pure quartz arenites in composition, with recrystalized quartz, abundant overgrowth textures, a large amount of quartz in the cement, and secondary porosity.

The petrographic composition of Chequamegon Sandstone suggests that minor tectonic changes took place within a geotectonic environment, that had been stable for a long time (possibly related to tectonic activity in the southern part of the US. Midcontinent). This resulted in larger supply of feldspar and different rock fragments. The petrographic composition and the maturity of the rocks allows us to distinguish Chequamegon Sandstone from Orienta and Fond du Lac sandstones. However, the distinction between the Cheguamegon Sandstone and Hinckley Sandstone is not so obvious.

It appears that it will be quite easy to distinguish Precambrian arkosic and volcanogenic sedimentary rocks from the overlying Late Cambrian sediments, using petrographic methods. In some locations there is a pronounced angular unconformity between the two systems. The heavy mineral composition of Cambrian rocks is characterized by a high content of phosphoritic faunal debris and the common occurence of glauconite, together with high contents of zircon and tourmaline. The rock fragments are dominated by different types of sedimentary rock, while the mineral components indicate a marine depositional environment. The lower Mt Simon sandstones show petrographic and heavy mineral compositions that differ greatly from the other Cambrian formations examined. In part they are comparable to the Hinckley Sandstone, and in part with the standard Rice Formation and Chequamegon Sandstone.

The lithostratigraphic parameters of the clastic rocks in the Lake Superior area can be used to correlate equivalent units along the MRS. In the northern part of the area the Jacobsville Sandstone may be correlated with certain parts of the basal conglomerate of the Orienta Sandstone (sample 23d), with the Orienta Sandstone, (samples 23a, 23b and 23c), and with the Devils Island Sandstone (samples 22a and 22b).

To the south comparative petrology will be discussed on a state by state basis.

5.2.1. Minnesota

The composition of quartz arenite and subarkose in the Lonsdale 65-1 samples, Lo-1, Lo-2 and Lo-3 (900 to 947'), with their increased level of secondary porosity, and common mineral overgrowths indicates that they may be equivalent to the Hinckley Sandstone. Whether the underlying sediments belong to the Solor Church Formation (Morey 1977), looking at the comparative petrology, may be debatable. The nature of the sediments and the petrographic composition of main rock-forming minerals suggest a possible Fond du Lac Formation association. However,other parameters such as the composition of the heavy mineral suite, and the occurrence of bituminous shales suggest a Solor Church Formation association. At the present stage of investigations we favor that interpretation.t

5.2.2. Iowa.

The samples of the upper portion of the Lehman #1 drill hole (Lm-1 and Lm-2 (2922')) show homotaxial characteristics similar to the Hinckley Sandstones. The rocks in the lower portion of the drill hole are very similar to the Fond du Lac Formation of Minnesota. Precambrian rocks penetrated in the McCallum #1 drill hole correspond to the upper part of the clastic rocks. Some of the characteristics, such as the high quartz content, the recrystallization of the quartzitic cement, and the abundant overgrowths may be indicative of the Hinckley Sandstone, while other features such as the increased amount of feldspar, the elevated amount of phyllosillicates, and fragments of metamorphic and sedimentary rocks suggest a similarity to the Chequamegon Formation. In the Fitzgerald #1 drill hole, the Lower Mt. Simon formation, with a petrographical composition astonishingly resembling the Chequamegon Sandstone rests directly on basalts. This may be added evidence for Anderson's et al. (1987) opinion that the lower portion of the Mt. Simon Sandstone may in some areas be correlateable to the upper part of the Precambrian clastics.

5.2.3. Nebraska.

Samples of four drill holes were examined. In the Koutney #1 drill hole, the section from 1690 to 2270' is identified as the St. Peter Sandstone and younger sediments. Sample Ko-86/8 is composed of oolitic ironstone that typically occurs in the St. Peter Sandstone of this area. The section from 2300 to about 2500' is composed of quartz arenites with petrographic characteristics suggestive of the Hinckley Sandstone. The lowermost part of this section is equivalent to sediments of the Fond du Lac Formation in Iowa. The Precambrian rocks of the Schroeder # 1 drill hole show sedimentary and petrographic similarities to the lower portion of Koutney #1 drill hole, and to some Precambrian rocks in Kansas, that are also thought to correlate with the Fond du Lac Formation. The homotaxial characteristics of the Idhe #1 Precambrian sedimentary rocks are similar to the standard Rice Formation rocks of Kansas and correlate with the uppermost part of the arkosic sequence. The samples of the Sullivan #1 drill hole consist of rocks assigned to the granite wash.

5.2.4. Kansas.

Precambrian rocks found in Kansas fall into four main categories (Table 4). Three of these may be recognized as distinct units that are petrologically similar to the clastics of the Lake Superior area. It appears that all three units are penetrated in the Livingood #1 drill hole. Another important factor that facilitated the correlation is the suggestion that the Hinckley Sandstone and equivalent rocks may be traced southward along the MRS into the subsurface of Iowa, Nebraska and Kansas.

The uppermost unit in the Livingood #1 drill hole (samples Li-3 and Li-4, from 3260 to 3823') is believed to be equivalent to the so-called standard Rice Formation. It is composed of reddish, pink, fine to medium grained, subangular, poorly rounded feldspathic sandstone (mostly subarkose), rarely arkose or quartz arenite. The sediments making up this unit are not solely the product of erosion of the MRS, but also may include detritus shed from other nearby areas such as an ancestral Central Kansas Uplift. Sediments similar to the standard Rice Formation have also been found outside the rift system. The petrographic composition, lihology and depositional features of the Rice Formation may be correlateable with the Chequamegon Sandstone of Wisconsin, the lower barren part of the Mt. Simon Sandstone in Minnesota and Iowa and the Red Clastics of Nebraska.

The lithology and petrographic characteristics of the sediments in the Livingood #1 drill hole from 3828 to about 4700 feet are analogous to the Hinckley Sandstone. They are composed of white to tan quartz arenites with minor subarkoses and siltstones. Abundant quartz overgrowths, development of secondary porosity, and quartzitic cement are the major petrographical factors indicating a common origin of these rocks with the Hinckley Sandstone and

TABLE 4

Well	Location	FORMATIONS—CLASTICS				FORMATIONS—VOLCANO-CLASTICS/BASEMENT	
		Rice Formation Chequamegon Ss. Mt. Simon Ss.	Hinckley Ss.	Fond du Lac Formation	Granite Wash	Basalts other Volcanics	Granites
Livingood #1	13-13S-2E	3260-3828	3828-4700	4700-4865			
Finn #1 (Catherine)	4-4S-7E			2245-3800		3800-3900	
Ireland #1	8-5S-7E				2295-2360		
Beach #1	3-4S-8E			1454-2164			
Blaney #1	3-5S-7E	2420-2500					2500-2570
Reese #1	22-19S-9W			3645-3880			
Hodgson #3A	32-16S-8W			3773-3905			
Neal #1	5-4S-8E			1623-1715			
Wood #1 (Crawford)	1-7S-3E		3162-3175			3175-3255	
Sedlacek #1	31-4S-8E	1920-2264					
Suggett #1	34-2S-8E	1780-	-2372				
Meyers #1 (Seneca)	19-3S-11E	750-?		750-?			2210-3256
Fagerberg #1	31-6S-8E			2114-2150			
Sherman #1	13-5S-3E	3140-3240					
Winkler #1	8-6S-6E					2595-2728	
Beck #1	14-5S-12E						2710-2745
Weakley #1	26-5S-7E	2015-2030					
Kratchovil #1	30-5S-7E					2500-2526	
Reilly #1	20-11S-3E					3170-3960	

Table 4. Preliminary lithologic comparison of volcanoclastic and clastic rocks in cuttings from drill holes in Kansas.

equivalent rocks found in a wide belt from Nebraska to Minnesota. Thus it may be possible to use the name Hinckley Sandstone with respect to similar rocks in Kansas.

A third distinct unit has been encountered in the Livingood #1 drill hole at the depth from 4720 to 4854 feet in samples Li-86/13, Li-86/14 and Li-86/15. This unit is best developed in Kansas in the Finn (Catherin) #1 drill hole where it is composed of pink to red arkose with a relatively high content of feldspar (up to 50% by volume). In contrast to the standard Rice Formation the sand grains are fairly well sorted and coarser grained. The most common heavy mineral of this formation is generally fresh magnetite. The lower portions of the sections examined are often micaceous, and contain an increased number of finer grained intervals (shales and mudstones). The cement in the lower portion of the formation is often dolomitic. The major homotaxial petrographic factors of this unit correlate well with the rocks in the Schroeder #1 drill hole in Nebraska, the lower portion of Lehman #1 drill hole in Iowa and the Fond du Lac Formation in Minnesota and Iowa. Local factors are believed to influence the specific composition and structure of this unit in Kansas.

The fourth category of rock recognized in Kansas is the so-called Granite Wash. It is residual material derived from weathering and erosion of the granitic basement rocks widely exposed in the area. Its thickness can vary greatly from a few to several hundred feet. No age can be assigned to the rocks of the Granite Wash, since they could have accumulated during a long time span.

The general stratigraphic succession is shown in table 5. The distribution and nature of the Precambrian sedimentary rocks that are in contact with the overlying Paleozoic formations, changes drastically over relatively short distances. This suggests a complicated weathering history in northeastern Kansas and southern Nebraska, coupled with a complex tectonic history, characterized by substantial vertical movement

This report includes only preliminary findings of the 11,300 feet deep,Texaco, Poersch #1 drill hole, completed in 1985 in Washington County, Kansas. Detailed sampling, examination, chemical analysis, thin section-and related studies on recently released core material is in progress, and hopefully will contribute significantly to our understanding of the rocks discussed in this report.

6. SUMMARY.

Even though the conclusions reached and the correlations proposed are very tentative as a result of the limited amount of material examined as part of this study, the petrographical and mineralogical studies of the Upper Keweenawan volcanogenic sedimentary and arkosic rocks associated with the MRS provide some insight in its structural and depositional development. Lithological, petrographical, and regional differences exist in both the aerial distibution and the nature of the sedimentary rocks encountered in the drill holes. But the major tectonic events that governed the sedimentation along the entire length of the MRS provided basic links between local lithologies. Petrographical studies providing

Table 5

Unit	Kansas & Nebraska	Iowa & Minnesota	Wisconsin & Michigan			Stage
Upper Keweenawan	Rice Series / Red Clastics	Lower Mt. Simon	Bayfield Group	Chequamegon Sandstone	Jacobsville SS	Clastic
		Hinckley Sandstone		Devils Island Sandstone		
		Fond du Lac Formation		Orienta Sandstone		
		Solor Church	Freda Sandstone			Volcanoclastic
			Nonesuch Shale			
			Copper Harbor Conglomerate			
Middle Keweenawan						Volcanic

Table 5. Comparative lithostratigraphy of Precambrian sedimentary rocks associated with the MRS. (Modified after Dickas, 1986).

stratigraphic information, have proven to be an excellent tool, allowing correlation of paleontologically barren Precambrian sediments throughout the Midcontinent rift trend.

The rocks in the north-central section of the MRS can be divided into three sequences: a Middle Keweenawan volcanic sequence, and an Upper Keweenawan volcanogenic sedimentary sequence followed by an arkosic sequence. Earlier K-Ar age determinations carried out for Texaco on basalts and gabbro encountered in the Poersch #1 drill hole in Washington County, Kansas, suggested that the rocks may be slightly younger than those in the Great Lakes region (Berendsen, and others, 1988). However, a recent date for the gabbro capping the Precambrian section in the Poersch #1 drill hole of 1195 m.y. indicates that rift activity in the southern portion of the rift was coeval with activity in the other segments (Van Schmus, Personal Communication). The samples from the various drill holes examined for this study show that no volcanogenic sedimentary rocks have been penetrated by the drill. Whether this indicates that there are few volcanogenic sedimentary rocks present, or whether they just have been missed by the drill in the various exploration holes, is an open question. The area underlain by basalt in Kansas is much less than farther north. This may result in a smaller contribution of volcanically derived material, and a larger amount of material derived from the rift shoulders to the sedimentary rocks. The long lasting period of crustal stability during which the Hinckley Sandstone in Minnesota was deposited, can also be recognized in coeval sediments along the entire MRS. The deposition of quartz arenites having a similar petrographic composition and texture, and deposited in a continental, aquatic environment is characteristic of this period, and can be recognized in nearly all the studied lithologies. The finding of these arenites in subsurface penetrations in Iowa, Nebraska, and Kansas allow us to reasonably correlate clastic rocks throughout the MRS trend.

The complicated regional Precambrian subcrop pattern of rocks associated with the rift in Nebraska and Kansas suggests that the area was broken up by a number of north-northeast- and northwest-trending faults that must have been repeatedly reactivated during pre-Paleozoic times. This resulted in a pattern of relatively small, narrow, elongated blocks each with its own lithology.

The sedimentary succession encountered in the Livingood #1 drill hole contains three distinct Precambrian units, parts of which can be recognized in other drill holes penetrating Phanerozoic rocks in Kansas. These informal units can also be recognized in the so-called "red clastics", the "cornhusker sandstone",and the lower part of the Mt. Simon Formation in Nebraska and southern Iowa.

7. PROPOSED ADDITIONAL STUDIES.

This study represents only a preliminary survey of the kind of work that should be conducted and expanded upon to better understand the nature, depositional history, and mineral potential of the rocks associated with the MRS. The results seem to indicate that the obtained information is very usefull for correlation and classification purposes of the volcanogenic sedimentary rocks and younger arkosics that were deposited in the rift environment.

The samples represent only a small amount of the total rock materials present in the various depositories. In addition core and cuttings from several new drill holes have become available for study, notably the deep drill holes by Texaco and Amoco in Kansas and Missouri, respectively. Studies that will help to refine the ideas presented in this report include:

1. Extend and continue petrographic studies on other available subsurface samples.

2. Conduct additional studies to better understand and carry Solor Church equivalent rocks southward from Minnesota into Iowa.

3. Where possible compare geophysical log responses with the rocks penetrated by the drill. Use this information to interpret the geology in drill holes for which geophysical logs are available, but where samples are not available or heavily contaminated.

4. Conduct mineralogical analysis of opaque and semiopaque minerals in the heavy mineral fraction.

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