THE GEOLOGY OF THE EASTERN MELLEN INTRUSIVE COMPLEX, WISCONSIN

by

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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).

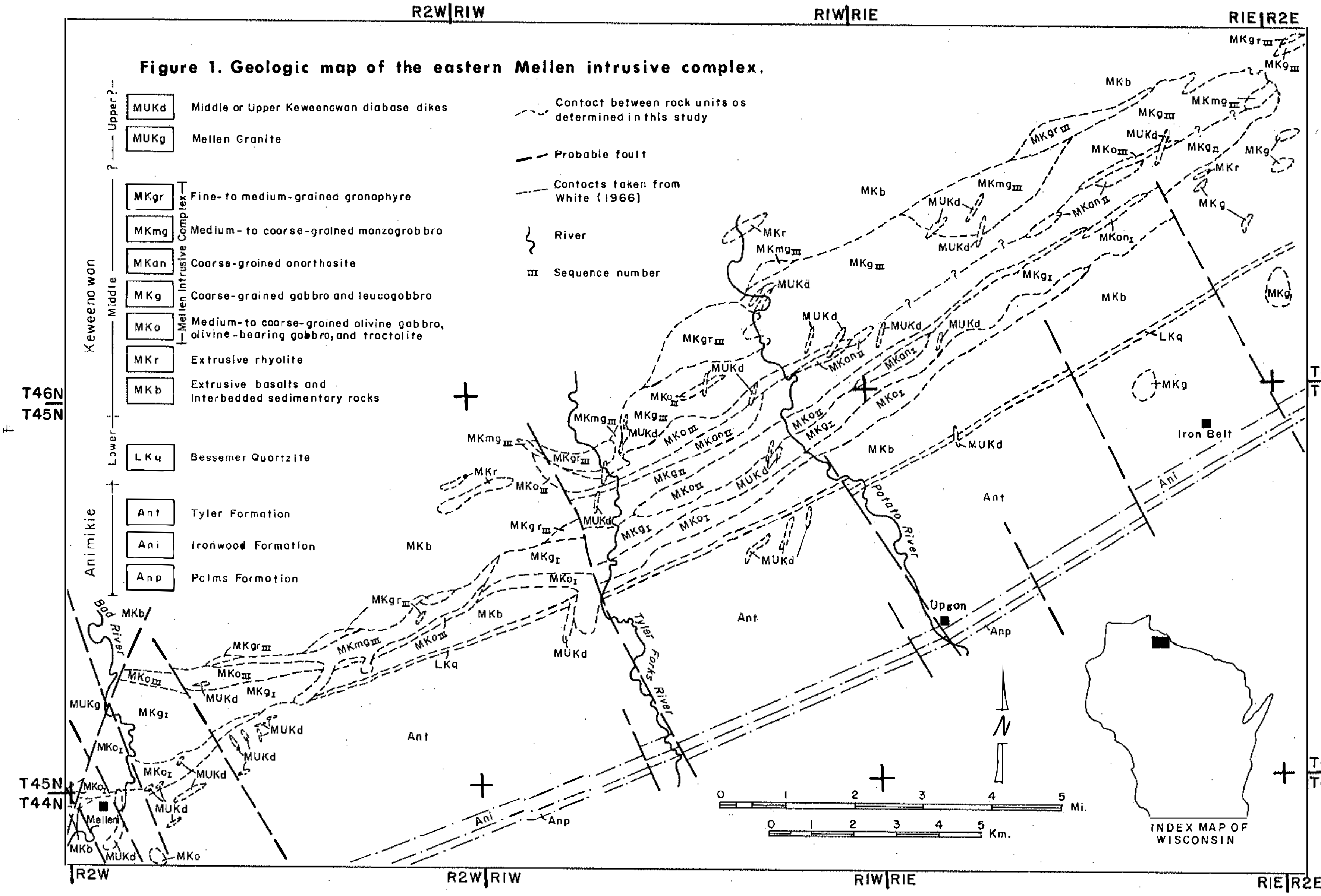


Figure 1. Geologic map of the eastern Mellen intrusive complex.

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

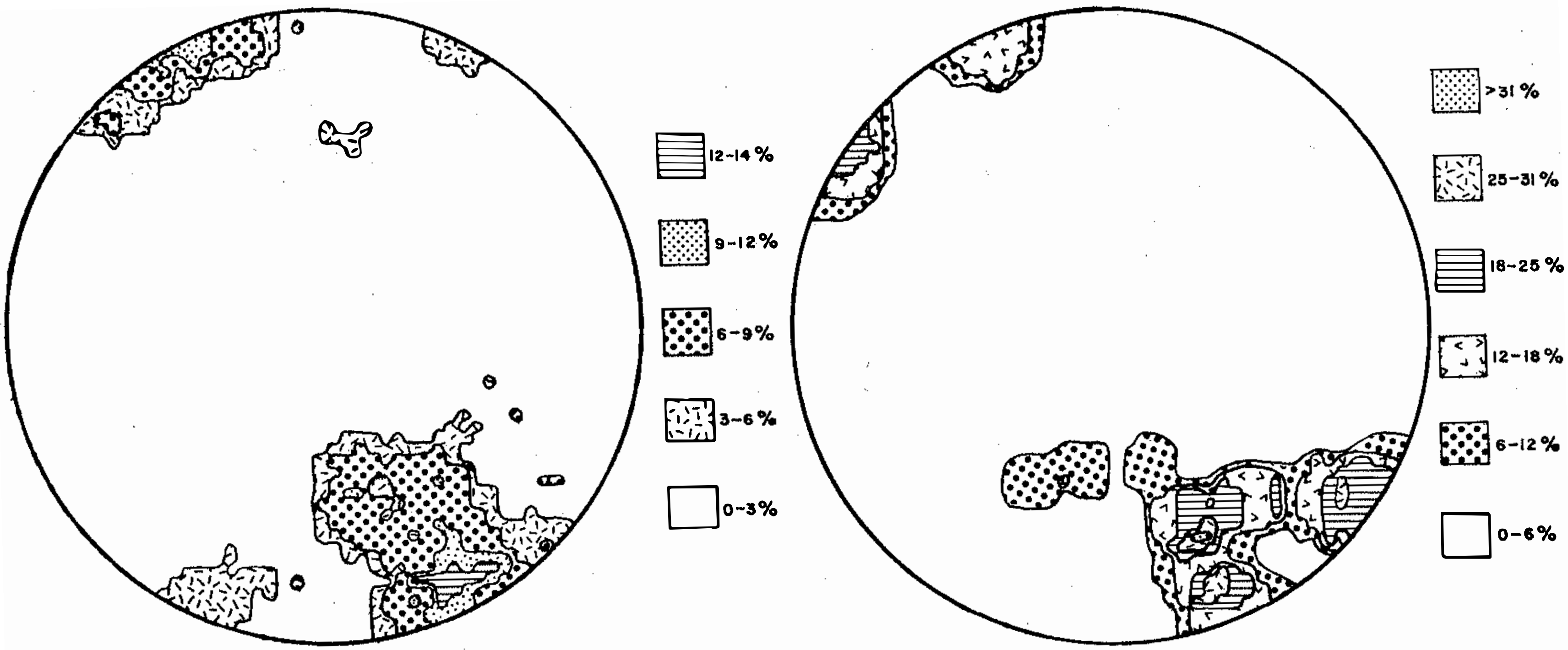
The Mellen igneous complex is a slightly discordant intrustion. Southwestward along its strike, the complex intrudes progressively older strata of the Lake Superior syncline's southern limb that have an average strike of N. 70° E. and dip of 72° NW in the study area. The eastern end of the Mellen complex 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

*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

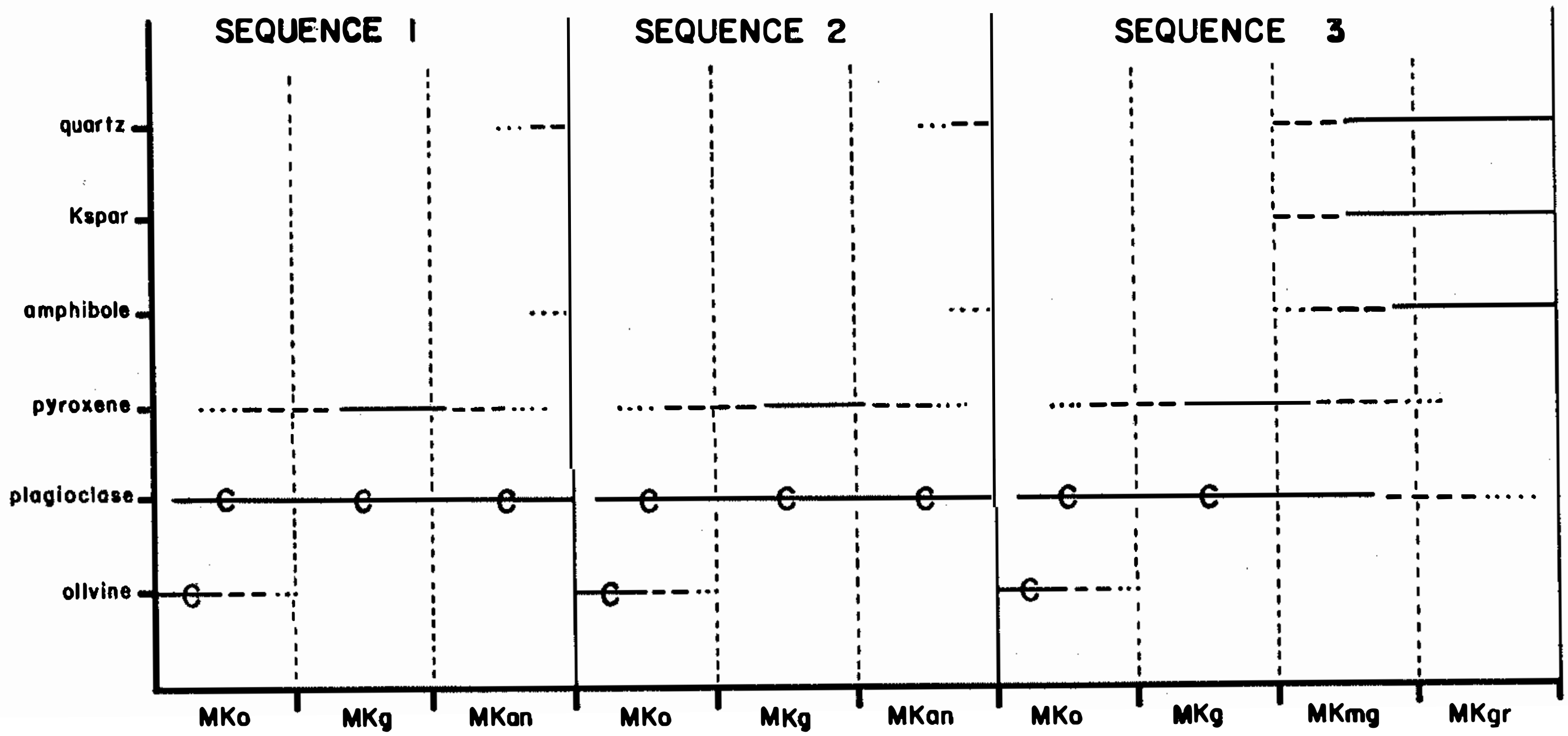


Figure 3. Diagram of inferred crystallization sequence in the eastern Mellen complex; cumulus phases denoted with C. (See Figure 1 for rock type descriptions.)

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

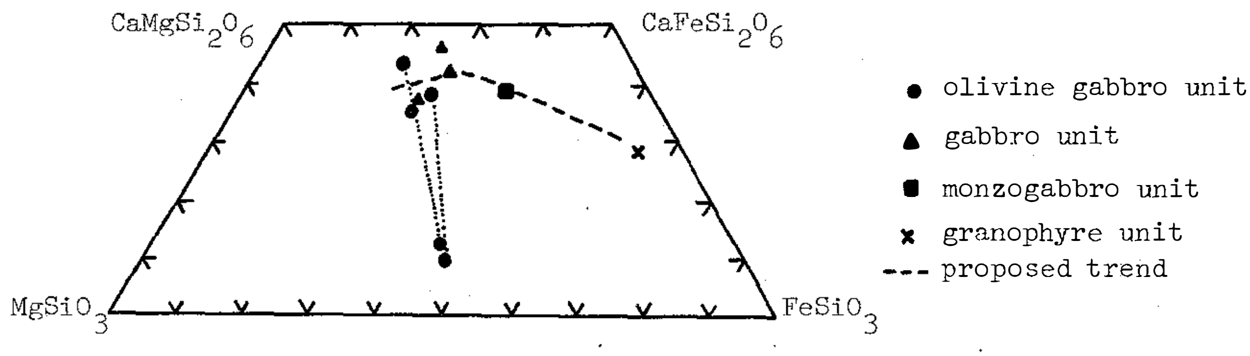


Figure 4. Pyroxene composition from rocks of sequence III.

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.

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APPENDIX: LOCATIONS FOR SPECIMENS USED IN THIS STUDY

UW 1607/1	SW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 3, T. 45 N., R. 1 W.
/4	NW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 3, T. 45 N., R. 1 W.
/6	SE$\frac{1}{4}$, SE$\frac{1}{4}$, Sec. 17, T. 45 N., R. 1 W.
/19	NW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 10, T. 45 N., R. 1 W.
/21	SW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 3, T. 45 N., R. 1 W.
/22	SE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 17, T. 45 N., R. 1 W.
/52	NW$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 34, T. 46 N., R. 1 W.
/56	NE$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 23, T. 45 N., R. 2 W.
UW 1624/1	NE$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 35, T. 46 N., R. 1 W.
/3	SE$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 2, T. 45 N., R. 1 W.
/4	SW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 2, T. 45 N., R. 1 W.
/5	SE$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 2, T. 45 N., R. 1 W.
/8	NE$\frac{1}{4}$, SE$\frac{1}{4}$, Sec. 10, T. 45 N., R. 1 W.
/9	SW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 11, T. 45 N., R. 1 W.
/56	NE$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 35, T. 46 N., R. 1 W.
/59	SW$\frac{1}{4}$, SE$\frac{1}{4}$, Sec. 22, T. 46 N., R. 1 E.
/61	NE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 16, T. 46 N., R. 1 E.
/65	NW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 3, T. 45 N., R. 1 W.
/66	NW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 3, T. 45 N., R. 1 W.
/69	NE$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 35, T. 46 N., R. 1 W.
/71	SE$\frac{1}{4}$, SE$\frac{1}{4}$, Sec. 14, T. 46 N., R. 1 E.
/73	SE$\frac{1}{4}$, SE$\frac{1}{4}$, Sec. 2, T. 45 N., R. 1 W.
/75	NE$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 14, T. 46 N., R. 1 E.
/76	NE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 13, T. 46 N., R. 1 E.
/77	SE$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 35, T. 46 N., R. 1 W.
/78	SW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 35, T. 46 N., R. 1 W.
/79	NW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 11, T. 45 N., R. 1 W.
/83	NW$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 5, T. 45 N., R. 1 E.
/84	SW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 1, T. 45 N., R. 1 W.