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Cover: An oblique photograph of a plastic raised relief map of Wisconsin by Hans J. Stolle a graduate student in the Geography Department, University of Wisconsin - Madison.

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PREFACE

"Geoscience Wisconsin" is a serial that addresses itself to the geology of Wisconsin -- geology in the broadest sense to include rocks and rocks as related to soils, water, climate, environment, and so forth. It is intended to present timely information from knowledgeable sources and make it accessible with minimal time in review and production to the benefit of private citizens, government, scientists, and industry.

Manuscripts are invited from scientists in academic, government, and industrial fields. Once a manuscript has been reviewed and accepted, the authors will submit a revised, camera-ready copy of the paper, and the Geological and Natural History Survey will publish the paper as funds permit, distribute copies at a nominal cost, and maintain the publication as a part of the Survey list of publications. This will help to insure that results of research are not lost in the archival systems of large libraries, or lost in the musty drawers of an open-file.

The three papers in this issue include geologic mapping, and detailed observational studies. Dave Tabet and Joel Mangham provide a new geologic map of Keweenawan units in the Mellen area in northwestern Wisconsin. Their petrographic and chemical studies clarify the intrusive sequences of the Mellen complex, and document crystal settling and multiple intrusion as the active agents in the petrochemical history of the body. Ron Stieglitz and Bret Rothwell examined freshwater heavy mineral grains along the Lake Michigan shoreline by electron microscopy methods. Their study identifies four main factors as agents in forming the observed textures. Doug Pride summarizes geochemical data from lakes in two areas - the Clam Lake area which includes units of the Mellen complex of known copper-nickel mineralization, and the Monico area which includes the zinc-copper deposits of Crandon (Exxon) and Pelican River (Noranda)

We encourage submission of manuscripts relating to Wisconsin geology. Special consideration will be given papers which deal with timely topics, present new ideas, and have regional or statewide implications.

Wisconsin Geological and Natural
History Survey

THE GEOLOGY OF THE EASTERN MELLEN INTRUSIVE COMPLEX, WISCONSIN

by

David E. Tabet[1] and Joel R. Mangham[2]

ABSTRACT

The eastern Mellen intrusive complex is a slightly discordant, sill-like layered intrusive located on the southern limb of the Lake Superior syncline. It is approximately 37 km long and as much as 6 km thick. The Mellen granite stock separates the eastern part of the complex from the Mineral Lake Intrusion, the western half of the complex. Primary planar strucutres in the complex indicate that it has a northeasterly strike and dips steeply to the northwest.

At least three separate intrusive sequences of basaltic magma were emplaced one on top of another to form the Mellen complex. Each sequence developed an olivine-rich lower part and a plagioclase-rich upper part as a result of crystal settling. Density currents produced rhythmic layering in the olivine gabbros and troctolites. The first two, or lowest sequences, contain mostly gabbroic rocks while the third also contains more highly indifferentiated rocks including monzogabbro and granophyre. Emplacement of each sequence took place after the preceding one had solidified, but the lack of chilled margins between them suggests that the earlier bodies were still hot at the time of subsequent intrusions.

Intrusion of the eastern complex occurred near the close of Middle Keweeawan extrusive activity. The complex was emplaced in the slowly subsiding southern limb of the Lake Superior syncline when the tilt of that limb was probably less than 10° to 15° to the northwest. No evidence for thrust faulting was found in or at the base of the complex. Thrust faulting along the Keweenawan and related faults probably occurred in the volcanic rocks north of the Mellen complex subsequent to intrusion.

INTRODUCTION

Previous Work

Geologic interest in the Lake Superior region has been fueled for over a century by the discovery and exploitation of mineral resources, notably

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of iron and copper, and by the numerous exposures of rocks covering long spans of Middle and Late Precambrian time. Regional studies of the Lake Superior area (Irving, 1883; Van Hise and Leigh, 1911; Aldrich, 1929) established the stratigraphy and defined the rocks, providing a framework for subsequent geologic investigations.

The eastern Mellen intrusive complex is an informal name for the eastern half of a slightly discordant, sill-like gabbroic complex called the Mellen intrusive complex. The western half, called the Mineral Lake Intrusion (Olmsted, 1969), is separated from the eastern complex by the Mellen granite stock. The eastern complex crops out over an area 6 km by 37 km, trending northeasterly from Mellen, Wisconsin, to near the Michigan state line (Fig. 1).

Hotchkiss (1923) postulated that the Mellen complex was a series of parallel laccolithic intrusions rather than a single laccoligh. Leighton (1954) studied the western end of the Mellen complex to determine the petrogenesis of the gabbroic, intermediate and granophyric rocks. Olmsted (1969) studied the entire western half of the complex, the Mineral Lake Intrusion, and proposed that the range of gabbroic rock types present resulted from a single intrusion of magma and its subsequent differentiation.

Statement of Problems

Our investigation represents the first detailed work on the eastern half of the complex. We sought to identify the range of rock types that make up the eastern Mellen complex and what process(es) played a part in their formation. The structure of the eastern complex was studied to determine whether it was a simple, composite or multiple intrusive. Ultimately we sought to determine what relationship intrusion of the Mellen complex had to the tectonic evolution of the region during Keewenawan time.

Procedures

This study is the result of detailed geologic mapping during the summers of 1973 and 1974, augmented by laboratory work consisting of petrographic microscopy and point counting and analysis of mafic minerals using a scanning electron microscope or an electron microprobe. Structural features were analyzed using Warner's (1969) computer program which plots and contours data points on a lower hemisphere and projects these plots onto an equal-area net.

Rock names for the medium- and coarse-grained intrusive rocks are from the scheme recommended by Streckeisen (1976). The term "granophyre" is applied to medium- to fine-grained rocks composed almost exclusively of granophyric intergrowths of quartz and potassium feldspar. The term "gabbroic" refers to all dark, medium- to coarse-grained rocks of the complex except the monzogabbro and granophyre.

GEOLOGIC SETTING

The Mellen intrusive complex intrudes Lower Precambrian through Middle Keweenawan and possibly Upper Keweenawan rocks on the steep, southern limb of the LakeSuperior syncline (Aldrich, 1929). The oldest rocks exposed are Early Precambrian granites, gneisses and greenstones which are uncomforably overlain to the north by Animikian layered rocks referred to as the Marquette Range Supergroup by Cannon and others (1970). The middle Precambrian Animikian sequence in Wisconsin begins with the locally present, 30-m thick Bad River Dolomite. The Bad River Dolomite is disconformably overlain by the 140-m thick Palms Quartzite, which grades conformably upward into the 180-m thick Ironwood Iron Formation. Unconformably above the Ironwood Iron Formation is a thick sequence of graywacks, sandstone, shales and slates of the 300-m thick Tyler Formation (Dorr and Eschman, 1970).

An erosional surface separates the Marquette Supergroup from the Upper Precambrian or Keweenawan rocks (Cooper, 1973). The lowest of the three major divisions of Keweenawan rocks, the Bessemer Quartzite, consists of a 75-m thick quartzite with a basal conglomerate. Lying with apparent conformity on this Lower Keweenawan formation is a sequence of Middle Keweenawan flood basalts; the lowest 30 m of flows has well developed pillow structures indicating deposition was subaqueous. White (1960) concluded from paleocurrent analyses that the volcanics flowed outward from the axis of the subsiding Lake Superior syncline and that interflow sediments were transported toward the axis from the basin margins. Continued subsidence and tilting on the southern limb of the syncline is expressed in the upper Middle Keweenawan flows and in the Upper Keweenawan sedimentary rocks by decreasing dips in the younger rocks and thickening of the units down-dip (White, 1966b). Chemical analyses of the volcanics (Cooper, 1973) show pronounced bimodal silica concentrations similar to those reported for Cenozoic continental rift zones (Christiansen and others, 1972). Near the close of the volcanic activity, during late middle Keweenawan and early Lake Keweenawan time, the Mellen complex intruded the older Keweenawan and Animikian rocks.

Upper Keweenawan rocks are divided into the lower Oronto Group and the upper Bayfield Group. The base of the Oronto Group, the 100- and 1800-m thick Copper Harbor Conglomerate, interfingers with the underlying lava flows and is apparently conformable with the Middle Keweenawan rocks (Halls, 1966). Conformably overlying the conglomerate is a 120-m thick unit of fine-grained sandstone and shale called the Nonesuch Formation. The Freda Sandstone forms the upper part of the Oronto Group and consists of a 3600-m thick sequence of interbedded sandstones and siltstones and some lenses of conglomerate (Hamblin, 1961).

The flay-lying, 1325-m thick Bayfield Group, consisting of the Orienta Sandstone, Devils Island Sandstone and the Chequamegan Sandstone in ascending order, rests unconformably on the Oronto Group (Hamblin, 1961). The feldspathic sandstones of the Bayfield Group exhibit an upward increase in maturity and sorting (Halls, 1966).

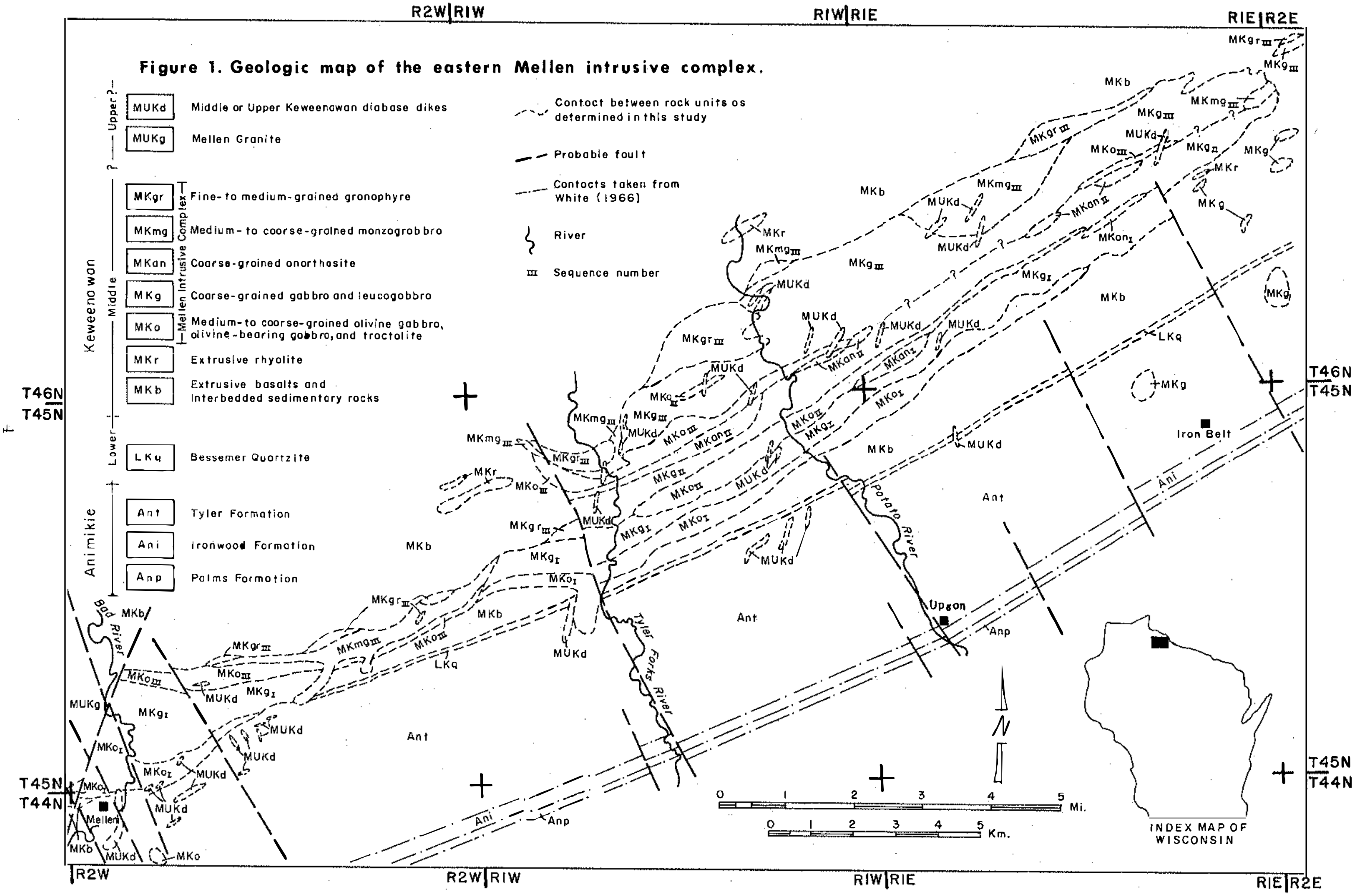


Figure 1. Geologic map of the eastern Mellen intrusive complex.

Formation of the Lake Superior syncline probably began with deposition of the Lower Keweenawan sediments and the Middle Keweenawan lavas with subsidence and infilling continuing approximately in balance through deposition of the Oronto Group (Craddock, 1972). The syncline was folded assymetrically with the strata on the north shore of Lake Superior having gentle southward dips and those in northern Wisconsin possessing steep dips to the north. In northwestern Wisconsin the axis of the Lake Superior syncline lies along a significantly uplifted horst that was first defined by Thiel (1956). This axial horst, named the St. Croix horst (Craddock and others, 1963), consists predominantly of Middle Keweenawan igneous rocks and is marked by the prominent Midcontinent Gravity High.

STRUCUTRE OF THE EASTERN MELLEN COMPLEX

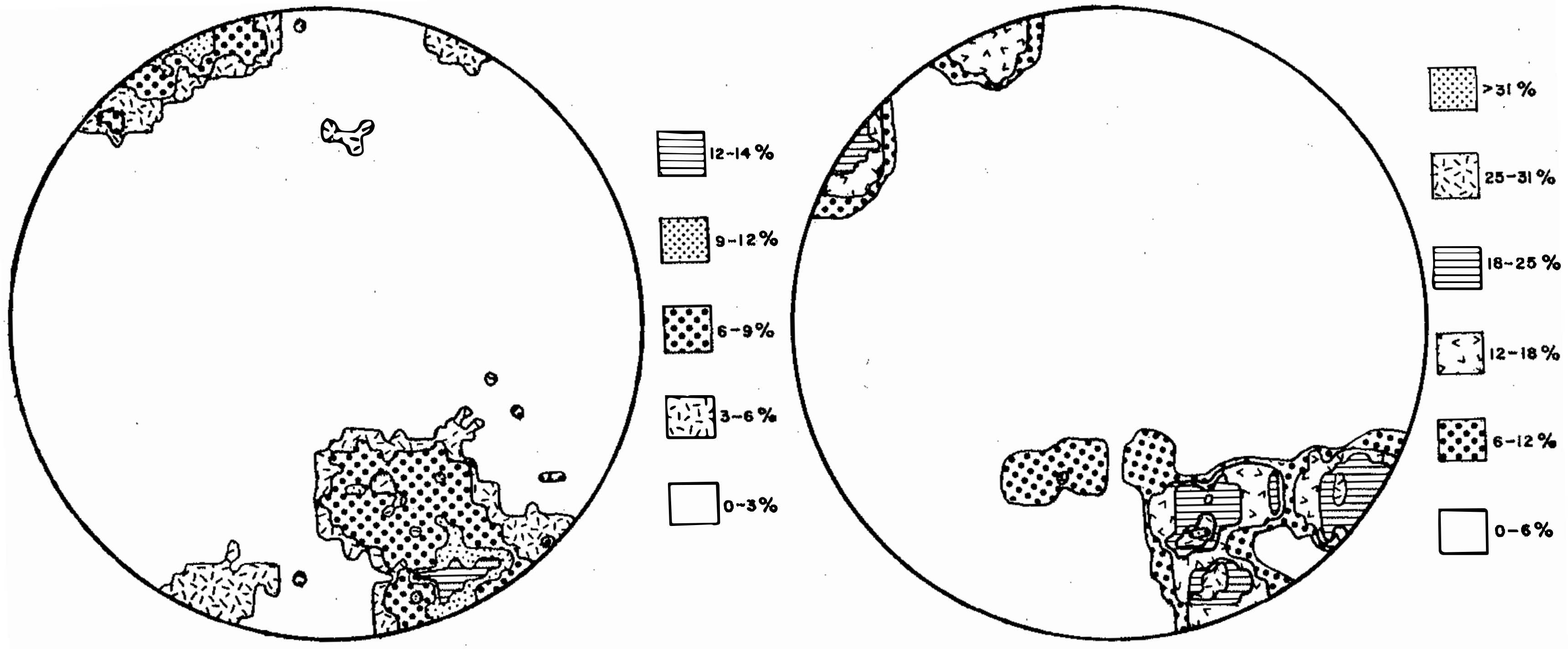
The Mellen igneous complex is a slightly discordant intrustion. Southwestward along its strike, the complex intrudes progressively older strata of the Lake Superior syncline's southern limb that have an average strike of N. 70° E. and dip of 72° NW in the study area. The eastern end of the Mellen complex is completely enclosed by Middle Keweenawan volcanic rocks, but 3.2 km east of Mellen, Wisconsin, the lower margin of the complex cuts through the Lower Keweenawan into the Animikian Tyler Formation while the upper margin of the complex remains bounded by the Middle Keweenawan lavas.

East of the Tyler Forks River, the eastern Mellen complex can be divided into three layered sequences of gabbroic rocks formed from successive intrusions of tholeiitic magma, one on top of another. The sequences, numbered I, II and III from south to north, average one km thick. Each is composed of gabbroic rocks containing olivine near the base, or southern contact, and grading northward to more feldspathic gabbroic rocks, including anorthosite. In addition the rocks of sequence III, the top sequence, include large bodies of monzogabbro and granophyre.

Contacts between rocks of different sequences are sharp and the unit above the contact is generally younger. Contacts within a sequence are usually gradational; however, sharp contacts have been found between the gabbro and olivine gabbro units, as in NW1/4, sec. 32, T. 46 N., R. 1 E. Such contacts indicate that the gabbro units are younger. The granophyre, with sharp contacts and some gabbroic inclusions, is younger than all surrounding gabbroic rocks. The monzogabbro unit has no exposed contacts, but appears to be slightly older than the granophyre.

West of the Tyler Forks River, the eastern Mellen complex is much thinner, and two sequences of gabbroic rocks can be distinguished which probably correspond to sequences I and III to the east. Contact relations in this part of the complex are the same as to the east; rocks to the north of a contact are usually younger, except where monzoggabbro and granophyre intrude the older rocks.

Igneous lamination (Wager and Brown, 1967), caused by the parallel alignment of the (010) faces on plagioclase laths, exists in the gabbroic



a) Data point concentration: S26°E, 7°SE

Corresponding igneous lamination orientation:
N64°E, 83°NW

Total number of points: 83

b) Data point concentraion: S24°E, 18°SE

Corresponding rhythmic layering orientation:
N66°E, 72°NW

Total number of points: 16

Figure 2. Computer-contoured, lower hemisphere stereographic pi diagrams of: a) poles to igneous lamination in the Mellen complex; b) poles to rhythmic layering in the Mellen complex.

rocks of the complex. A pi diagram of 83 readings on igneous lamination (Fig. 2) shows a maximum corresponding to an average latitude of N. 64° E., 84° NW. The strike of igneous lamination tends to parallel the basal contact of each sequence. Thus, since the igneous lamination shows the sequence bases dip about 10° more steeply than the surrounding bedding, the complex as a whole may be inferred to have a dip corresponding to that of the igneous lamination.

Rhythmic layering (Wager and Brown, 1967), is best developed in the olivine gabbro unit of sequence II between the Tyler Forks and Potato Rivers. The rhythmic layers are approximately 10 cm thick and have melanocratic bases grading upward to more leucocratic tops. In addition, olivine crystals vary in composition from Fa_{38} at the bottom to Fa_{42} at the top of a layer, indicating crystal settling and differentiation occurred within each individual layer after it was deposited by a density current. A pi diagram of 16 readings indicates an average rhythmic layering orientation of N. 66° E., 72° NW (Fig. 2).

As seen from offsets of the complex's contacts, five faults with minor apparent strike-slip displacements cut perpendicular to the strike of the complex (Fig. 1). It is possible that these faults formed to relieve torsionalforces caused by differential northwestward tilting along the southern limb of the Lake Superior synclinc (Aldrich, 1929). No evidence for shearing or thrusting was found along the base of the complex.

PETROLOGY

The complex has been divided into three similar intrusive sequences. These sequences are subdivided into the rock units described below based on their differing mineral assemblages. The rocks of sequences I and III are all gabbroic types while sequence III also contains monzogabbro and granophyre. All the units are composed of hypidiomorphic intrusive rocks that are exposed in low outcrops lacking any distinctive topographic expression. Modes of various coarse-grained rocks are presented in Table 1.

Olivine Gabbro Units

The lowest part of all three sequences consists of an olivine gabbro unit which may contain the following rock types: olivine-bearing gabbro (less than 5 percent modal olivine), olivine gabbro, olivine gabbronorite and troctolite. Both leucocratic and melanocratic varieties of these rocks are found. All the olivine gabbro units are lense-shaped and discontinuous along the length of the complex. They are thickest where the complex itself is thickest, particularly in the area between the Potato and Tyler Forks Rivers. Exposures of the olivine gabbro units are commonly dark brown due to the weathering of oliving; fresh surfaces are very dark gray or black. Texturally the rocks are mostly coarse-grained orthocumulates.

The modal composition differs for the olivine gabbro unit of each sequence; however, within each unit similar gradational trends occur. The

Table 1. Modes of rocks of the eastern Mellen complex (volume percent).

Specimen number*	UW 1624/65	UW 1624/59	UW 1607/4	UW 1607/21	UW 1624/71	UW 1607/22	UW 1624/5	UW 1607/52	UW 1607/56	UW 1624/69	UW 1624/61
Plagioclase	25.7	54.6	70.2	46.6	63.9	77.0	83.6	44.6	40.5	27.9	28.9
Olivine	72.4	26.1	12.7	4.7	-	-	-	-	-	-	-
Clinopyroxene	-	7.4	2.9	37.1	27.2	8.1	3.4	11.0	2.8	11.4	1.2
Orthopyroxene	-	1.3	5.6	4.7	4.6	4.5	0.5	-	-	-	-
K-feldspar	-	-	-	-	0.3	2.4	-	11.7	20.4	25.4	22.4
Quartz	-	-	-	-	0.4	0.8	3.9	6.1	5.3	20.7	18.6
Opaques	1.9	10.0	4.8	3.6	3.3	3.5	-	5.4	2.5	3.8	2.0
Apatite	-	trace	-	0.1	0.3	0.1	1.2	0.9	2.6	1.4	-
Amphibole	-	-	-	-	-	-	0.9	-	24.5	3.8	11.3
Biotite	-	0.6	-	0.4	-	1.6	-	-	1.4	-	-
Chlorite	-	-	3.8	0.8	-	2.0	2.4	11.0	-	-	15.2
Serpentine	-	-	-	2.0	-	-	-	-	-	-	-
Epidote	-	-	-	-	-	-	0.1	-	-	0.2	0.4
Sericite	-	-	-	-	-	-	-	9.3	-	5.4	-
	mela-troctolite	olivine gabbro	olivine leuco-gabbro	olivine-bearing gabbro	gabbro	leuco-gabbro	anorthosite	monzogabbro	monzogabbro	monzogabbro	granophyre

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*The specimens are in the depository at the Department of Geology and Geophysics, University of Wisconsin-Madison; for sample locations see Appendix A.

The olivine gabbro belt of sequence I is composed mostly of olivine gabbro and troctolite and is most mafic in its lowest levels and thickest sections. Sequence II has the most mafic rocks of the complex. Immediately west of the Potato River it consists of rhythmically layered mela-troctolite, but it becomes more plagioclase-rich eastward finally passing laterally into olivine-bearing gabbro in the thin eastern end of the belt. The olivine gabbro unit of sequence III is the least mafic of all, consisting primarily of olivine gabbro and olivine-bearing gabbro, and again being most mafic immediately west of the Potato River. Thus each olivine gabbro unit grades upward and laterally from its lowest, thickest mafic portion to more leucocratic rocks.

In the troctolites of the complex, olivine crystallized first and is a cumulus phase (Fig. 3). Olivine and plagioclase appear to have formed synchronously in the olivine gabbros of each sequence since some anhedral olivine crustal poikilitically enclose subhedral plagioclase crystals and vice versa. In olivine-bearing gabbros, all of the olivine crystals formed as an intercumulus phase. Most olivine crystals are quite fresh; however, in some rocks kelyphitic rims are developed to varying stages. Magnetite and biotite also formed from the reaction between olivine crystals and a late, water-rich fluid, especially in the rocks of sequence III.

Plagioclase, as subhedral to euhedral albite-twinned crystals between 1 and 10 mm in length, is a cumulus phase in most of the rocks in the olivine gabbro units. The plagioclase crystals commonly have thin normally zined rims. Smaller plagioclase crystals also exist as a later intercumulus phase.

Two pyroxenes, augite and inverted pigeonite, are intercumulus phases in the olivine gabbro units, except in loca, very thin pyroxene-rich layers. Both pyroxenes crystallized at nearly the same time since either may contain inclusions of earlier olivine or plagioclase. The pyroxenes commonly have an ophitic to subophitic texture with coarse crystals ranging from 1 mm to 40 mm across. The inverted pigeonite has two sets of exsolved clinopyroxene lamellae, one coarse and one fine, in an orthopyroxene host. The augite has fine parallel lines of inclusions and may be simply twinned while the inverted pigeonite has neither of these features.

Gabbro Units

Gabbro, gabbronorite and the leucocratic varities of these two rock types are mapped together as the gabbro units and occur stratigraphically above the olivine gabbro units of all the sequences. Leuco-gabbro and gabbro are the most abundant rock types. The gabbro units weather to a medium gray, lighter in color than most exposures of the olivine gabbro units. Weathering tends to bleach the plagioclase crystals; this is great value in estimating the relative abundance of plagioclase and thus the difference between gabbro, leuco-gabbro or anorthosite. Weathering also emphasizes the ophitic texture. The gabbro units are composed of medium-grained to very coarse-grained orthocumulates.

The abundance of plagioclase, and thus leuco-gabbro, is greatest near the tops of the gabbro units and also adjacent to anorthosite units since

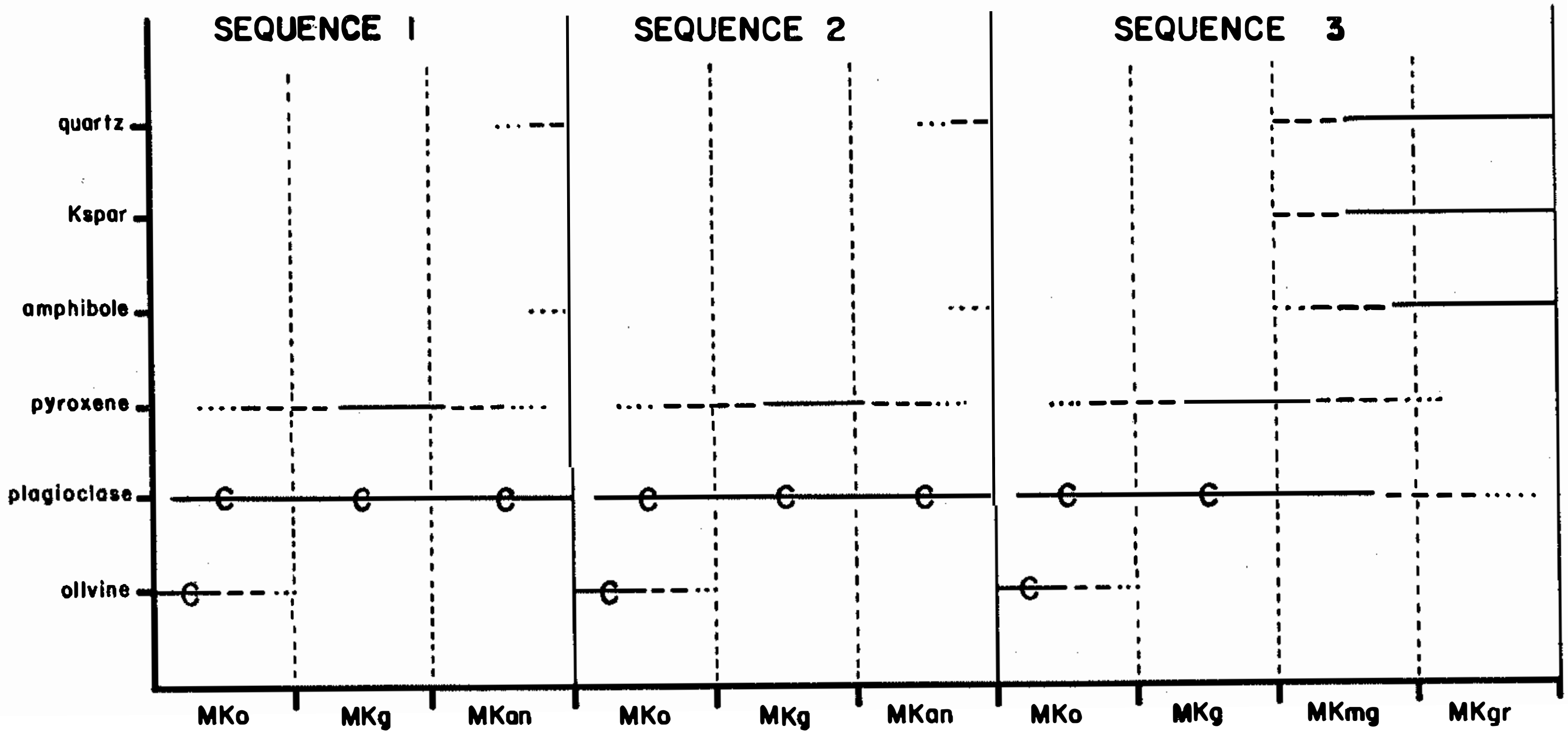

Figure 3. Diagram of inferred crystallization sequence in the eastern Mellen complex; cumulus phases denoted with C. (See Figure 1 for rock type descriptions.)

the boundaries between the gabbro and anorthosite units are gradiational. In the eastern end of the study area a bimodal distribution of plagioclase crystal sizes is evident in many outcrops of the gabbro units. Irregularly shaped areas composed of large (1 cm) and small (1 mm) plagioclase laths are separated by sharp boundaries from areas containing only small laths. Since the An_{55} composition of the most calcic large crystals is less calcic than the An_{60} composition of the small crystals, these smaller crystals may indicate renewal with more calcic magma during crystallization.

Plagioclase is the earliest formed phase and the only cumulus phase in the rocks of the gabbro units. While a few crystals show thin normally zoned rims, the plagioclase in most of the units occurs as coarse subhedral to euhedral crystals with no zoning.

Pyroxenes in the gabbro units throughout the complex are intercumulus phases. They occur as anhedral, ophitic or subophitic crystals 5 to 10 mm in diameter. Two pyroxenes, twinned augite and inverted pigeonite, are present. The pyroxenes crystallized after the plagioclase but poikilitically include only plagioclase.

Quartz is present separately or graphically intergrown with orthoclase in the interstices between plagioclase grains. Biotite, hornblende, apatite, magnetite and chlorite are also present in minor amounts.

Anorthosite Units

Irregular bodies of anorthosite, composed of 84 percent or more plagioclase, overlie the gabbro units of sequence I and II. In the thin sections studied, pyroxene makes up less than 5 percent of the rocks and thus, relative to pyroxene, the plagioclase abundance is more than 90 percent. The anorthosite specimens studied show limited variation in mineralogy. Exposures of the medium- to coarse-grained anorthosite units are similar to those of the gabbro units, except that they weather to a lighter gray due to the greater abundance of plagioclase.

Plagioclase was the first mineral to crystallize in the anorthosites; no poikilitic inclusions are found in it. Normal zoning of the plagioclase and common embayments of other minerals into the plagioclase crystals indicate some adcumulus growth.

Coexisting subophitic augite and inverted pigeonite, both up to 1 or 2 cm in diameter, probably crystallized second. Schiller structure is present in the augite, but no twinning was observed.

Late stage minerals include hornblende, apatite, quartz and opaque minerals. The opaques, magnetite and trace amounts of chalcopyrite, occur as fine-grained anhedral crystals between plagioclase grains.

Monzogabbro Unit

This unit occurs only in sequence III and is stratigraphically above or intrudes the earlier gabbroic rocks. It is primarily made up of monzogabbro with some local occurrences of monzodiorite. Weathered surfaces show a distinct contrast between the dark gray-brown mafics and plagioclase, and the small, irregular patches of pink potassium feldspar. Green and brown staining makes the plagioclase difficult to distinguish on either weathered or fresh surfaces. The monzogabbro unit is composed mostly of coarse-grained rocks. The major minerals vary greatly in abundances; the modes of monzogabbros (see Table 1) range with increasing abundance of quartz and potassium feldspar from rocks that are nearly gabbros to those that are nearly granophyres. No strong geographical trend of rock type variation was discernable, although the monzogabbro unit is closely related spatially to the rocks of the granophyre unit.

Plagioclase is probably the earliest formed phase, but it does not appear to be cumulate. It forms subhedral to euhedral crystals up to 6 or 7 mm long. Albite twinning is visible in some crystals while sericitic alteration has obliterated any recognizable twinning in other crystals. Both unzoned and normally zoned crystals are present.

Augite, in untwinned crystals 1 to 2 mm across, has a subophitic texture with the palgioclase in some specimens. The augite is clearly a later-formed phase than the palgioclase, but its relationship to other minerals is obscured by alteration of the crystal rims by a late fluid phase to amphibole or an amber-colored, cryptocrystalline mineral.

Magnetite crystals are subhedral to euhedral, 1 or 2 mm in diameter and have a partly developed skeletal character. It could not be determined whether the subhedral magnetite crystals were inclusions in the pyroxene or were formed from alteration of the pyroxene during late-stage mineralization.

Quartz and potassium feldspar are important constituents occurring interstitially to plagioclase. At one extreme all the clear quartz crystallized in wormy or graphic intergrowths with fine hematite-dusted orthoclase. At the other extreme the heavily dusted, red-colored orthoclase and minor clear quartz occur separately. Quartz and orthoclase intergrowths form coronas around some plagioclase crystals.

Granophyre Unit

At the top of sequence III are bodies of rock comprising the granophyre unit. This unit is granitic in mineralogy; however, the large amounts of granophyrically intergrown quartz and potassium feldspar present makes the term "granophyre" an appropriate name. There is little difference in the brick-red color of fresh and weathered granophyre surfaces. The granophyres vary from medium-grained to fine-grained porphyritic rocks. They also vary from hematite-rich to hematite-poor, potassium feldspar-rich rocks. The latter are generally found east of the Potato River.

The first mineral to crystallize in the hematite-rich granophyres was plagioclase which generally forms subhedral phenocrysts from 1 to 3 mm long. Twinning is visible in the few crystals that are not too heavily sericitized, and the crystals are either unzoned or normally zoned.

Potassium feldspar and quartz exist separately or graphically intergrown in the granophyres. Quartz is usually present in amounts subordinant to the potassium feldspar, especially in the hematite-rich varieties. Anhedral crystals of clear quartz up to 1 cm in diameter along with anhedral potassium feldspar crystals and granophyric intergrowths up to 2 mm in diameter probably crystallized from a late fluid phase, in places reacting with earlier formed plagioclase to form coronas or completely replacing the plagioclase.

Amphibole occurs as small radiating green pleochroic crystals and stubby 1-mm grains or as secondary brown varieties replacing pyroxene. The late-formed amphibole crystals are mostly restricted to the plagioclase interstices, but some large amphibole crystals cut across plagioclase crystals.

Clinopyroxene is a minor constituent of the granophyres. It occurs as untwinned, anhedral grains 1 to 2 mm in diameter which are either completely or partially replaced by amphibole and chlorite.

Magnetite in the granophyre unit is anhedral and less than 1 mm in diameter. In some specimens the magnetite is disseminated throughout the rocks, while in other specimens it occurs as elongate clusters up to 6 mm, possibly pseudomorphs after a mafic mineral.

MINERALOGY

There are no systematic changes from one sequence to the next in the major minerals of the complex (Table 2). Comparison of the mineral analyses for similar rock units in each sequence shows only small differences. The olivines from the olivine gabbro unit of sequence I are the most iron rich, with those from sequence II and III very close in composition. The plagioclase crystals in the olivine gabbro units of sequence I have the highest average anorthite content with those from sequence II having the lowest anorthite content. Comparison of clinopyroxene compositions from rock units in one intrusive sequence to the corresponding units in another intrusive sequence shows little variation in composition. The same is true for the few orthopyroxenes that were analyzed. The similarity in mineral chemistry betwees the sequences indicates all three tapped the same magma source; the differences probably reflect the variations in cooling histories for the sequences.

Within each sequence the same differentiation trend is apparent. In sequences I and II, where cooling and differentiation were interrupted by intrusion of subsequent sequences, a poorly developed trend of depletion of magnesium and calcium in the younger rock units is present. However, this trend is pronounced in sequence III where cooling produced monzogabbro and granophyre as well as gabbroic rock types. A plot of pyroxene compositions (Fig. 4) from sequence III demonstrates the trend toward less magnesium- and calcium-rich minerals. Accompanying the trend in the pyroxenes is a general reduction in anorthite content upward through sequence III.

Table 2. Representative mineral compositions from the eastern Mellen complex (sample locations in Appendix A).

Sequence	Unit	Olivine		Clinopyroxene		Orthopyroxene	Plagioclase	
I	olivine gabbro	Fa_{47}	UW 1624/8	$Ca_{39}Mg_{36}Fe_{25}$	UW 1607/6	--	An_{75}	UW 1607/6[1]
		Fa_{50}	UW 1624/83	$Ca_{43}Mg_{32}Fe_{25}$	UW 1624/83	--	An_{75}	UW 1624/8[2]
I	gabbro	--		$Ca_{43}Mg_{32}Fe_{25}$	UW 1624/9	--	An_{71}	UW 1624/9[2]
		--		$Ca_{42}Mg_{27}Fe_{31}$	UW 1624/73	--	An_{60}	UW 1624/79[2]
		--		$Ca_{28}Mg_{37}Fe_{35}$	UW 1624/79	--	An_{57}	UW 1607/22[1]
II	olivine gabbro	Fa_{41}	UW 1624/84	$Ca_{37}Mg_{43}Fe_{20}$	UW 1607/1	--	An_{60}	UW 1607/1[1]
		--		$Ca_{40}Mg_{32}Fe_{28}$	UW 1624/76	$Ca_{8}Mg_{44}Fe_{48}$	An_{61}	UW 1624/4[2]
II	gabbro	--		$Ca_{37}Mg_{44}Fe_{19}$	UW 1607/19	--	An_{57}	UW 1607/19[1]
III	olivine gabbro	Fa_{41}	UW 1624/65	$Ca_{35}Mg_{38}Fe_{27}$	UW 1607/4	--	An_{64}	UW 1607/4[1]
		Fa_{36}	UW 1624/66	$Ca_{38}Mg_{33}Fe_{29}$	UW 1624/75	$Ca_{10}Mg_{45}Fe_{45}$	An_{72}	UW 1624/3[2]
		Fa_{51}	UW 1624/78	$Ca_{44}Mg_{35}Fe_{21}$	UW 1624/78	$Ca_{12}Mg_{44}Fe_{44}$	--	
III	gabbro	--		$Ca_{42}Mg_{29}Fe_{29}$	UW 1624/1	--	An_{81}	UW 1624/1[2]
		--		$Ca_{47}Mg_{27}Fe_{26}$	UW 1624/77	--	An_{60}	UW 1624/77[2]
		--		$Ca_{37}Mg_{37}Fe_{26}$	UW 1607/21	--	An_{60}	UW 1607/21[1]
III	monzogabbro	--		$Ca_{39}Mg_{22}Fe_{39}$	UW 1624/69	--	--	
III	granophyre	--		$Ca_{28}Mg_{7}Fe_{65}$	UW 1624/56	--	An_{30}	UW 1624/56[2]

[1] Average plagioclase composition

[2] Composition of plagioclase crystal core

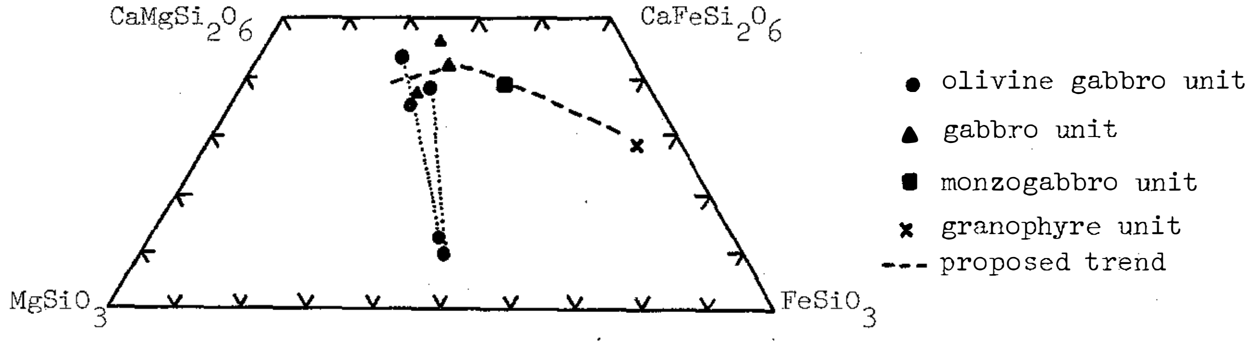

Figure 4. Pyroxene composition from rocks of sequence III.

CONCLUSIONS AND DISCUSSION

Recent tectonic hypotheses for Keweenawantime in the Lake Superior region regard this as a period of continental rifting along the axis of the present Midcontinent Gravity High (Craddock, 1972; Chase and others, 1973). Basin subsidence and deposition of the Lower Keweenawan conglomerate and sandstone may correspond to the initial stages of continental rifting. Basaltic and rhyolitic lavas poured out along the axis of this shallow, initially water-filled basin; slow subsidence kept pace with lave accumulation. The bimodal distribution of silica contents of the extrusives is consistent with the hypotheses of continental rifting (Christiansen and others, 1972).

Intrusions of the slightly discordant Mellen complex into the slowly tilting southern limb of the Lake Superior syncline occurred near the end of the period of volcanism. The attitude of rhythmic layering in the eastern complex indicates that intrusion took place prior to major tilting of the southern flank of the syncline. The dip of the layering in the complex and the surrounding sedimentary and volcanic rocks have the same average dip, 72° to the northwest. If the depositional plane of the rhythmic layering was horizontal, then the surrounding rocks would also have been nearly horizontal; however, the layers were more likely deposited with initial dips up to 10° to 15°, like those known to exist in other layered complexes (Wager and Brown, 1967). Thus, it can be inferred that intrusion of the Mellen complex occurred when the surrounding strata were inclined no more than 10° to 15° to the northwest.

The western part of the complex may have formed from only one pulse of magma (Olmsted, 1969) while the eastern complex was formed from at least three sheet-like intrusions, corresponding to the three sequences discussed. Differential crystal settling rates and density currents produced rhythmic layering and they are probably also responsible for the development within each intrusive sequence of the gabbroic units discussed. A lack of chilling at the contacts between intrusive sheets shows that the previous sheet was still hot at the time of intrusion.

Similar multiple intrusive histories have been reported for other basic intrusions around the Lake Superior region. The Duluth complex may also have a history of multiple sheet intrusions (Mancuso and Dolence, 1970) and is probably contemporaneous with the Mellen intrusion. Phinney (1972) describes the northern prong of the Duluth Complex as a series of intrusive sheets of gabbroic rocks with granitic material along its upper margin. The Deer Lake intrusion in Minnesota is reported to have formed from five gabbroic sheets, each intruded successively above the preceding one, each sheet differentiating and cooling before the next intrusion (Berkeley, 1972).

The granophyre of the Mellen complex is probably derived from the original basaltic magma that formed the rest of the complex. The third (last) sheet either tapped a more completely differentiated magma or underwent complete differentiation itself to produce the granophyre magma. A similar genesis is argued for the Duluth granophyre by Babcock (1960). The bimodal distribution of silica-poor gabbroic rocks versus silica-rich granophyres in the Mellen and Duluth complexes is typical for anorogenic igneous intrusions.

No evidence of thrust faulting was found in the intrusive rocks of the eastern Mellen complex. Geophysical work (White, 1966a) and a pronounced thinning of the lava pile north of Mellen suggest that the Keweenawan fault extends westward from Michigan to the north of the Mellen complex, on trend with the Lake Owen fault to the west of the complex.

ACKNOWLEDGMENTS

The writers are indebted to Campbell Craddock, for his friendly help and guidance during their thesis work on the eastern Mellen complex. Darrell Henry and Rick Whitman provided untiring assistance in the field. Everett Glover, Charles Grigsby and Herbert Wang helped in the laboratory work, and Michael Woolridge drafted illustrations for this paper. Finally, we appreciated the constructive criticism of the manuscript by Stewart McCallum and Roger Cooper.

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APPENDIX: LOCATIONS FOR SPECIMENS USED IN THIS STUDY

UW 1607/1	SW¼, SW¼, Sec. 3, T. 45 N., R. 1 W.
/4	NW¼, SW¼, Sec. 3, T. 45 N., R. 1 W.
/6	SE¼, SE¼, Sec. 17, T. 45 N., R. 1 W.
/19	NW¼, NW¼, Sec. 10, T. 45 N., R. 1 W.
/21	SW¼, NW¼, Sec. 3, T. 45 N., R. 1 W.
/22	SE¼, NE¼, Sec. 17, T. 45 N., R. 1 W.
/52	NW¼, NE¼, Sec. 34, T. 46 N., R. 1 W.
/56	NE¼, SW¼, Sec. 23, T. 45 N., R. 2 W.
UW 1624/1	NE¼, SW¼, Sec. 35, T. 46 N., R. 1 W.
/3	SE¼, NW¼, Sec. 2, T. 45 N., R. 1 W.
/4	SW¼, SW¼, Sec. 2, T. 45 N., R. 1 W.
/5	SE¼, NW¼, Sec. 2, T. 45 N., R. 1 W.
/8	NE¼, SE¼, Sec. 10, T. 45 N., R. 1 W.
/9	SW¼, NW¼, Sec. 11, T. 45 N., R. 1 W.
/56	NE¼, NW¼, Sec. 35, T. 46 N., R. 1 W.
/59	SW¼, SE¼, Sec. 22, T. 46 N., R. 1 E.
/61	NE¼, NE¼, Sec. 16, T. 46 N., R. 1 E.
/65	NW¼, SW¼, Sec. 3, T. 45 N., R. 1 W.
/66	NW¼, SW¼, Sec. 3, T. 45 N., R. 1 W.
/69	NE¼, SW¼, Sec. 35, T. 46 N., R. 1 W.
/71	SE¼, SE¼, Sec. 14, T. 46 N., R. 1 E.
/73	SE¼, SE¼, Sec. 2, T. 45 N., R. 1 W.
/75	NE¼, SW¼, Sec. 14, T. 46 N., R. 1 E.
/76	NE¼, NE¼, Sec. 13, T. 46 N., R. 1 E.
/77	SE¼, NW¼, Sec. 35, T. 46 N., R. 1 W.
/78	SW¼, SW¼, Sec. 35, T. 46 N., R. 1 W.
/79	NW¼, NW¼, Sec. 11, T. 45 N., R. 1 W.
/83	NW¼, NE¼, Sec. 5, T. 45 N., R. 1 E.
/84	SW¼, NW¼, Sec. 1, T. 45 N., R. 1 W.

SURFACE MICROTEXTURES OF FRESHWATER HEAVY MINERAL GRAINS

by

Ronald D. Stieglitz[1] and Bret Rothwell[2]

ABSTRACT

Scanning electron microscopy indicates that a wide variety of mechanical and chemical features are present on heavy mineral grains collected from the shore of Lake Michigan. Many microtextures common to these freshwater beach and back beach dune sands appear similar to those reported by others from marine environments (Setlow and Karpovich, 1972; Lin and others, 1974). Differences, particularly on garnet grains, may be the result of chemical conditions.

Detailed observations of the heavy mineral suite in a sedimentary deposit should supply useful information concerning depositional environments provenance and diagenetic history. Actually many problems remain because the relative importance of contributing factors such as relict original textures, composition, crystallography, depositional conditions, and diagenesis have not as yet been effectively separated. Additional complications in the present study area include possible mixing of material between environments and a complex source of supply of grains from glacial till.

Key words: Surface microtextures, Heavy minerals, S.E.M., Freshwater

INTRODUCTION

Early studies by Biederman (1962) Porter (1962), and Krinsley and Takashi (1962) described micromorphogenetic surface features of quartz sand grains as imparted by various sedimentary processes. The study of sediment grain surface features was continued by Krinsley and Donahue (1968), Krinsley and Margolis (1969), Fitzpatrick and Summerson (1971) and others. These studies sought to delineate significant textural features and to interpret their occurrence in terms of the sediment's provenance and depositional environment. Following the establishment of a basis for environmental discrimination, the technique has been applied in many studies of different types of deposits.

Studies of heavy mineral assemblages sought to interpret the provenance and deposition of clastic deposits based on the type, abundance, and distribution of component heavy minerals within a particular assemblage. The study of textural features of heavy mineral grains, as related to the distribution and significance of heavy mineral suites, was neglected.

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Recently, with the realization that all types of clastic grains in a sedimentary deposit may supply useful information, the two types of studies have been combined (Stieglitz, 1969a; Stieglitz and Rothwell, 1972). Quartz and heavy mineral grains from the marine environment along Florida's coast were studied and reported on by Setlow and Karpovich (1972). Merkle and Ferrell (1972) used a scanning electron microprobe to identify individual heavy mineral grains by textural and compositional criteria. Lin and others (1974), in an excellent study, documented the occurrence of surface microtextures of heavy minerals from the coast to Israel.

PURPOSE

This report seeks to document and illustrate different types of surface textures observed on several common kinds of heavy mineral grains from freshwater environments. Comparisons of these textures with textures reported previously by other workers from marine environments may lead to a fuller understanding of how textures are formed in each environment and an appreciation of which textures are truly distinctive of each.

Secondly, and possible most important, we wish to illustrate some of the problems remaining in the study of surface textures of heavy minerals and quartz grains as well, and problems with their application to environmental determinations. Schneider (1970) also addressed some aspects of this subject. However, it does not seem to be given enough consideration in most investigations.

Finally, we want to make suggestions of ways to overcome at least some of these problems as well as to point out possible additional applications for surface textural studies of heavy minerals.

METHODS

The sediment samples are of the heavy mineral assemblage from the beach and back-beach dunes along the Lake Michigan shore at Terry Andrae-Kohler State Park, Wisconsin (Fig. 1). Dubois (1972) reported magnetite, ilmenite, garnet, epidote, zircon, amphibole, and pyroxene as being common heavy constituents of the locale's sediment. These heavy minerals are concentrated by wave action in dark layers and lag pockets of beach sand. The area's energy system and sediment transport were subjects of a study by Turner (1972).

Between 900 and 1,000 individual grains were viewed under the JEOLCO/JSM-3 scanning electron microscope of the Surface Studies Laboratory at the University of Wisconsin-Milwaukee. Approximately 1/10 of that number were studied in some detail. Grains were hand picked under optical microscopes following initial electromagnetic separation of the bulk sand. Primary concerns of the study were restricted to those mineral types (1) most abundant in a size range from 1.5ϕ (350μ) to 4.0ϕ (62.5μ), (2) readily identifiable under plane- and polarized-light microscopes, and (3) easily selected by hand. In particular, grains of magnetite, amphibole, pyroxene, and garnet were studied in detail. Grains were analyzed with the attached Nuclear Diodes Micro analyzer as a further check on identification.

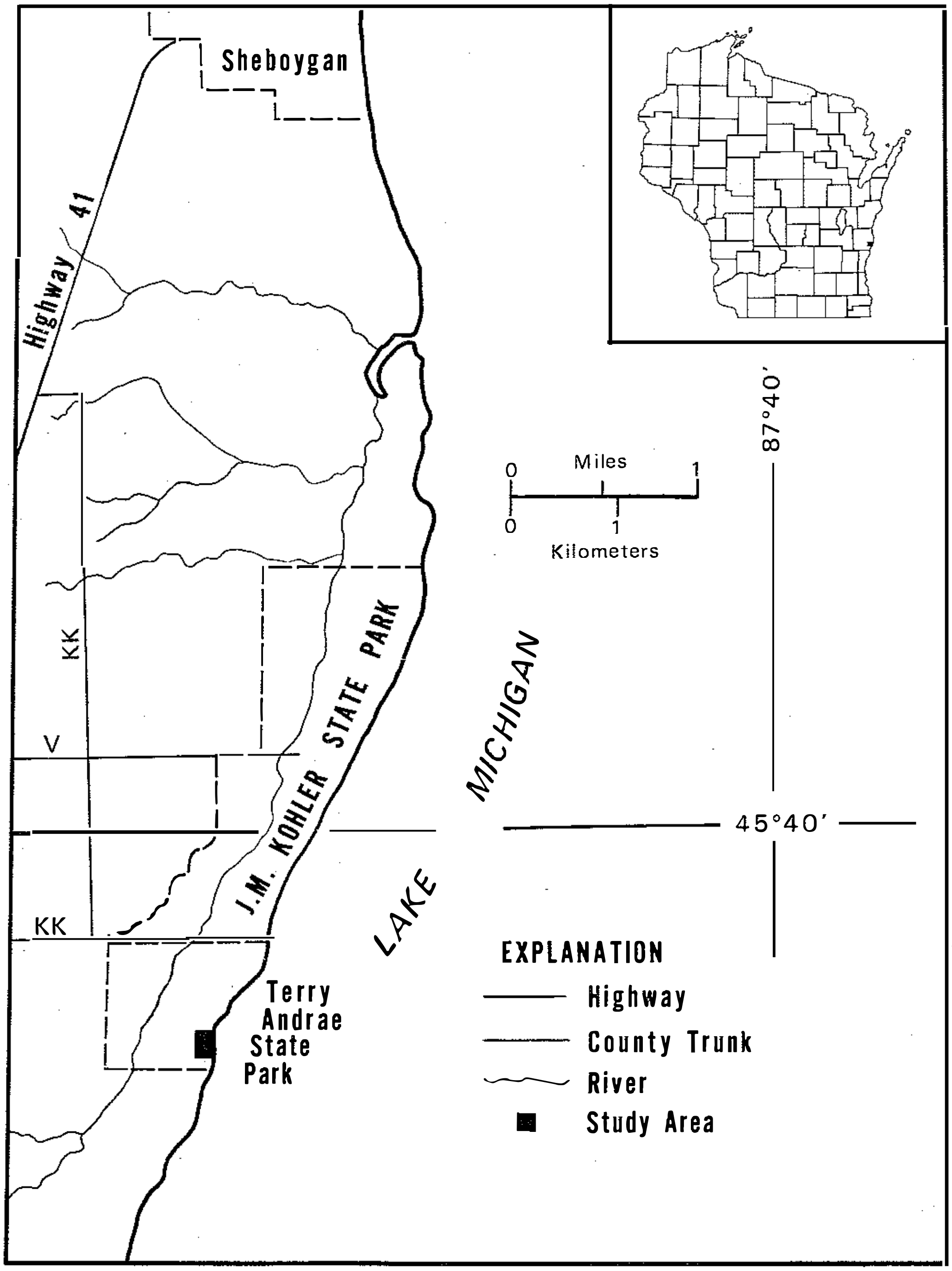

Figure 1. Generalized location map of the sample area. Modified from Turner (1972).

MICROTEXTURES

Our study was originally intended simply to sample several different, but adjacent, freshwater environments, catalog the textures observed, and determine which textures were characteristic or most abundant in each. As the work progressed it became apparent that separation of the various environments in this manner was not possible. We feel that there are a number of reasons why environmental distinctions are difficult to make. This section will describe the prominent textures displayed by several different kinds of heavy minerals. A discussion of the complicating factors will be reserved for a later section.

Mechanically produced features, etch features, overgrowth features, as well as some possible relict original textures were observed. The criteria for recognizing mechanical and chemical features have been presented in several papers (Margolis 1968; Margolis and Kennett 1971) and a useful summary is presented by Margolis and Krinsley (1974). In general, we have classified as mechanical features various kinds of pits and scratches often randomly distributed over the grain surface, and rather large blocky features with distinct outlines. Solution features observed include crystallographically oriented or controlled pits, rather deep tunnel-like pits and several extensive features where etching has accentuated apparent differences in composition or crystallographic orientation (Fig. 2D). In some instances solution has rounded edges or outlines of earlier features or somewhat subdued relief over large parts of grains. Overgrowths have produced crystallographically oriented positive features on some grains. Other types of both solution and overgrowth features have been recognized on quartz grains (Margolis and Krinsley, 1974). Possible relict original textures are suggested by clusters of relatively deep steep sided pits found on parts of some grains.

Although relatively little is known about the range of mechanical or chemical features to be expected on heavy mineral grains, even less is known about original textures of any type of grains.

Magnetite

Magnetite grains of the samples studied exhibited distinctive features which are characterized with a high degree of confidence. Commonly, the grains appear porous, almost spongelike (Fig. 2A); large relatively flat areas that may be relict crystal faces suggest octahedral crystals. The raised surfaces of breakage blocks (Fig. 2B) are more nearly planar than those of quartz grains. The sides of blocks exhibit steplike fracture patterns. Small shallow mechanically-produced pits are irregular in outline and are randomly distributed over the surface.

Surface textures interpreted as the result of chemical solution were not uniform on all grains viewed. Solution was extensive on most grains, as revealed by reduction of sharp mechanically produced features. Many grains exhibited a platy or furrowed appearance in some views (Fig. 2C). This same feature is apparently common on magnetite grains from the coast of Israel

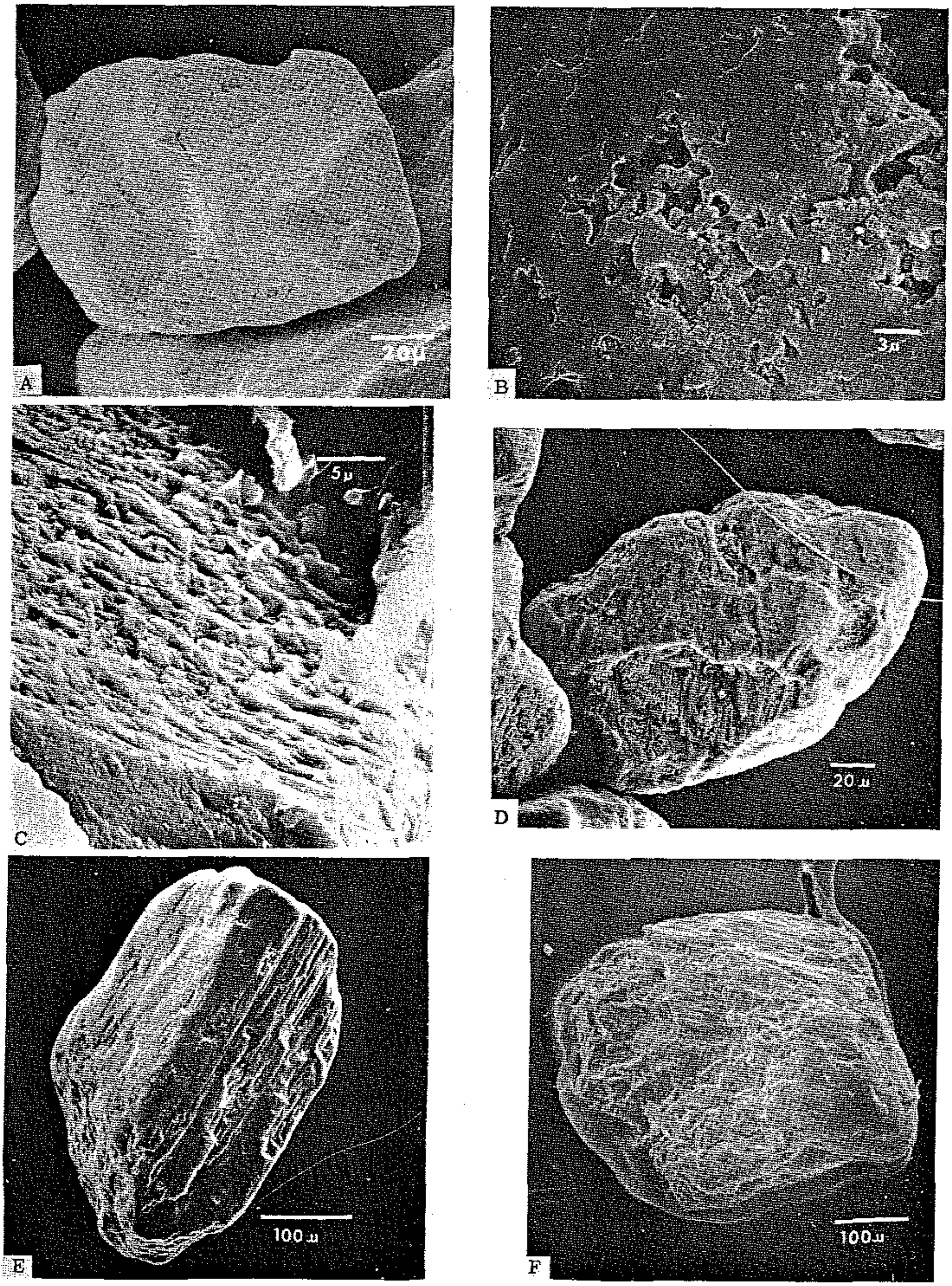

Figure 2. A: Porous appearing magnetite grain. B: Higher magnification of the magnetite surface texture. Note relatively flat breakage block surface and lack of V-shaped pits. C: Platy, step-like pattern exhibited by many magnetite grains. Approximately perpendicular view to that shown in B. D: Blocky, lattice-like solution pattern of magnetite. E: Amphibole grain. Note well developed cleavage parallel to grain elongation. F: Pyroxene grain. Note cleavage well developed but not as extensive as on grain in E.

(Lin and others, 1974). A small number of magnetite grains exhibited a striking blocky pattern. A similar pattern of solution-modified texture (Fig. 2D) was reproduced by etching laboratory-crushed magnetite with H_2SO_4.

Many magnetite grains exhibit clusters of steep sided deep pits on some raised surfaces (Fig. 2B). Scheider (1970, Figs. 2 & 3) illustrated the surface of a weathered but untrasported quartz grain and suggested that some textures observed on sedimentary grains may be relict features of this type. Pits such as those in Fig. 2B seem best interpreted as relicts on the higher flat parts of grains because these surfaces probably represent part of the original outline of the grain whereas lower areas develop by the removal of blocks of material; particularly during glacial transport. In addition, we feel that other original textures in addition to grain boundary indentations such as crystal or gas bubble inclusions may be more common than generally believed.

Amphibole and Pyroxene

The similar properties of amphibole and pyroxene observed in hand specimen or thin section carry over into the micromorphologic surface character of the grains (Figs. 1E & 1F). Numerous species of each group are reported from Lake Michigan beach sands and add to the problem of deriving a specific group of identifying features. For example, hornblend has a wide range of composition which produces a variety of physical properties (Berry and Mason, 1959). How that range or the differences within a pyroxene series such as the enstatite-hypersthene series influence surface textures is not known.

Surface textures on amphibole-pyroxene grains from the freshwater environment observed during this study appear similar to those described by Setlow and Karpovich (1972) from the marine environment. Cleavage of pyroxene grains, although well developed, is in many cases not continuously parallel with grain elongation. At high magnification (5000X), individual cleavage traces seem to show greater linear continuity and are closer together than on amphibole (Figs. 3A and 3B). Although many cleavage surfaces appeared fresh, chemical alteration of grains of either the pyroxene or the amphibole group appeared significant. In some instances, the cleavage faces have apparently been smoothed and the relief subdued (Fig. 3C). Some grains (Fig. 3A) presented a splintered appearance with sharp angles and reentrants. In other cases, small blocks have been removed (Fig. 3D) and the control of crystallinity is evident but the initiating cause, whether chemical or mechanical, is not clear.

Garnet

The garnet group exhibits development of surface textures, which reflect the influence of compositional differences. Imbricate wedge markings are common on both light-colored and dark-amber garnets (Figs. 4A and 4B). Well-developed symmetrical features apparently identical to those illustrated by Setlow and Karpovich (1972) are also exhibited. These crystallographically controlled features may have either positive or negative relief (Fig. 4A and

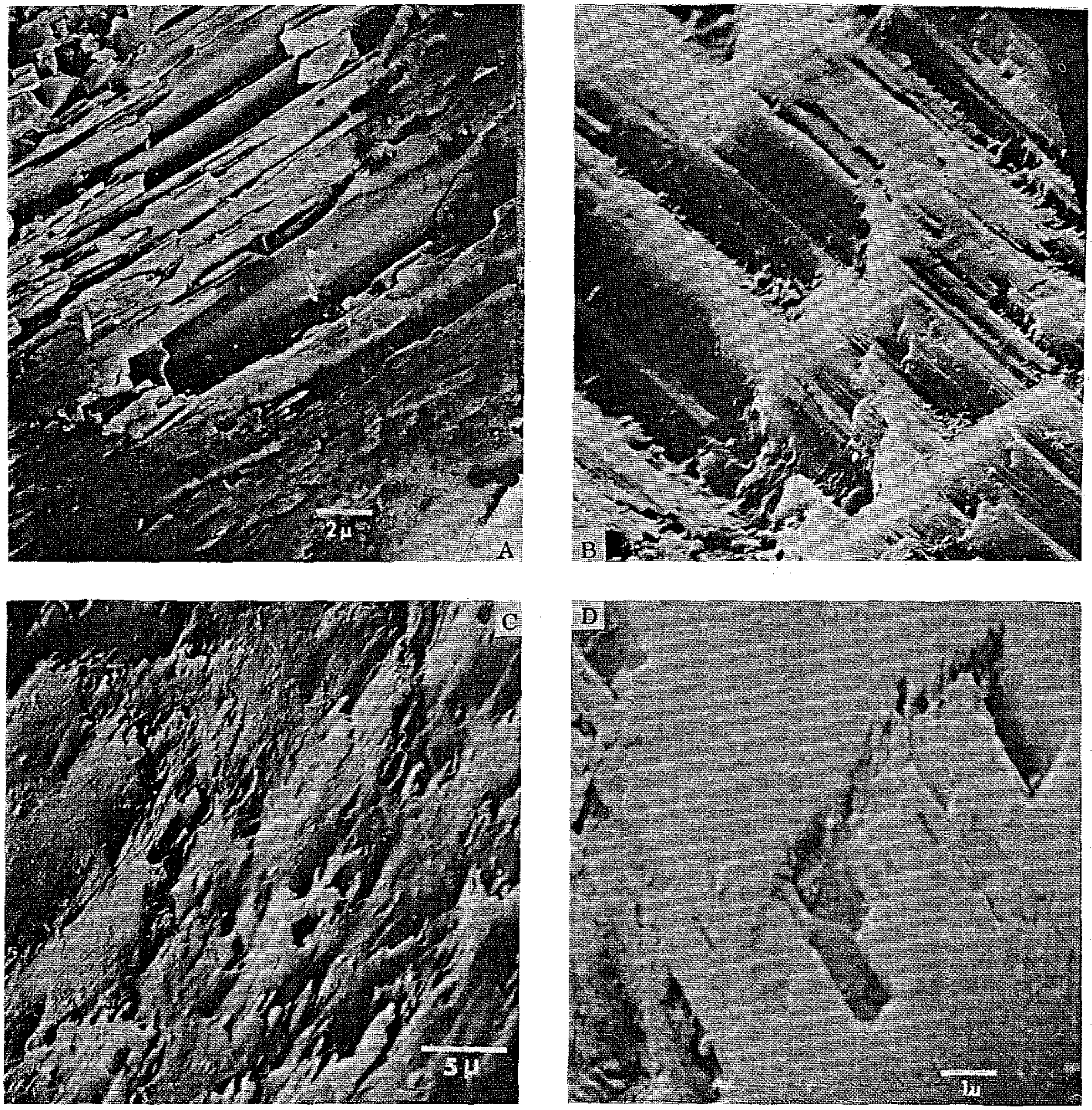

Figure 3. A: Higher magnification of amphibole cleavage faces. Note sharp edges and lack of smaller scale features. B: Higher magnification of pyroxene cleavage faces. C: Amphibole cleavage faces smoothed and subdued by solution. D: Small cleavage controlled features on an amphibole cleavage face.

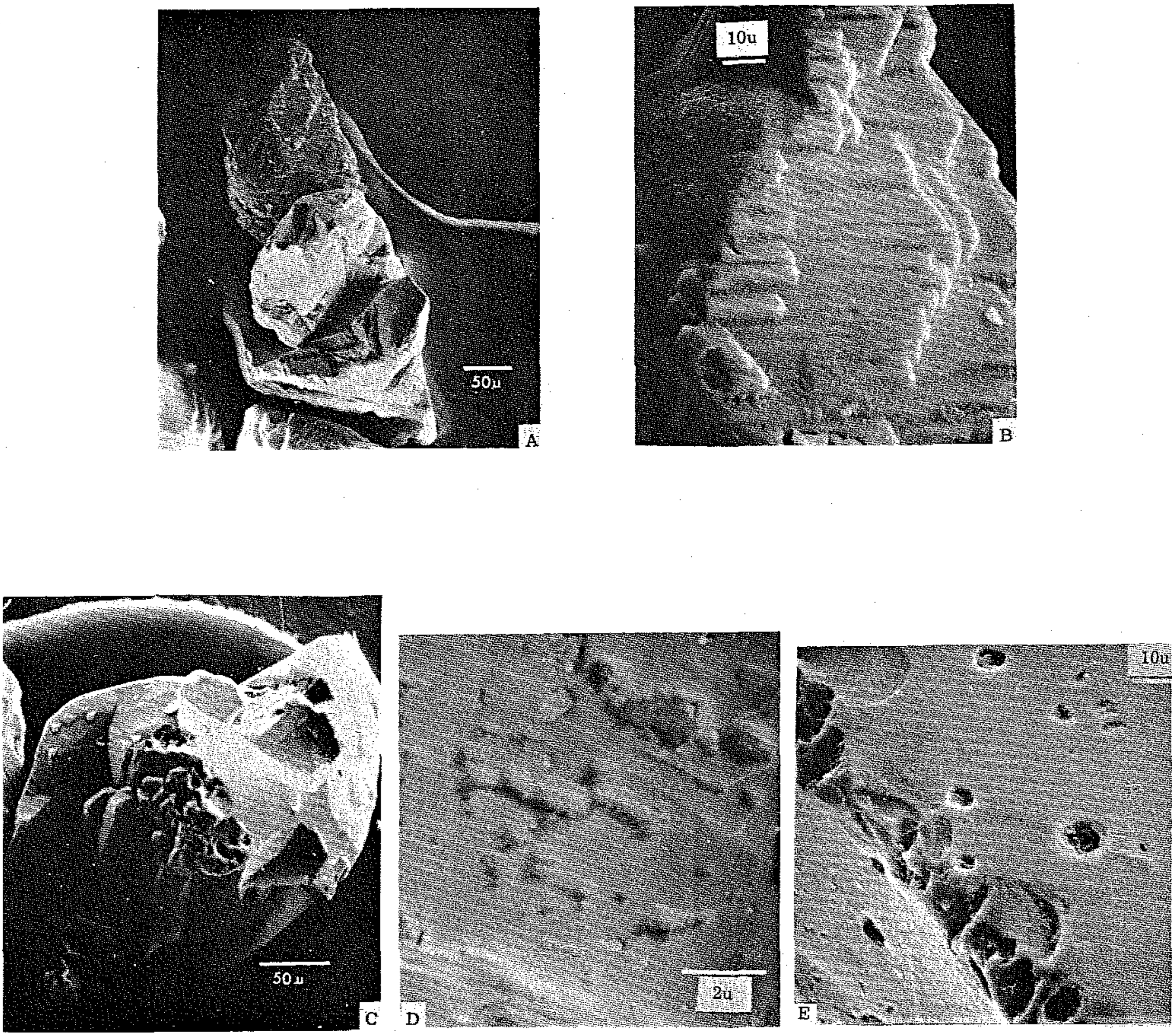

Figure 4. A: Garnet grains. Top grain covered by imbricate wedge markings. Middle grain has a well formed octahedral etch feature. B: Higher magnification of the imbricate wedge markings shown in A. C: Garnet grain modified by solution in the central part with octahedral shaped depressions on the upper right. D: Garnet grain with shallow, flat-bottomed pits and rectangular and tetrahedral shaped pits modified by solution. E: Deeper rounded pits on a garnet grain. Note also the crescent shaped mechanical features on the upper right and along the grain edge.

4C). It has been suggested that both wedge markings and the faceted features are formed by overgrowths on the grains (Simpson, 1976).

Setlow and Karpovich (1972, Fig. 4B), illustrate grains covered with "Mounds"; these grains appear similar to grains described by Stieglitz (1969b) as having a somewhat spalled appearance, although the Florida coastal examples do not seem to be as badly corroded. These grains possibly result from modification of imbricate wedge markings originally formed on rounded grain surfaces.

Parts of many grain surfaces are pockmarked by subround pits. These pits appear to be of two types when viewed closely. One type is flat bottomed and shallow and may result from solution modification of earlier mechanically formed features (Fig. 4D). Pits of the second type (Fig. 4E) are relatively deep, in some instances tunnel-like, as reported previously (Stieglitz, 1969b), and apparently result from grain solution or solution modification of relict inclusions.

Another common feature on garnet surfaces are small rectangular-to tetrahedral-shaped pits formed by impact. Removal of the small chips on impact seems to be influenced by crystallography, because a subparallel orientation of elongation can be seen. The orientation may differ from surface to surface. These features may be enlarged by solution in directions controlled by crystallography and may join to produce a somewhat anastomosing texture (Fig. 4D).

DISCUSSION

In contrast to the number of papers concerning quartz microtextures, studies of heavy mineral grains by the electron microscope are few. Until surface features of grains other than quartz are documented for a wide variety of environments and assemblages, unique characterizations of microtextures for a particular locale are of doubtful validity. Furthermore, the influence of many aspects of grain history cannot be effectively segregated until such documentation exists. Study of material from restricted environments or prepared under controlled laboratory conditions seems necessary to determine whether or not a suite of microtextures characteristic of specific environments exists, as appears to be the case with quartz grains. Recent studies (Setlow and Karpovich 1972, Lin and others 1974, Simpson 1976) have begun to answer some of the questions and establish a firmer base for interpretations.

Heavy minerals would seem to be ideally suited to adding another dimension to the study of clastic deposits. First, they have a range of hardness values, magnetite $5\frac{1}{2}$ - $6\frac{1}{2}$, pyroxenes and amphiboles about 6, epidote 7, garnet 7 - $7\frac{1}{2}$, zircon $7\frac{1}{2}$, and they should behave somewhat differently under different abrasion conditions. Second, because they vary in composition and crystallography, chemically induced microtextures may be imprinted on a grain during weathering, transportation, deposition, or diagenesis which will supply information on the chemical conditions at each of these times. Because of dissimilar responses to chemical conditions, it may be possible for one type of mineral grains to become etched while another develops overgrowths. If the stability fields for each mineral can be accurately determined experimentally, heavy minerals may supply a history of the chemical conditions experienced by a deposit.

In our study different microtextures were recognized but they did not seem to be specific enough to draw environmental interpretations. Surface features observed did not appear mutually exclusive for beach and back-beach dune samples. Textures observed, however, are useful in comparison to those reported from marine environments. For example, minerals such as amphibole and pyroxene exhibit cleavage on small-sized grains. This is apparently true of grains from both marine (Setlow and Karpovich, 1972) and nonmarine areas sampled in this study. However, some minerals, such as those in the garnet group and magnetite, seem to exhibit subtle differences of texture, perhaps as a result of petrogenesis, composition, crystallography, or the chemical conditions of the depositional environment. Hoblitt and Larson (1975) present striking evidence of etch features on magnetic minerals. The artificially etched grain illustrated in Figure 2D and others observed from our samples exhibit this type of selective solution. This may also explain the furrowed appearance of many magnetite grains in that possibly laminae of different crystal orientation or composition are preferentially removed. Subtle differences in the composition and crystallinity of magnetite from different sources (Fleischer, 1965) may influence the shape, size and/or abundance of features present. If this can be demonstrated for other minerals a tool may be available to determine the source of even very small particles. Comparison of the sand or silt grain with artificially etched samples from the supposed source rocks may provide supportive evidence.

In the region from which our samples were obtained other factors, in addition to composition and crystallographic differences, further complicate environmental determinations by heavy mineral grain surface microtextures. Foremost of these is that the sand in the area is derived from wave erosion of lake bluffs composed of till. The glacial deposits of the area contain material from a number of sources including crystalline and sedimentary rocks as well as previous glacial deposits of northern Wisconsin, Michigan and Canada. Therefore, the till contains a mixed assortment of fresh and recycled grains, some of which may have been transported long distances, while others may have been carried only a short distance by the ice. Another problem in the sample area is that local mixing of material among the shallow water, beach, and back-beach dune systems may occur seasonally or with irregular periodicity. Grains may move relatively short distances into another environment and retain features developed previously.

Although we did observe a great many individual grains, the observations are nevertheless limited when compared to the complexity of the source and depositional systems. Baker (1976), as well as other studies, have indicated a statistical approach may be required to evaluate the significance of surface microtextures. Many studies of quartz grain microtextures have similar drawbacks, resulting in some uncertainty as to the mutual exclusiveness of individual textures. The "glacial" appearing microtextures reported by Setlow and Karpovich (1972) from Gulf of Mexico beach sands is a case in point.

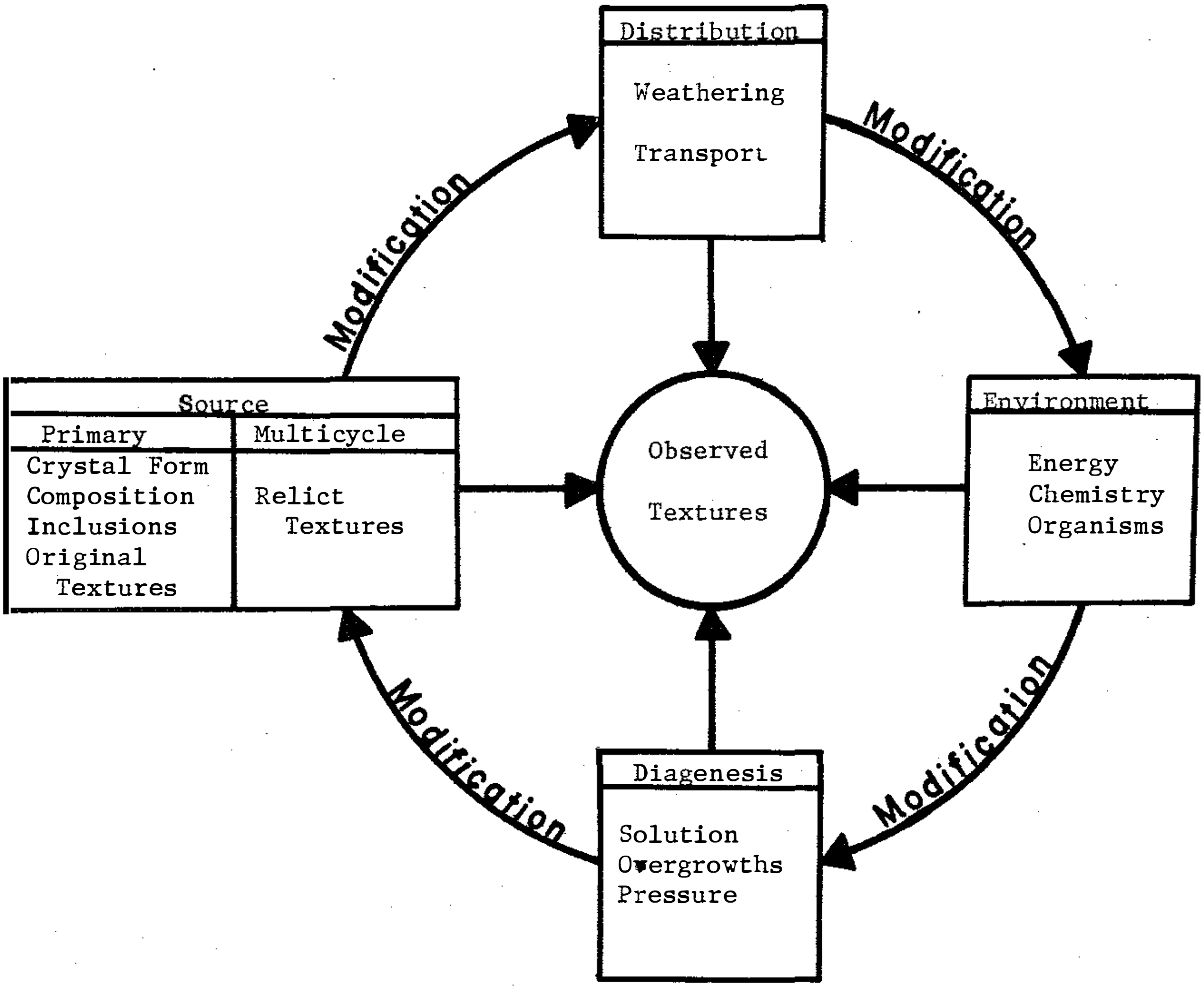

Figure 5. Factors affecting grain surface microtextures.

Figure 5 is a summary of the multiple factors which can affect the microtextures observed on a clastic grain. Basically they can be grouped into four categories: 1) features characteristic of a particular source, 2) features which may be imprinted onto the grain during weathering or transport prior to its arrival in the environment of deposition, 3) features developed in the depositional environment, and 4) features developed by diagenetic processes after deposition. The separation of the categories is somewhat arbitrary, particularly between distribution and deposition, but it does allow for a more complete concept of the total process. Features developed at any point in the history of a grain may be preserved and be observed when the grain is sampled. Correspondingly, some of the features developed may be obliterated or modified by a succeeding process. Microtextures developed during diagenesis can be observed in addition to or as modification of any of the preceeding categories of textures when the grain is from an ancient deposit. When the grain is recycled by subsequent erosion diagenetic microtextures may be modified by processes acting during distribution or deposition. Recently, Potter (1968) has shown that garnets may be significantly affected by intrastratal solution. Rahmani (1973) described intricate solution features on various kinds of heavy mineral grains from Cretaceous-Paleocene sandstones. Such multicycle source materials are probably common in nature.

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COPPER, LEAD, ZINC, NICKEL, AND SILVER IN LAKES OF THE CLAM LAKE AND MONICO REGIONS, NORTHERN WISCONSIN

by

Douglas E. Pride[1]

ABSTRACT

The accumulation of copper, lead, zinc, nickel, and silver in lake sediments from the Clam Lake and Monico regions has been studied to provide information on the potential for anomalous mineralization in the underlying Precambrian bedrock. The high organic content of the lakes suggests that the metals in part were fixed within the sediments by absorption onto organic debris.

A positive linear relationship exists between the mean metal contents of Cu, Pb, Zn, and Ni and the mean weight percent organic matter in the lakes, when the data are plotted on semilog paper. The relationship is most clearly demonstrated by lead and nickel. Confidence limits were calculated for the regression of Cu, Pb, Zn, and Ni upon organic matter, and data points falling above the upper limits may represent anomlous metal concentrations within the lake sediments.

The northern part of the Clam Lake region, and the area around Monico in the Monico region, are of greatest interest with regard to possible mineralization in the Precambrian bedrock. In the Clam Lake region, at the 95% level of confidence, Beaver, Tea, Coffee, Mineral, Potter, and Buffalo lakes exhibit anomalous concentrations of one or more of Cu, Pb, Zn, and Ni. The same is true for Ogemago, Sequilla, Kechewaishke, and Tank lakes in the Monico region. At the 99% level, significant metal concentrations in the Clam Lake region occur in Beaver, Tea, Coffee, and Potter lakes; and in the Monico region, in Ogemaga, Kechewaishke, and Tank lakes. Generalizations with respect to silver are difficult because of the low concentrations and the spotty nature of the data. Additional work should be done to more clearly define the potential for anomlous mineralization in the Precambrian rocks of the two regions.

INTRODUCTION

Large areas of the Precambrian bedrock of Canada and the northern United States are covered by glacial deposits. Where the glacial material is local in origin, it may reflect quite well the underlying bedrock composition. However, in regions where it was derived at some distance from the point of deposition, the underlying composition will be poorly represented. Drainage in the shield region generally is characterized by swamps, bogs, and poorly-developed stream patterns. The transported nature of the debris and the poorly-developed drainage present special problems for standard techniques of geochemical exploration such as bedrock sampling, and soil and stream sediment sampling.

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Recently, attention has turned to lake sediment geochemistry as a guide to anomalous mineralization in regions of buried bedrock. The initial efforts in North America have been conducted largely in the shield region of Canada. Little has been published on lake sediment geochemical exploration in the United States. In the present study lake sediment samples were collected from two regions in northern Wisconsin (Figure 1). The purpose was to provide data for copper, lead, zinc, nickel, and silver that may help in determining the potential for anomalous mineralization in the underlying Precambrian bedrock.

The locations of the lakes to be sampled within the two regions shown in Figure 1 were chosen so as to traverse as much of the Precambrian geology as possible. Regional trends in the underlying rocks are shown by Dutton and Bradley (1970). Bedrock information, the locations of the lakes, and the locations of samples within the lakes are shown in Figures 2-5.

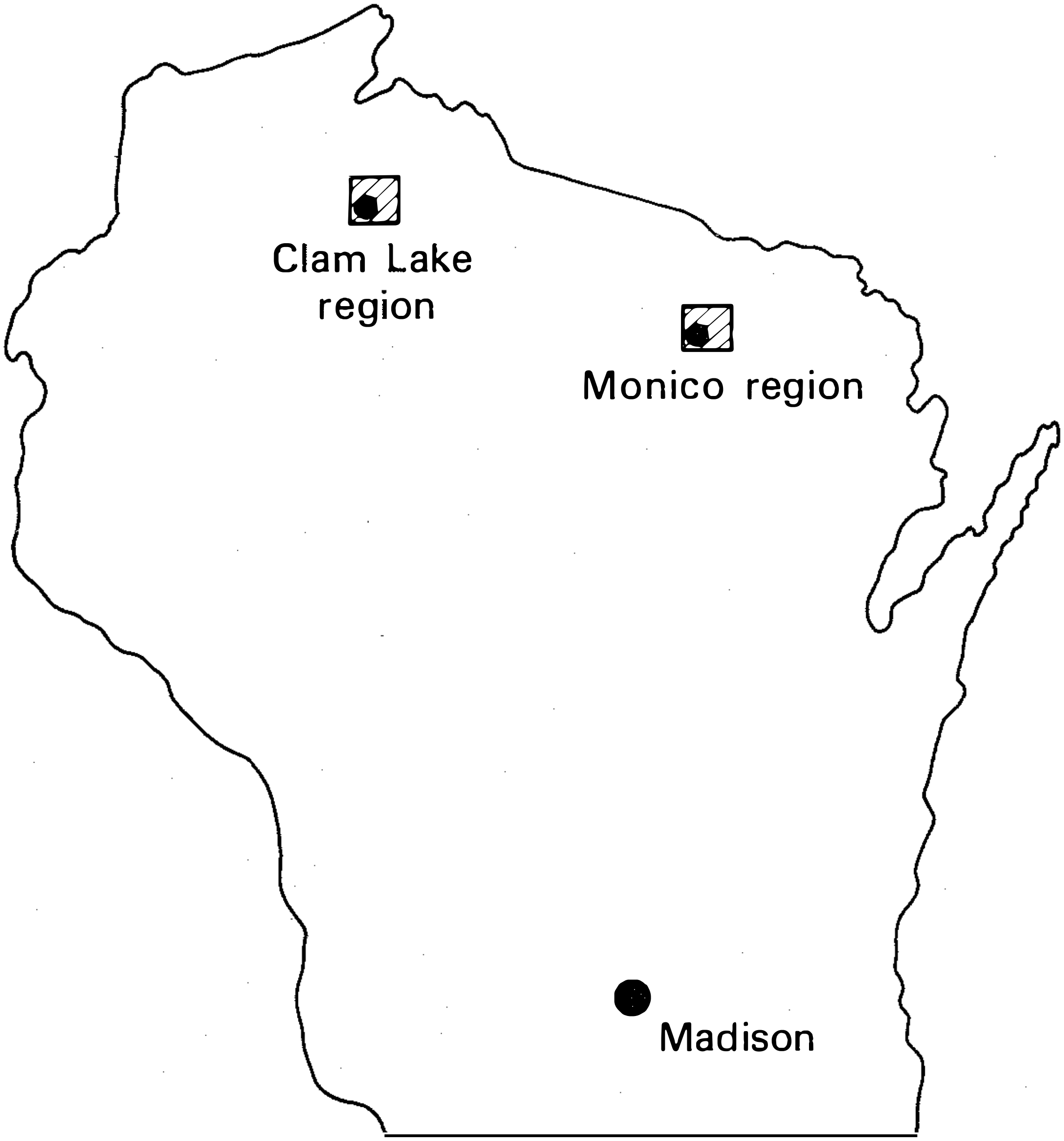

Figure 1. Locations of the Clam Lake and Monico study regions in northern Wisconsin.

Important clues to anomalous mineralization may be transmitted to the lake basins in solution and/or suspended sediment within stream or surface runoff. Groundwater circulating in contact with the underlying bedrock also may transmit important information to the lake sediments. Most of the surface material, even in areas where bedrock outcrops are present, is glacial in origin. Metal anomalies thus become difficult to interpret.

The intent of the present study was to identify potential anomalies resulting (1) from groundwater circulating in contact with the bedrock beneath the lakes, and/or (2) from surface waters draining anomalous rock outcrops. Multiple samples were taken from each lake, the purpose being to separate significant bedrock anomalies from anomalies that might be spawned by metal-rich glacial erratics. The number of samples ranged from 2 to 11, depending on the size of the lake (Figures 4, 5).

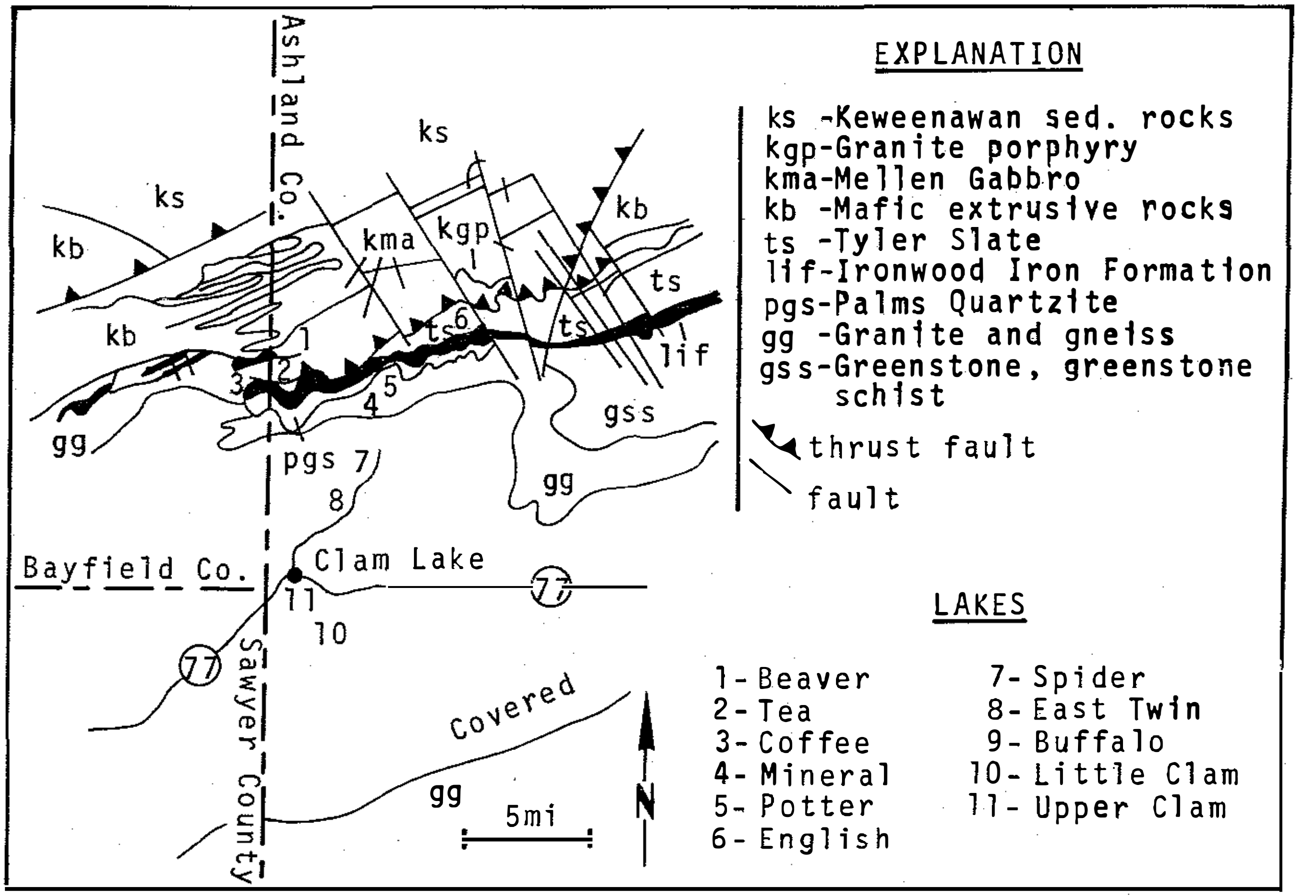

Figure 2. General geology and locations of lakes sampled in the Clam Lake region (geology from Dutton and Bradley, 1970).

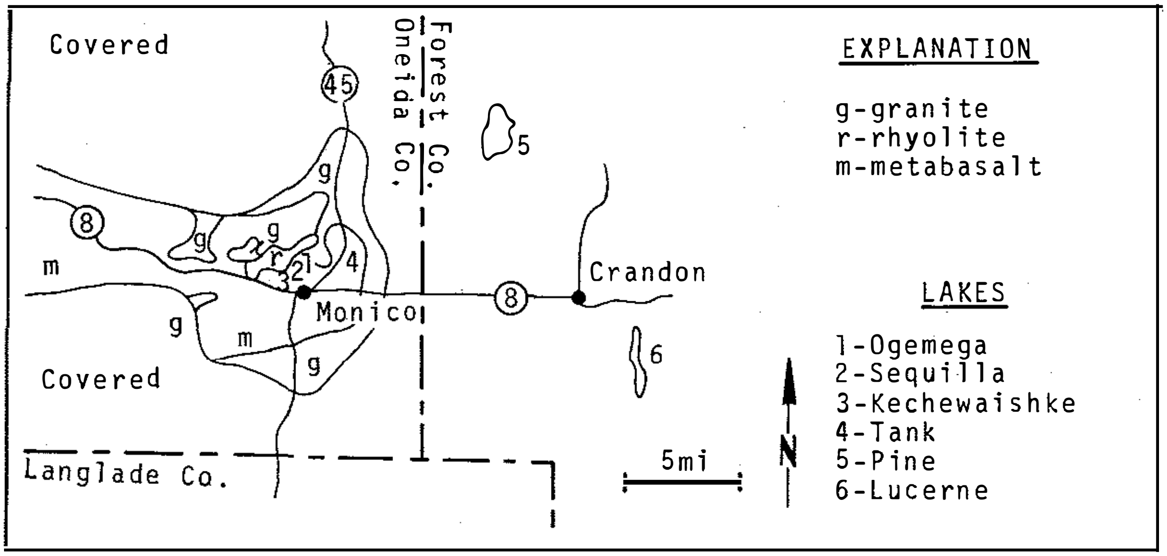

Figure 3. General geology and locations of lakes sampled in the Monico region (geology from Dutton and Bradley, 1970).

FIELD AND LABORATORY STUDY

Sediment samples were collected from a 3.65-meter aluminum boat using a drop-core sample device. The device consists of a heavy stainless steel collar into which is threaded a 30-cm long plastic core barrel. The collar is equipped with a butterfly valve, and samples are taken in such a way that none of the water and sediment remaining in the barrel upon retrieval has touched any metal. The water depth was determined by measuring the length of nylon line needed to take the sample. Following retrieval, the samples were transferred to plastic bags and the sampler was thoroughly rinsed in preparation for the next sample station. The pH of each water-sediment sample was determined upon completion of the sample program for each lake. Indicator paper was used for the pH measurements. Some accuracy thus was sacrificed, but it permitted direct determination of the pH without first having to return the samples to the laboratory. The locations of the sample stations within each of the lakes in the two regions under investigation are shown in Figures 4 and 5.

In the laboratory, two statistically equal portions were selected from each sample: one for elemental analysis, the other for organic determination. The sub-samples selected for chemical analysis were digested in a hot mixture of nitric and perchloric acids, and the residue was heated until dry and leached with 1 M hydrochloric acid. The leachate was diluted with demineralized double distilled water and analyzed for Cu, Pb, Zn, Ni, and Ag with a Perkin-Elmer 303 atomic absorption spectrophotometer. Weight percent organic matter in the samples was determined by measuring the loss in dry weight following digestion in concentrated hydrogen peroxide.

In addition to chemical and organic analyses, one sample from each lake (two from the larger lakes) was subjected to x-ray analysis, to give some measure of the bottom sediment mineralogy. Samples to be x-rayed first were digested in hydrogen peroxide to limit masking effects that the large amounts of organic matter might have on the sample mineralogy.

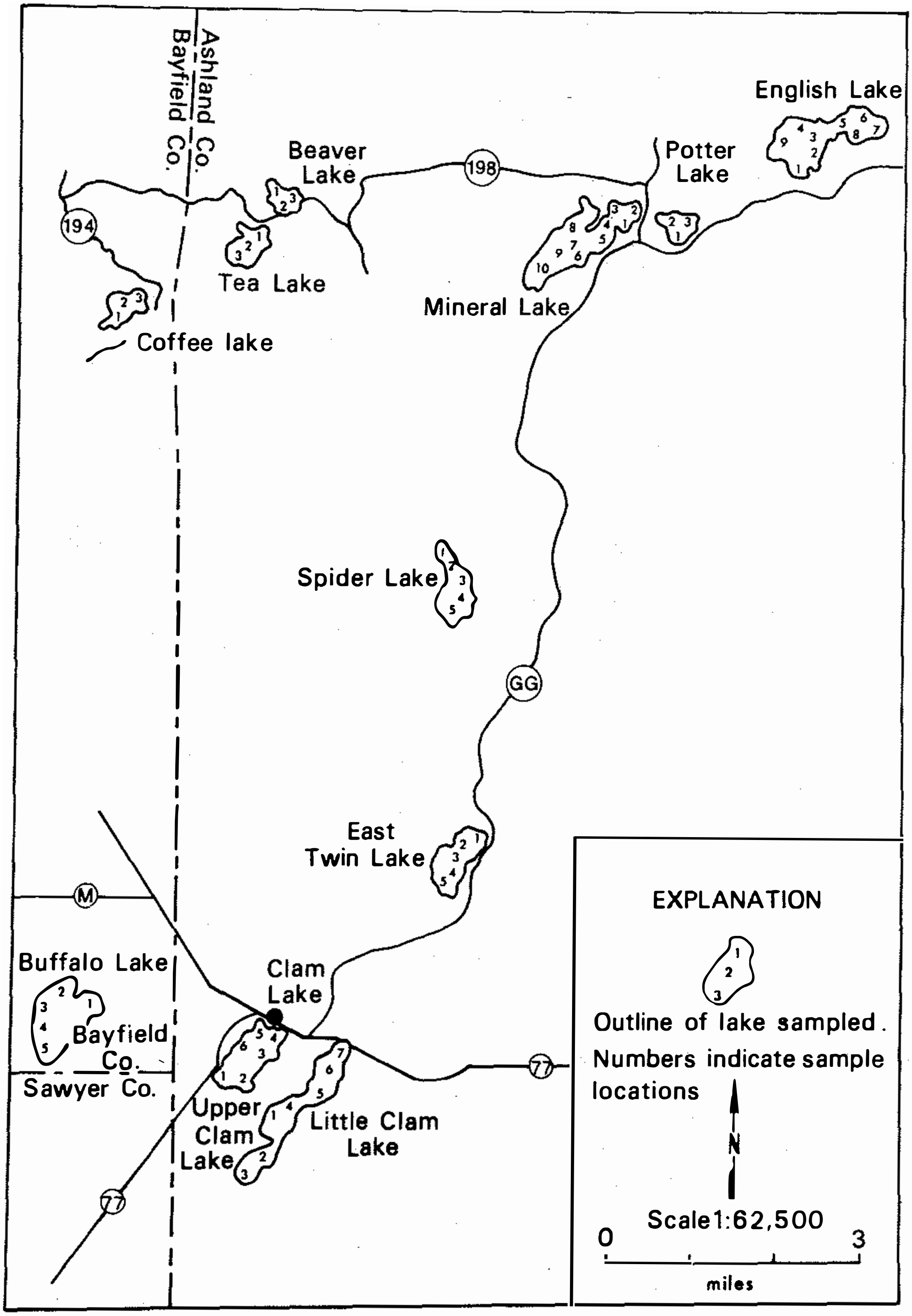

Figure 4. Locations of lakes and sample points within lakes, Clam Lake region.

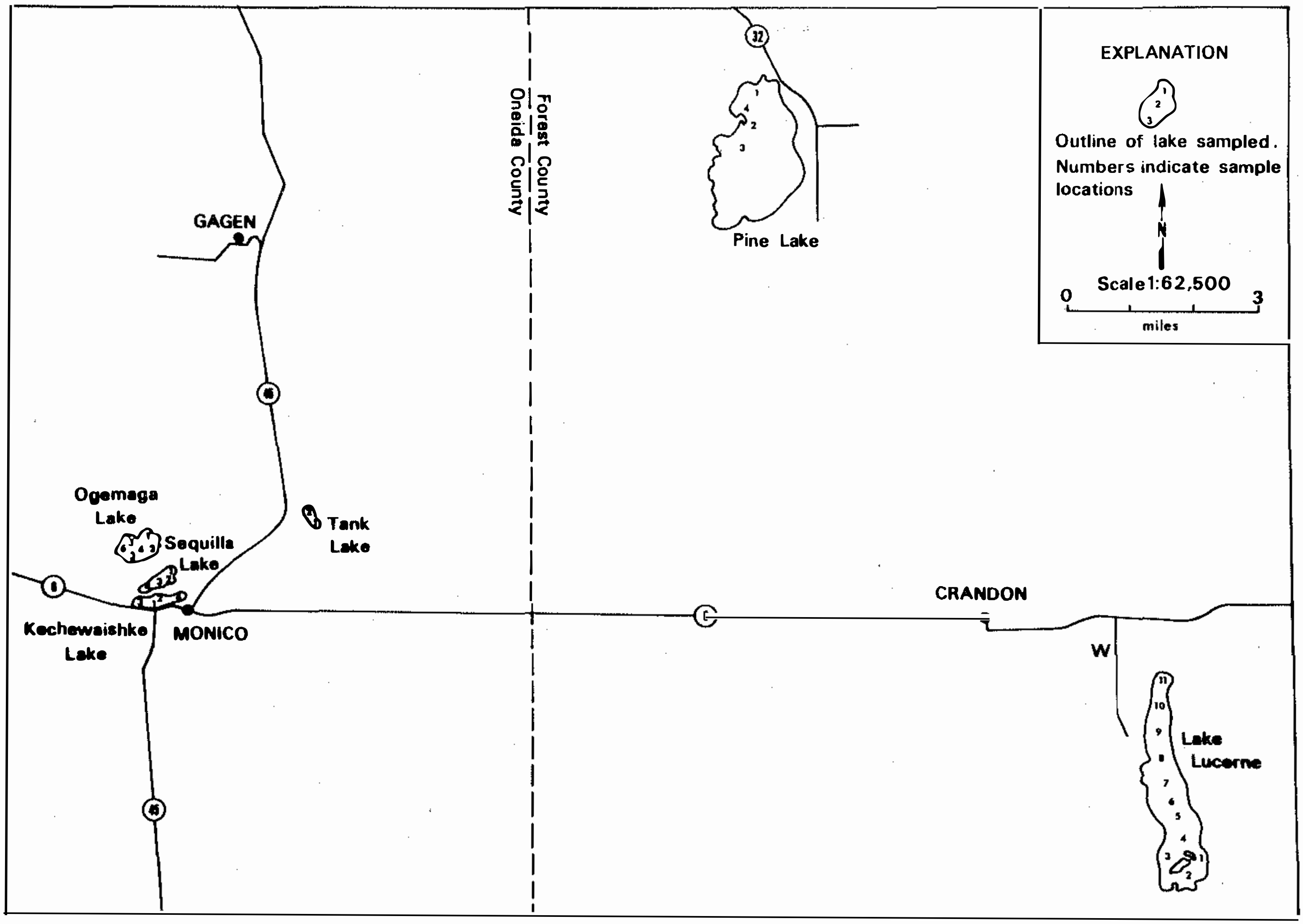

Figure 5. Locations of lakes and sample points within lakes, Monico region.

RESULTS AND DATA EVALUATIONS

Metals accumulate in lake sediments through a variety of complex chemical and biochemical processes. Adsorption of metals onto clay minerals, and onto the hydrous oxides of iron and manganese, as well as accumulations through metal-organic complexing, all may be important in fixing metals within lake sediments.

Specific clay content and the content of the hydrous iron and manganese oxides were not measured. X-ray studies indicate some component of clay minerals in the sediments, in addition to quartz and feldspar. Thus, the potential exists for at least some fixation of metals onto clay minerals. However, the high organic contact (Table 1), dark color, and strong odor of many of the fresh samples suggest that the environment was reducing in nature; and a reducing environment may strongly influence metal accumulations on both clay minerals and the hydrous oxides (Timperly and Allan, 1974). These authors have suggested that in the presence of sulfide ion and organic matter, under reducing conditions, metals accumulate either as metal sulfides or metal-organic complexes, and not by cation exchange onto clays or other silicate minerals. In addition, the hydrous oxides of iron and manganese probably play a minor role in metal accumulations within reducing environments, as they are unstable under reducing conditions (Garrels, 1960; Timperly and Allan, 1974).

Metal sulfides were not noted in the x-ray patterns, and thus metal-organic complexing probably is of greatest importance in concentrating metals within the lake sediments. The relationships of mean concentrations of Cu, Pb, Zn, and Ni to mean weight percent organic content (Table 2) for the 17 lakes from the Clam Lake and Monico regions are shown in Figure 6. The data are plotted on semilog paper, with the metal concentrations measured by the logarithmic scale. The equation for each of the lines is given at the lower right of the graph. The positive relationship between metal concentration and organic matter is most clearly shown by lead and nickel. One-tailed "t" tests were run to determine whether or not the regression coefficients for the equations shown in Figure 6 are significantly greater than zero, that is, whether or not a positive relationship exists between metal concentrations and organic content of the sediments. The coefficients for Pb and Ni were shown to be greater than zero at the 95% level of confidence. The levels were 80% and 50% respectively for Zn and Cu. The influence of organic matter upon Zn and Cu concentrations thus were less than expected, even at the high levels of organic content shown in Table 2. With this qualification, the data for Zn and Cu were subjected to the same manipulations as the data for Pb and Ni.

Because of the influences of organic matter on metal concentrations, the problem was one of determining which of the lakes may contain concentrations in excess of those due to background contributions. It was felt that data points located considerably above the regression lines shown in Figure 6 might reflect anomalous metal concentrations. To this end, the 95% and 99% confidence limits for the regression of the mean contents of Cu, Pb, Zn, and Ni upon the mean organic content were determined, and are shown in Figure 7. Data points falling above the upper confidence limits may be anomalous. Thus, the regression lines are taken to represent background contributions, and the upper confidence limits the threshold values for the various metals.

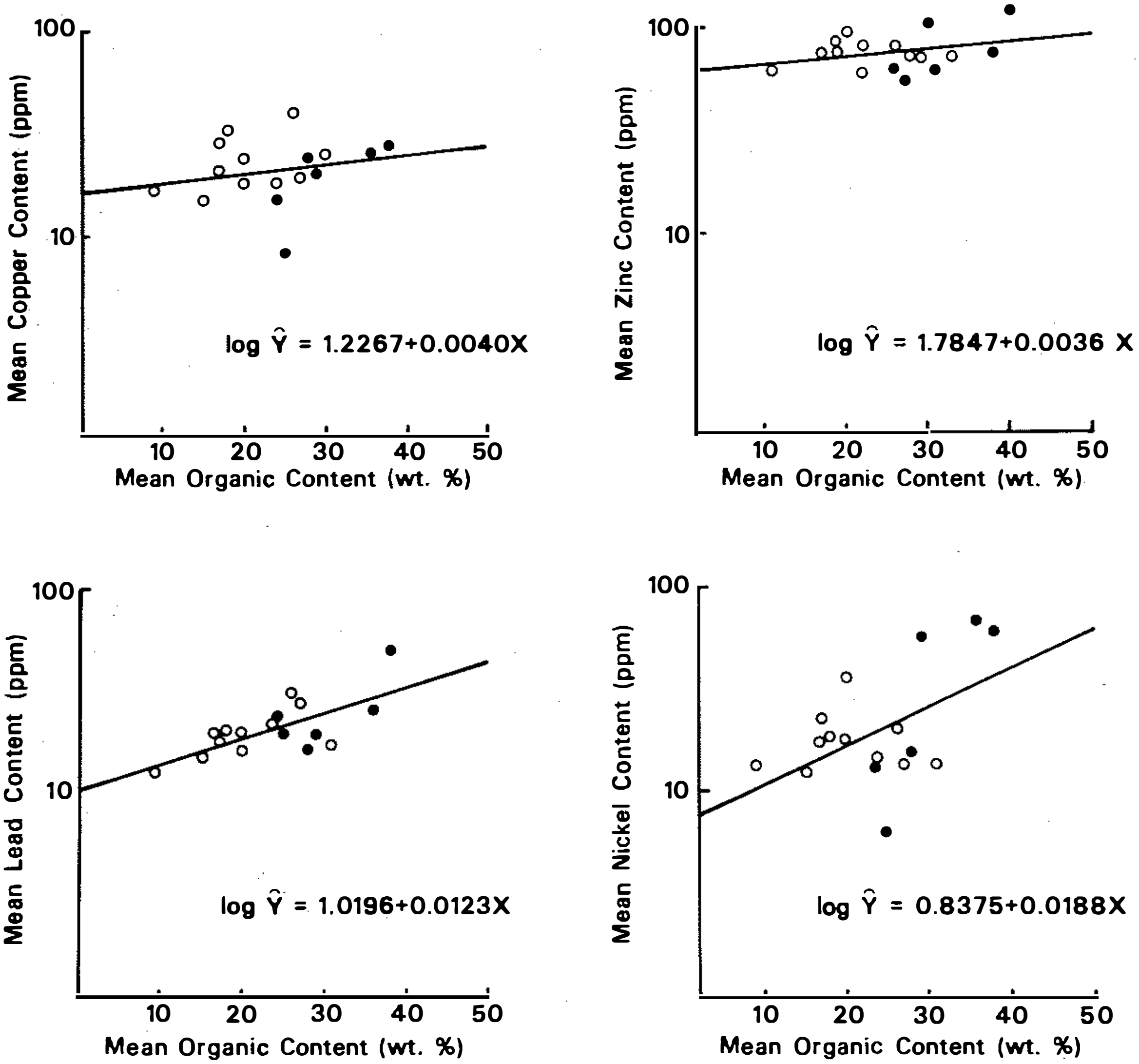

Figure 6. Mean contents of Cu, Pb, Zn and Ni versus mean organic contents in lakes from the Clam Lake and Monico regions, northern Wisconsin (0 = Clam Lake region, ● = Monico region). The equation for the line is given at the lower right for each graph.

CONCLUSIONS AND COMMENTS

Several of the lakes from both the Clam Lake and Monico regions exhibit potentially anomalous metal concentrations at the 95% and 99% levels of confidence (Tables 3, 4). The northern part of the Clam Lake region and the area near Monico appear most promising. Multiple element anomalies exist at the 95% level (Table 3) in Beaver, Tea, Coffee, Mineral, and Potter lakes from the northern Clam Lake region, and in Kechewaishke Lake in the Monico region. Cu-Pb and Cu-Zn anomalies persist at the 99% level (Table 4) in Beaver and Coffee lakes, and Kechewaishke Lake exhibits a Pb-Zn anomaly also at the 99% level (Table 4).

Rock outcrops are evident in both the northern Clam Lake and Monico regions (Dutton and Bradley, 1970), and the trace element chemistry thus may accurately reflect the characteristics of the underlying bedrock. The problem becomes one of differentiating between mineralized versus unmineralized bedrock. For example, high average nickel contents in Ogemaga, Sequilla, and Kechewaishke lakes (Table 2) near Monico may reflect the composition of the basalts that outcrop nearby (Fig. 3, Table 1). However, Cu values in these lakes are not correspondingly high, and the high nickel values plus the elevated contents of lead and zinc in Kechewaishke Lake (Table 2) may indicate abnormal mineralization in the underlying bedrock. The geology of the northern Clam Lake region is complex (Figure 2), and the metal anomalies noted in Tables 3 and 4 also may reflect contributions from unmineralized bedrock. However, the persistence of the multiple metal anomalies at the 99% level of confidence suggests that anomalous mineralization may be present in the area.

Silver concentrations are low throughout the two study regions, with concentrations ranging only to 13 ppm and rarely exceeding 5 ppm (Table 1). Notably, samples containing more than 5 ppm contain at least 25 weight percent organic matter. Samples from Sequilla and Kechawaishke lakes contain some silver, but these concentrations also may reflect the composition of the nearby basalts.

It should be noted that lead contamination from gasoline for motor boats is a possibility in all but the very small lakes. This may be particularly true for Buffalo Lake in the Clam Lake region (Table 3), as it is subjected to considerable motorized boat traffic. Lead anomalies probably are of greater significance in lakes exhibiting anomalous concentrations of one or more of the other trace metals.

The lake sediment sampling program provides intriguing clues to the possible existence of anomalous mineralization in rocks of the northern Clam Lake region and in the vicinity of Monico in the Monico region. Additional sampling of lakes and available outcrops should be undertaken to further define the potential for significant bedrock mineralization.

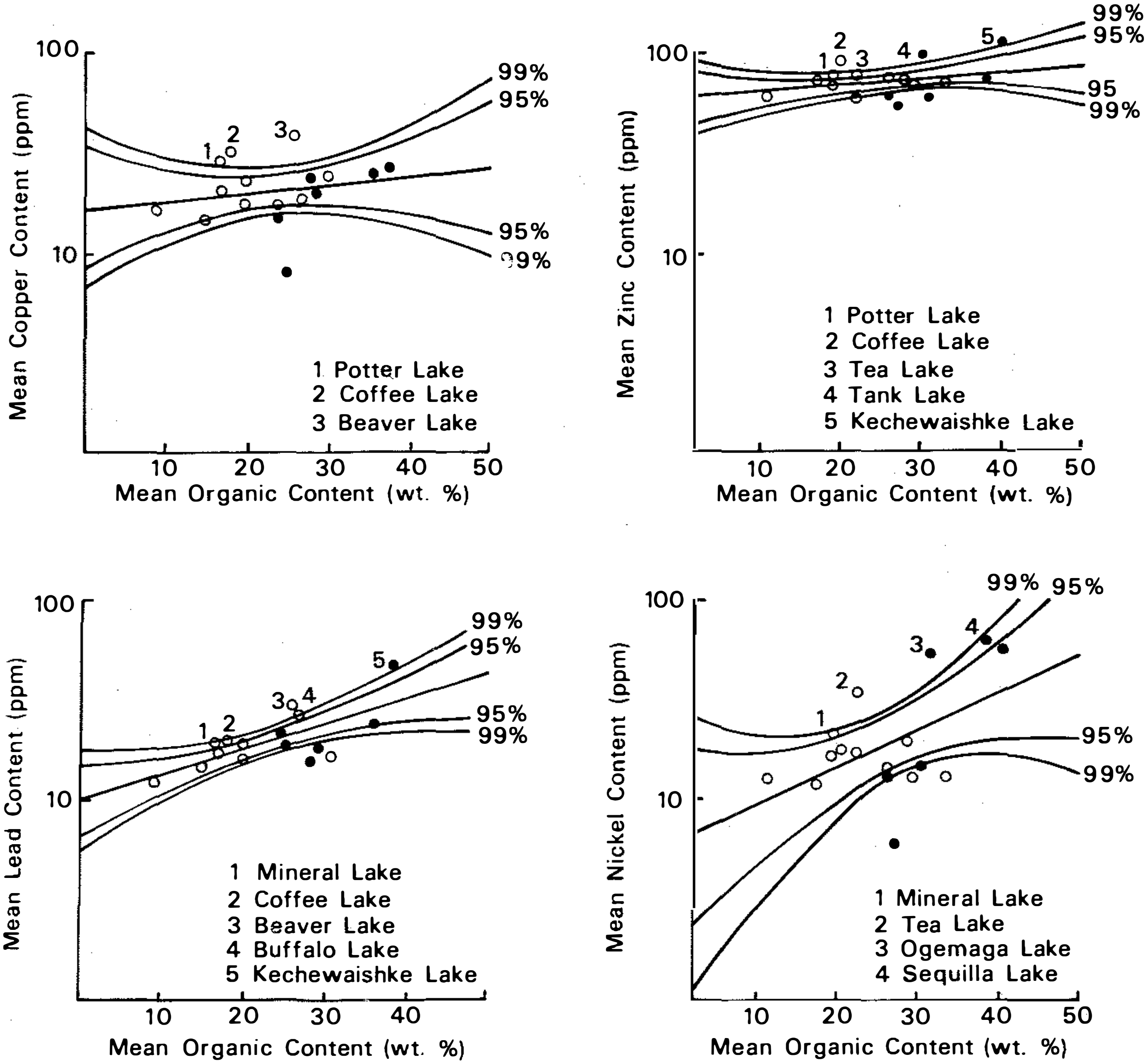

Figure 7. 95 percent and 99 percent confidence limits for mean contents of Cu, Pb, Zn and Ni about the least squares lines shown in Figure 6. Numbers indicate lakes from which the mean metal content falls above the 95 percent and 99 percent confidence limits.

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Table 1. Analytical data on lake geochemistry

Lake		Cu (ppm)	Pb (ppm)	Zn (ppm)	Ni (ppm)	Ag* (ppm)	Organic content (wt.%)	pH+	water depth (feet)	nearby bedrock
Clam Lake Area										
Beaver	1	47	39	83	21	3	28	4.5-5.0	11	
	2	36	29	83	20		26	4.5-.50	15	
	3	37	22	55	18		21	4.0-4.5	7	
Tea	1	29	23	91	16		24	4.0-4.5	29	
	2	28	26	101	21	3	20	4.5-5.0	46	
	3	14	9	48	69		17	4.5-5.0	21	
Coffee	1	28	16	104	21		17	4.5-5.0	9	
	2	45	28	115	20	5	23	4.5-5.0	14	
	3	25	15	60	14		14	4.5-5.0	10	
Mineral	1	27	23	81	16		25	4.5-5.0	9	
	2	32	24	87	16		24	4.5-5.0	10	
	3	31	8	70	23		20	4.5-5.0	8	
	4	6	12	35	6		4	4.5	4	granite
	5	25	24	81	34		22	4.5-5.0	17	granite
	6	9	15	74	15		9	4.5-5.0	12	
	7	21	26	95	17		21	4.5	18	
	8	19	15	78	20		14	4.5-5.0	12	
	9	20	26	87	53		21	4.5-5.0	20	
	10	19	15	65	16		14	4.5-5.0	15	
Potter	1	26	19	78	16		14	4.0-4.5	8	
	2	30	10	80	20		14	4.0-4.5	9	
	3	30	25	77	14		23	4.0-4.5	8	
English	1	11	3	31	7		7	4.5-5.0	10	
	2	23	20	53	17		22	4.5-5.0	12	
	3	13	--	59	34		23	4.5-5.0	15	
	4	4	4	28	5		2	4.5	15	
	5	19	16	67	19	9	26	4.5	10	granite
	6	14	13	71	21		24	4.5-5.0	14	
	7	36	38	86	22	4	28	4.5-5.0	34	
	8	26	22	69	17		26	4.5-5.0	14	
	9	19	28	71	13		21	4.5-5.0	14	

Spider	1	5	6	51	10		8	4.5-5.0	10	
	2	3	16	47	15		5	4.5-5.0	10	
	3	34	18	83	14		21	4.5-5.0	20	
	4	17	12	102	11		18	4.5-5.0	20	
	5	16	22	86	12		21	4.5-5.0	20	
East-Twin	1	47	11	50	8		25	5.0	5	
	2	15	25	55	11		38	5.0	10	
	3	25	28	100	17		25	5.0	10	
	4	13	5	12	12		31	4.5-5.0	5	
	5	25	16	80	15	13	38	4.5-5.0	5	
Buffalo	1	22	39	81	11	3	32	4.5	18	
	2	25	24	104	19		30	4.5	18	
	3	14	18	35	12		26	4.5	8	
	4	22	35	104	15		32	4.5	17	
	5	11	17	31	8		15	4.5	10	
Little Clam	1	15	21	90	14		27	4.0-4.5	9	
	2	18	17	82	17		25	4.0-4.5	9	
	3	12	10	75	12		29	4.0-4.5	10	
	4	19	51	56	16		15	4.0-4.5	5	
	5	21	--	68	12		27	4.0-4.5	5	
	6	25	31	87	15		23	4.0-4.5	8	
Upper Clam	1	31	17	74	18			5.0-5.5	16	
	2	20	21	53	17			5.0-5.5	11	
	3	12	7	37	10			5.0-5.5	7	
	4	6	8	82	5			5.0-5.5	10	

Monico Area

Ogemaga	1	19	15	46	94		29	4.0-4.5	3	
	2	14	24	68	192		33	4.0-4.5	2	
	3	13	30	60	26		26	4.0-4.5	4	
	4	28	20	65	--		29	4.0-4.5	5	
	5	24	16	70	7		--	4.0	4	basalt
	6	19	11	56	8		--	4.0	4	
Sequilla	1	21	15	82	164		44	5.0-5.5	10	
	2	23	16	65	12		30	5.0-5.5	11	
	3	31	33	83	76	12	39	5.0-5.5	15	
	4	26	36	68	10		30	5.0-5.5	20	

Kechewaishke	1	17	65	124	48	7	41	5.5	20	basalt
	2	29	25	93	16		33	5.5	17	
	3	22	50	141	149		44	5.5	15	
	4	38	54	112	18	4	32	5.5	16	basalt
Tank	1	23	17	101	15		28	4.5-5.0	10	
	2	25	14	101	15		27	4.5-5.0	12	
Pine	1	4	23	53	4		34	4.5	5	
	2	20	27	78	12		--	4.0-4.5	12	
	3	6	23	59	--		33	4.0-4.5	20	
	4	3	1	31	6		1	4.0-4.5	5	
Lucerne	1	4	7	49	4		4	4.0-4.5	10	
	2	19	12	50	11		--	4.0-4.5	10	
	3	4	4	22	10		4	4.0-4.5	15	
	4	17	39	73	14		29	4.0-4.5	42	
	5	21	16	64	11	3	29	4.0-4.5	56	
	6	8	21	64	24		27	4.0-4.5	65	
	7	22	32	82	15		34	4.0-4.5	70	
	8	17	21	51	11		13	4.0-4.5	55	
	9	17	42	76	13		29	4.0-4.5	52	
	10	20	34	76	21		29	4.0-4.5	45	
	11	12	28	73	13		23	4.0-4.5	20	

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* because of machine fluctuations, Ag contents recorded only when exceed 2 ppm

\+ pH measurements made with indicator paper

Table 2. Summary of analytical data on lake geochemistry

Lake	Mean Cu (ppm)	Mean Pb (ppm)	Mean Zn (ppm)	Mean Ni (ppm)	Mean Organic Content (wt. %)	pH range
Clam Lake Area						
Beaver	40	30	74	20	26	4.0-5.0
Tea	24	19	80	35	20	4.0-5.0
Coffee	33	20	92	18	18	4.5-5.0
Mineral	21	19	75	22	17	4.5-5.0
Potter	29	18	78	17	17	4.0-4.5
English	18	16	59	17	20	4.5-5.0
Spider	15	15	74	12	15	4.5-5.0
East Twin	25	17	71	13	31	4.5-5.0
Buffalo	19	27	71	13	27	4.5
Little Clam	18	22	76	14	24	4.0-4.5
Upper Clam	17	13	62	13	9	5.0-5.5
Monico Area						
Ogemaga	20	19	61	55	29	4.0-4.5
Sequilla	25	25	75	66	36	5.0-5.5
Kechewaishke	27	49	118	58	38	5.5
Tank	24	16	101	15	28	4.5-5.0
Pine	8	19	55	6	25	4.0-4.5
Lucerne	15	23	62	13	24	4.5-5.0

Table 3. Significant metal concentration at 95 percent level of confidence

Metal Lake	Cu	Pb	Zn	Ni
Beaver	X	X		
Tea			X	X
Coffee	X	X	X	
Mineral		X		X
Potter	X		X	
Buffalo		X		
Ogemaga				X
Sequilla				X
Kechewaishke		X	X	
Tank			X	

Table 4. Significant metal concentration at 99 percent level of confidence

Lake \ Metal	Cu	Pb	Zn	Ni
Beaver	X	X		
Tea				X
Coffee	X		X	
Potter	X			
Ogemaga				X
Kechewaishke		X	X	
Tank			X	

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"Geoscience Wisconsin", a report series covering significant geoscience research pertaining to Wisconsin geology, is published by the Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension. The purpose of the series is to provide increased awareness of the geoscience research done in Wisconsin and to provide a vehicle for the communication of scholarly geologic research pertinent to Wisconsin. Although compilations and review papers will be considered for publication, the main object of the series is to publish high-quality, original research papers of general interest on all phases of the geology of Wisconsin.

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