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MIDDLE KEWEENAWAN BASIN EVOLUTION INFERRED FROM GEOPHYSICAL ANALYSIS OF A STRONGLY MAGNETIC INTRUSION, CLAM LAKE, WISCONSIN

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ABSTRACT

The unexposed Clam Lake intrusion along the southern shore of Lake Superior is defined entirely on aeromagnetic and gravity surveys, and petrochemical analysis of two drill cores. The layered, medium-- to coarse-grained, mafic-rich gabbro of Middle Proterozoic Keweenawan age is emplaced into an Archean granite gneiss. Analysis suggests that significant rotation and evolution of the Middle Proterozoic Keweenawan basin occurred in the middle Keweenawan during emplacement of plutonic bodies and during extrusion of lava.

The Clam Lake geophysical anomaly of northern Wisconsin is marked by a +15 mgal gravity anomaly, a 7,000 gamma aeromagnetic anomaly with a wavelength of 5.5 Km, modified by a significant remanent Keweenawan polarization. Model analysis yields an average susceptibility contrast of 0.026 cgs units for a source exhibiting surface relief and having a thickness significantly greater than its depth of burial, which is only slightly over 20 m at one point. The same source configuration using a density contrast of 0.5 gcm^{-3} also yields a satisfactory fit to the residual Bouguer gravity anomaly. Strong layering observed in the drill core is due largely to changes in cumulate mineral phases of plagioclase, clinopyroxene, and magnetite and ilmenite. The unit contains up to 18 percent $Ti0_2$; however, no abnormal concentration of vanadium or other trace elements was detected (data appended at end).

Plagioclase is strongly oriented at 30º from the vertical and suggests that the intrusion has been rotated 10 to 20º from the vertical; the paleomagnetic data show no evidence of rotation. We conclude that the natural remnant magnetization was acquired in the subsolidus stage in its cooling history, and that rotation of the body occurred during or slightly after emplacement.

INTRODUCTION

Since the 1800s magnetite--rich minor gabbroic bodies have been known to occur in the middle Proterozoic rock of the Lake Superior region. Regional aeromagnetic surveys of northern Wisconsin in the mid-1970s disclosed high amplitude, short wavelength anomalies in the vicinity of Round Lake and Clam Lake (figure l). Such anomalies are uncommon, and are usually caused by rather unique geologic formations. Both anomalies had been identified from regional dip needle surveys in the l920s, and subsequently attracted the interest of mining companies searching for iron and ferro-alloy materials. The body at Round Lake was drilled by New Jersey Zinc in 1959 with additional work by International Minerals Corporation in l972. These studies identified a normally polarized, gabbroic body about 12 km across that is marked

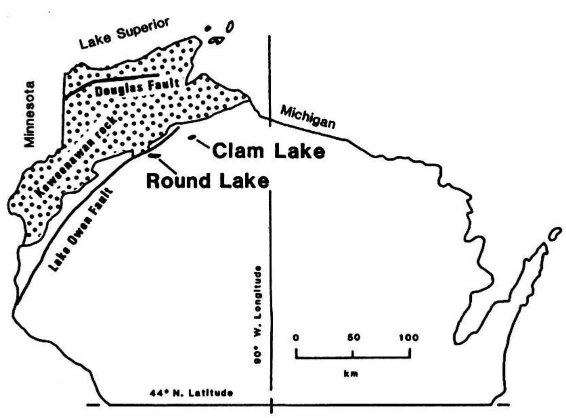

Figure 1 *Map of northern Wisconsin showing general location of the Round Lake and Clam Lake magnetic anomalies. Both anomalies are south of the southern bounding fault of the Middle Proterozoic Keweenawan horst.*

by a -40,000 gamma aeromagnetic anomaly and a +9 mgal gravity anomaly (Stuhr, 1976) (1 mgal = 10 ms^{-2}; 1 gamma = 1 nannotesla). Drilling defined the body as a strongly layered, funnel-shaped intrusion. Ervin (1977) reported that the +7,000 gamma, 5.5 km diameter anomaly near Clam Lake, Ashland County, contained a significant remnant component, which he estimated to have an approximate declination of 60º west and an inclination of 30º to 50º. Kean and Swingen (1981) subsequently undertook a paleomagnetic analysis of two drillcores from Clam Lake and found the paleopole position to be consistent with a middle Keweenawan age.

This present study was initiated for the purpose of comparing the Clam Lake body to other Proterozoic units in the area and for evaluating whether or not normally polarized magnetic gabbro units might host commercial titanium-vanadium deposits. Our conclusions suggest that combined geophysical analysis can be used to place various Middle Proterozoic units into a temporal setting, constrain emplacement history, and assist in tectonic analysis of the Midcontinent Rift System.

GEOLOGIC SETTING

Formation of crust in the Lake Superior region occurred over a long period, beginning with the Archean (2,500 Ma) granite-greenstone period and culminating with the Keweenawan (1,150 Ma) rifting and associated upwelling of mantle-derived magma in the Midcontinent Rift System (Wold and Hinze, 1982). The main stage of Keweenawan igneous activity consisted of at least two separate successions of lava flows and associated plutonic rock that were emplaced over a relatively short time span, about 1,140 to 1,120 Ma. These were emplaced into an evolving rift system that extended from Lake Superior to at least as far south as southern Kansas. Middle Proterozoic tectonic activity in the Lake Superior region consisted of the accumulation during middle Keweenawan time of a thick sequence of lava flows and mafic intrusives in asymmetric half-grabens (Mudrey and Dickas, 1988), and isostatic adjustments of major faults (the Douglas, Keweenaw, and Lake Owen faults; Wold and Hinze, 1982). The faults generally define a major horst (the St. Croix Horst) that formed a highland and shed detritus into flanking depositional basins.

Two major intrusive sequences invade Keweenawan volcanic rock in Wisconsin, the Mellen and the Mineral Lake intrusive suites (Tabet and Mangham, 1978; Klewin, 1987; Leighton, 1954; Olmsted, 1969). Both are sill-like bodies of troctolite, olivine gabbro, and related mafic rock containing about eight percent ferrodiorite and eight percent granophyre and granite. South of these bodies lies a terrane of Archean granite and gneiss of the Puritan batholith (Sims and others, 1985). The Clam Lake body is intrusive into this Archean crystalline terrane (Mudrey and others, 1982).

The intrusion of the slightly discordant Mellen complex into the slowly tilting southern limb of the Lake Superior syncline occurred near the end of volcanism. The attitude of the rhythmic layering in the eastern part of the complex indicates that intrusion took place prior to major tilting of the southern flank of the syncline (Tabet and Mangham, 1978; Klewin, 1987). The layering in the Mellen intrusion and bedding in the bounding Keweenawan volcanic rock indicate that intrusion of the Mellen complex occurred when the surrounding strata were inclined no more than 10º to 15º to the northwest.

Beginning in the l950s analysis of paleomagnetic data from Keweenawan rock disclosed two predominant directions; an older, reversely polarized sequence and a slightly younger, normally polarized sequence (DuBois, 1962). Work in the 1970s suggested that this paleomagnetic difference was correlated with a difference in rock type and had petrogenetic significance (Weiblen and Morey, 1980). The older, reversely polarized sequence was found to consist of a more anorthositic suite, whereas the normally polarized sequence was found to consist of a more common high-alumina troctolitic sequence. Mineral exploration programs in the 1960s identified several gabbro-hosted massive nickel sulfide occurrences, all of which were contained in normally polarized magnetic units. Mineral evaluation of the reversely polarized units failed to discover economically interesting non-ferrous base metal; however, several titaniferrous gabbro units were found to contain economically interesting concentrations of vanadium. The most noteworthy such body is the Round Lake intrusion near Hayward, Wisconsin, in which 50 million tons of 1.5 percent vanadium were found in rock consisting of 72 percent titaniferrous magnetite.

CORE ANALYSIS

Two bore holes penetrate the Clam Lake intrusion (figure 2). AS-105 is a vertical hole drilled on the maximum of the magnetic anomaly by Inland Steel in 1955. The second hole, AS-111, is inclined hole drilled by National Lead Company in 1976 to test an electromagnetic anomaly on the north flank of the magnetic anomaly. It is located approximately 152 m northwest of the first hole, and was drilled to 121.9 m at an angle of 65° to N. 15° W. The material recovered in the two holes was 29 and 22 m respectively, of glacial material over a layered, medium-to coarse-grained, mafic-rich gabbro containing considerable magnetite and ilmenite and minor pyrrhotite. Modal analyses are given in Table 1 and Figure 3. The variation in composition is due largely to changes in cumulate phases. Oxide poor zones are composed of cumulus plagioclase (An_{46-50}) and clinopyroxene ($Wo_{41}En_{47}Fs_9Ac_3$) with oxides restricted to the post-cumulus fraction. In contrast, the oxide-rich layers include magnetite and ilmenite in the cumulus fraction as well. Strongly oriented plagioclase occurs parallel to the boundaries in both types of layers and at about 30° to the axis of the vertical drill core (AS-105) (figure 4). This is most

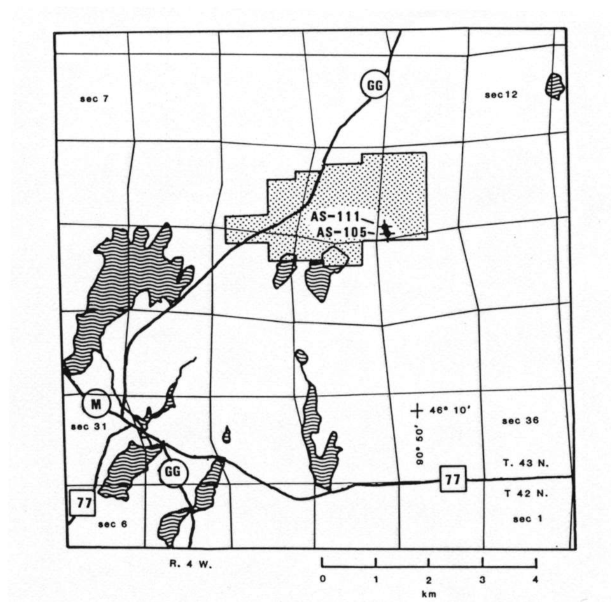

Figure 2 *Map in the vicinity of the Clam Lake anomaly (T. 43 N., R. 4 W., Ashland County, Wisconsin) showing location of bore holes AS-105 and AS-111, and field gravity stations. Area of diagram corresponds to gridding magnetic and gravity modeling; small irregular polygon surrounding bore holes is the outline of the modeled Clam Lake intrusion. Flight lines for the aeromagnetic survey are generally at 800 m spacing along section lines.*

Table 1. *Modal analyses of Clam Lake intrusion (AS-105, 505 ft north 750 E of SW corner, sec. 14, T. 43 N., R. 4 W; AS-111, SW1/4SW1/4 sec. 14, T. 43 N. R. 4 W.). (AS-105 by E. Griffin; AS-111 by M. Wilcove; mineral composition by J.F. Olmsted,; tr, trace).*

Modal composition	Mineral composition						Clinopyroxene			
	Plagioclase	Clinopyroxene	Opaques	Alteration	An content core-rim	Wo	En	Fs	Ac	Ct
AS-105-104	12	8	69	11	44	41	47	8	3	1
AS-105-144	56	36	6	2	46	40	46	10	2	0.7
AS-105-165	17	17	57	9	47	41	48	8	3	0.8
AS-105-178	20	8	60	12	49	41	47	10	2	0.3
AS-105-188	2	2	88	7	50	41	47	9	3	0.3
AS-105-216	52	34	9	5	46					
AS-105-240	24	28	35	14	45	40	46	10	2	0.6
AS-105-334	58	23	17	3	48	41	47	9	3	1
AS-111-083	32	32	33	3	44-50					
AS-111-160	34	26	36	tr.	49-53					
AS-111-172	30	30	37	3	50-53					
AS-111-197	4	82	12	2	46-51					
AS-111-230	36	24	38	2	51-51					
AS-111-252	30	26	40	3	48-45					
AS-111-259	37	30	26	7	42-35					
AS-111-360	42	41	17	tr.	51-53					
AS-111-398	37	25	34	3	50-53					
Dikes										
AS-111-112	46	33	21		38-37					
AS-111-300	50	33	13	tr.	43-26					

Table 2. Chemical analyses of Clam Lake intrusion; major elements in perecent, minor elements in parts per million

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	39.4	21.20	45.37	7.08	27.3	46.6	26.98	26.55	45.6	46.59	45.2
TiO_2	7.21	13.1	4.03	18.74	10.72	4.56	10.43	10.72	6.4	4.60	4.9
Al_2O_3	17.1	8.15	14.60	4.69	15.4	20.2	10.51	10.26	11.3	11.91	10.6
Fe_2O_3	22.72	43.34	12.38	64.44	31.61	15.23	36.83	37.92	5.7	19.58	2.4
FeO									11.6		13.2
MnO	0.19	0.27	0.18	0.37	0.18	0.17	0.25	0.25	0.18	0.21	0.23
MgO	6.63	5.79	4.69	4.77	6.00	4.43	5.86	5.31	5.3	4.62	4.8
CaO	4.02	5.61	9.68	1.45	7.80	4.30	8.17	7.63	9.9	8.43	10.0
Na_2O	2.14	0.95	4.23	0.02	1.68	3.72	1.49	1.56	3.0	2.71	2.4
K_2O	0.14	0.24	0.51	0.27	0.12	0.23	0.37	0.30	0.28	0.63	0.81
P_2O_5	0.07	0.03	0.08	0.05	0.05	0.06	0.01		0.02		0.46
BaO		0.00	0.00	0.00	0.00		0.00		0.02		
LOI		0.00	3.23	0.00	0.00		0.00		0.82		
Sum	99.9	98.68	98.98	101.88	100.1	100.1	100.90	100.46	99.26	100.58	94.54

1. AS-105-144, anal. by McGill University, XRF.
2. AS-105-155, anal. by Technical Services Laboratory, ICAP.
3. AS-105-214, anal. by Technical Services Laboratory, ICAP.
4. AS-105-230, anal. by Technical Services Laboratory, ICAP.
5. AS-105-240, anal. by McGill University, XRF.
6. AS-105-334, anal. by McGill University, XRF.
7. AS-111-160, anal. by McGill University, XRF.
8. AS-111.398, anal. By Technical Services Laboratory, ICAP.
9. AS-111-109, diabase dike, anal. by NL Industries.
10. AS-111-259, diabase dike, anal. by Technical Services Univesity, ICAP
11. AS-111-309, diabase dike, anal. by NL Industries.

obvious and quite striking in the oxide-rich layers (figure 5). The orientation increases to about 40º in deeper parts of the core, suggesting a flattening, possibly related to the boundary of the intrusion. The inclined borehole (AS-1ll) was drilled parallel to the mineralogic banding, and hence gives a more uniform composition, especially in terms of the oxides, than does the vertical borehole (AS-105).

Major and selected trace element data were obtained, along with microprobe data of major mineral phases to help characterize the body (table 2). The unit is extremely rich in TiO_2; however, no abnormal concentrations of vanadium or other trace elements were detected. Examination of the chemical data and study of plots of Ti versus other elements, except Mg, shows strong correlation, either negative in the cases of Si, Al, Ca, or alkalies; or positive in the case of total Fe (figure 6). These are to be expected as the former are the elements of plagioclase and the latter of the oxides. The nearly complete lack of correlation between Ti and Mg is attributable to the increase of both oxides and clinopyroxene at the expense of plagioclase in the more leucocratic rock. Where oxides reach about 40 percent, clinopyroxene also decreases. This is shown in a plot of modal analyses (figure 3). Modal and textural data indicate that clinopyroxene and plagioclase are cumulus in the more leucocratic layers with post-cumulus oxide, and that in the oxide-rich layers, magnetite and ilmenite also become cumulus.

The high iron content may be due to well understood igneous sedimentation or cumulus and post-cumulus processes. Preliminary microprobe analysis by Olmsted of the oxides shows that the magnetite and ilmenite have equilibrated at 600 ºC (Buddington and Lindsley, 1964). Metamorphic appearing symplectic amhibole reaction rims

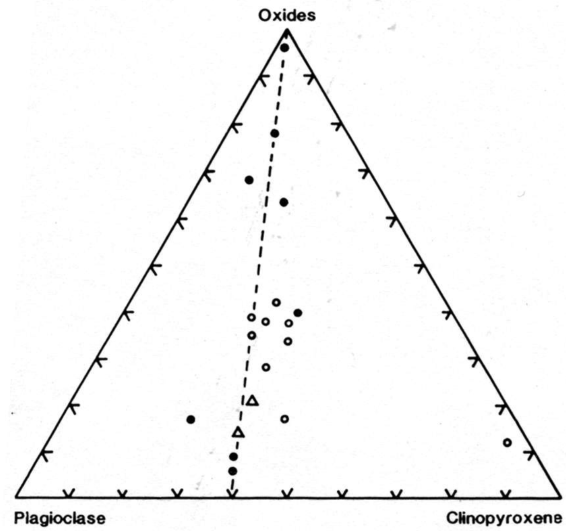

Figure 3 *Plot of modal analyses. Closed circles, AS-105; open circles, AS-111. was drilled parallel to a layer and hence shows greater uniformity than AS-05. The trend line (dashed) suggests modal variation is by the addition of opaque oxides, and the clinopyroxene-plagioclase ratio is reasonably constant.*

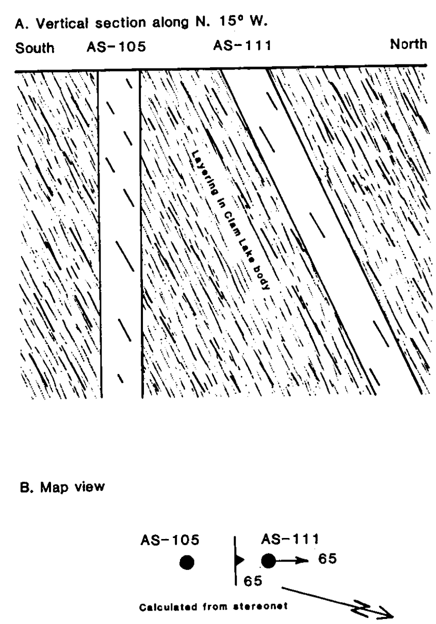

Figure 4 Diagrammatic section through AS-105 (vertical) and AS-111 (inclined) along N. 15° W. showing orientation of layering in the Clam Lake body.

between oxides and plagioclase indicate that reequilibration continued in the subsolidus.

GEOPHYSICAL PROPERTIES

Laboratory measurements of magnetic susceptibility and density are shown in table 3. Samples were selected to be representative of the gabbro in the part of the core from which they were taken, so the susceptibility log should reflect the general character of the intrusion. Although they indicate the unusually strong magnetization of the intrusion, the susceptibility magnitudes must be used with some caution for several reasons. The variability in the value for a given sample reflects the capability of the small sensor head to resolve the high amplitude, short wavelength variations in susceptibility caused by large, highly-magnetic crystals within the core. The high values are not representative of the body as a hole, so the average susceptibility calculated from the observed magnetic field will be lower. Uncertainty is also introduced by limitations in instrument calibration. The normal measuring range of the instrument used in this study extends to 0.040 cgs units (1 cgs unit of susceptibility equals 4p SI units of susceptibility), which is quite adequate for most rock. However, because of the unusually high susceptibility of the core, the majority of the values reported in table 3 for AS-105 required extrapolation of the calibration curve, introducing a small, but unknown amount of uncertainty.

Figure 5 Photomicrograph of representative magnetite-rich gabbro in the Clam Lake body, width = 4 cm.

In material of such high susceptibility, a part of the induced magnetic field opposes the external, inducing field, resulting in a decrease in the effective inducing field and a lower apparent susceptibility. This phenomenon, called self-demagnetization, is always present, but only becomes significant if rock contains more than 5 to 10 percent magnetite (Telford and others, 1976). Modal analysis of samples in either core indicates maximum oxide content in the range of 50 to 80 percent of which at least half may be magnetite in combination with ilmenite. The effect of self-demagnetization is that the apparent susceptibility, as deduced from the observed magnetic field, will be less than the true susceptibility by some unknown amount.

GEOPHYSICAL SURVEYS

An aeromagnetic survey of northern Wisconsin (Karl and Friedel, 1975; Zietz and others, 1971) shows the Clam Lake intrusion to be marked by a 7,000 gamma anomaly with a wavelength of approximately 5.5 km (figure 7). The high amplitude and short wavelength require a strongly magnetic, shallow source.

With the exception of an anomaly lying to the north-northwest that is associated with the Mellen instrusion, the magnetic anomaly is largely surrounded by a region of relatively low magnetic relief reflecting the granitic country rock. The two anomalies are separated by a minimum with a magnitude of approximately 1,300 gammas. To further define the Clam Lake anomaly, a detailed gravity survey was conducted in the immediate vicinity of the intrusion (figure 8) The lack of access and of adequate elevation control due to the swampy surface conditions of the area limited the density of the gravity coverage.

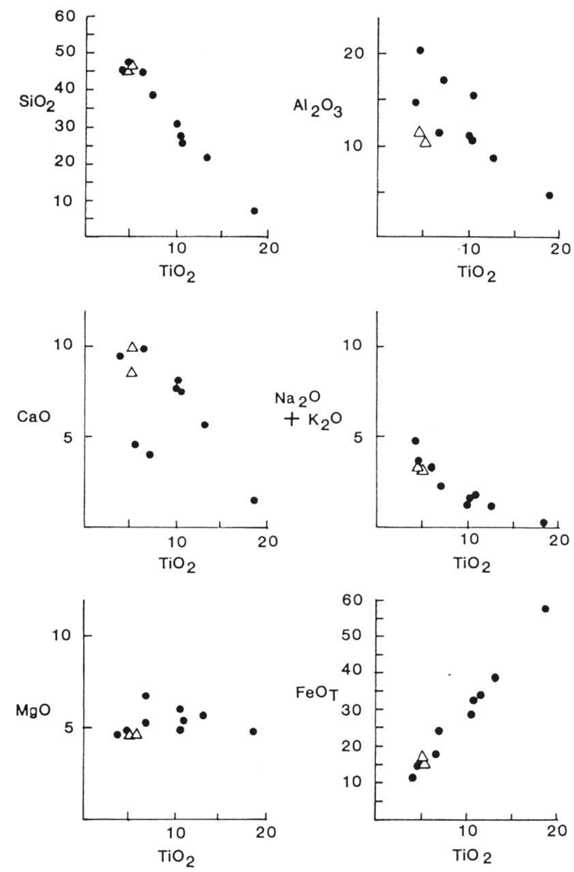

Figure 6 Plots of Ti02 vs. various oxides. Triangles are two analyses of fine-grained diabase dike that intrudes the Clam Lake intrusion.

MAGNETIC INTERPRETATION

Magnetic anomalies caused by induction in the earth's field normally have a minimum on the poleward side The magnetic declination in the region is 2.5° E, whereas the observed minimum is on the northwest side of the positive anomaly, suggesting the presence of a significant remnant polarization in the source body. As an anomaly of such intensity must be associated with a highly magnetizable source, a remnant polarization reflecting the inducing field direction at the time of emplacement is not unexpected. A paleomagnetic study of the cores yielded an average inclination and declination of 35° and 72° W., respectively, suggesting that the intrusion is of middle Keweenawan age (Kean and Swingen, 1981).

Using these parameters and an inclination of 70° for the present earth's field of 59,600 gammas, the total intensity magnetic field was reduced to the pole using the FFS algorithm (Ervin, 1976) and enhanced to accommodate remnant polarization. The computed vertical-field magnetic anomaly (figure 7b) is slightly oval-shaped with an east-northeast trending axis and with a narrow, westward elongation, suggesting extension of the source in a westerly direction, possibly along a fracture.

Model analysis of the anomaly was made using a series of vertical prisms to represent the source. A geologically reasonable solution could not be obtained if the source were assumed to have a horizontal top surface. The best-fitting model field (figure 7c) was computed from a source having surface relief (figure 2 and 9) and a uniform susceptibility of 0.026 cgs units. For

Table 3. Magnetic susceptibility and density of Clam Lake core samples

	Sample number (Feet from collar)	Hole depth (meters corrected for 65^{O} inclination in AS-111	Susceptibility (cgs units)	Density (gcm^{-3})
AS-105	101.6	31.0	0.52-0.72	4.20
	155.4	47.4	0.052-0.064	4.01
	163.5	49.8	0.030	3.45
	188.5	57.4	0.052	3.97
	214[a]	65.2	0.004	2.99
	230	70.1	0.060	4.52
	293.6[a]	89.5	0.018-0.021	3.60
	346.2[a]	105.5	0.002	3.17
	350.5	106.8	0.060	4.52
AS-111	82.75	22.9	0.031	3.52
	160.5	44.4	0.035	3.62
	171.5	47.4	0.032	3.62
	197	54.4	0.0-0.014	3.45
	230	63.6	0.025-0.030	3.58
	252	63.6	0.027-0.035	3.60
	360	99.5	0.014	3.28
	398	109.9	0.035	3.59
	111.5	30.8	0.010	3.18
Dikes	259.5	71.7	0.004	3.12
	300	82.9	0.006	3.16

[a] Sample taken from labradorite-rich zone.

computation, the source was assumed to extend to a depth of 29 km, but the field configuration is insensitive to the bottom depth when the thickness is much greater than the depth of burial.

GRAVITY INTERPRETATION

The gravitational field is somewhat complex in this area, as shown on the state gravity map (Ervin and Hammer, 1974; Ervin, and Thompson, 1991). After some experimentation, a simple regional trend, estimated from the data compiled for the state map, was subtracted from the Bouguer anomaly field (figure 8a) to obtain the residual anomaly due to the Clam Lake intrusion (figure 8b). The negative values in the northeast are part of a broad gravity low

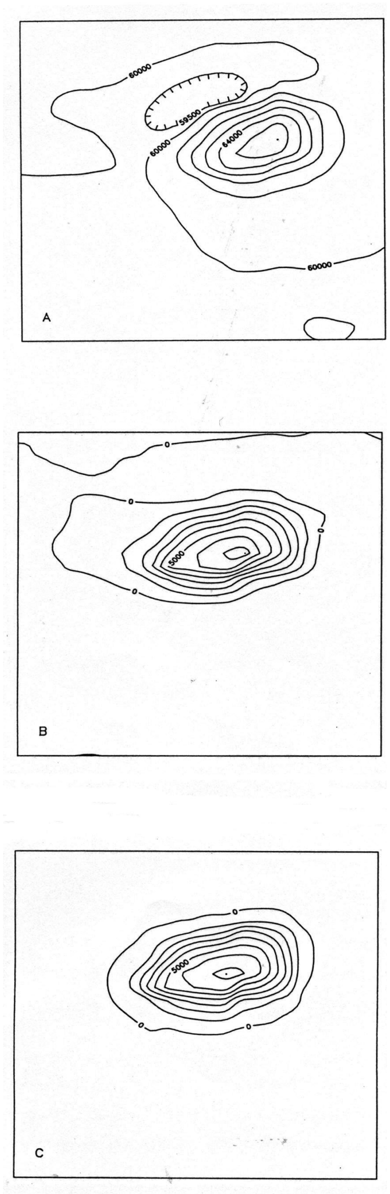

Figure 7 a Observed total intensity magnetic field from J. Karl and Friedel (1975). The survey was flown at an elevation of 150 m above the land surface along north-south flight lines spaced 0.8 km apart. Contour interval, 1000 gammas; **b** Vertical magnetic field after reduction to the present magnetic pole. Contour interval, 1000 gammas; **c** Vertical magnetic field calculated from model. Contour interval, 1000 gammas. See text for discussion

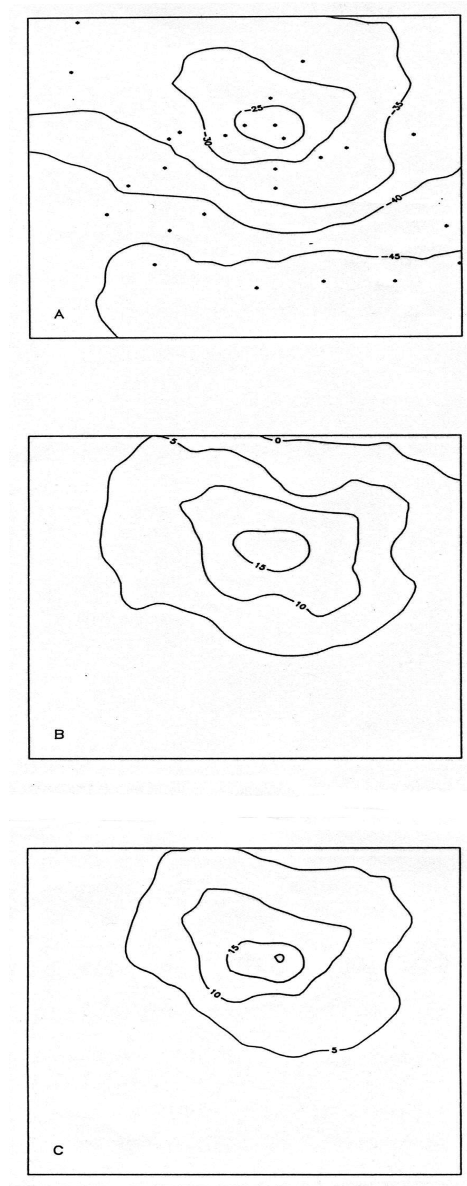

Figure 8 a Observed Bouguer anomaly gravity field. Contour interval, 5 mgal. An additional 10 field stations immediately adjacent to the diagrams were included in the contouring; **b** Residual Bouguer anomaly gravity field. Contour interval, 5 mgal. See text for discussion; **c** Gravity field calculated from model. Contour interval, 5 mgal.

centered outside the study area. A second, smaller anomalous mass is apparently located southeast of the intrusion, but the data density is riot sufficient to resolve the two sources.

The difficulty in selecting a correct regional trend and the lower data density do not permit the gravitational field to be modeled with the same resolution as the magnetic fie1d. However, the same source configuration (figure 9) as the magnetic model and a uniform density contrast of 0.5 gcm^{-3} yields a good approximation (figure 8c) to the residual anomaly (figure 8b), exclusive of the previously--noted secondary mass to the southwest.

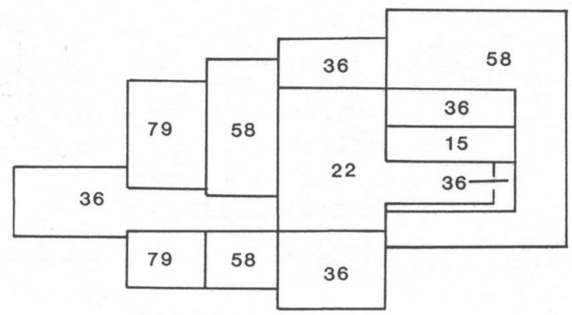

Figure 9 Plan view of prism model showing depth below surface in meters to the top of the body. See text for discussion.

DISCUSSION

Although the lithologic logs show the intrusion to contain thin layers having lower densities and susceptibilities than the magnetite-rich, mafic gabbro, modeling demonstrated that the individual contributions of these layers to the observed gravity and magnetic fields are so small relative to the dominant effect of the magnetite-rich, mafic gabbro that they cannot be discerned. The model density and susceptibility are therefore average values for the intrusion as a whole and, although close to the appropriate value for the magnetite-rich, mafic gabbro, may be expected to be somewhat less due to the presence of these layers.

The model density contrast yields an intrusion density of 3.2 to 3.3 gcm^{-3} assuming the country rock to have a density of 2.7 to 2.8 gcm^{-3}. This is intermediate to the measured values for basalt and magnetite-rich, mafic gabbro in hole AS-105 (table 3) and within the lower part of the density range calculated from the mineral composition. The model susceptibility also falls within the lower limit of the measured values for this hole and are consistent with susceptibility information reported by National Lead Company (not shown).

The model values do not agree well with the measured values for AS-105, nor do the measured values for the two holes agree (table 3). In AS-l05, the magnetite-rich, mafic gabbro densities are extraordinarily high, ranging from 3.97 to 4.52 gcm^{-3}, approximately 0.9 gcm^{-3} higher than in hole AS-111. The susceptibilities are also exceptionally high, with a dramatic difference between the two holes. The large variation is particularly unusual because of the close proximity of the holes--only about 152 m apart.

The location each hole relative to the edge of the intrusion and the orientation of the holes with respect to the mineral layering are the most probable source of the apparent horizontal zonation. Within the uncertainty of the hole positions and the limits of the model resolution, which is based on data gridded at a 0.5 km interval, hole AS-105 is located near the margin of the intrusion, whereas AS-111 penetrates into the interior and presumably reflects a slower cooling history.

Chemical and petrographic data indicate an unusual Fe-rich basic intrusion, undoubtedly the product of extensive differentiation combining fractionation, magma convection, and crystal settling. Some unknown part of the intrusion has been lost to erosion, but an extensive mass remains at depth as shown by drilling and geophysical modeling. Internal structure of the body is shown in the two cores, one of which demonstrates a more massive interior. Iron appears to be concentrated at the upper levels of the intrusion, particularly in the core closest to the edge, whereas the zone of high iron content in the center is more diffuse.

The paleomagnetic data of Kean and Swingen (1981) indicate that the Clam Lake intrusion has not been rotated after it acquired its paleomagnetic signature; however, the direction of mineralogic banding in AS-111 relative to the inclination of the borehole strongly suggests that erosion must cut across the phase layering at a high angle. An apparent rotation of 10° to 20° from the vertical is indicated which is in agreement with the calculated rotation of the Mellen complex to the north, but less than the inclination of the Keweenawan lavas in the Mellen area (Mudrey and Brown, 1988). This also is less than the 60° dip of the phase layering. The resolution of the potential field models is insufficient to distinguish (such) as small a deflection as the 10° to 20° rotation. The dip of 60° from horizontal of the phase layering in the core implies that the body was either (a) emplaced in a tipped position or (b) magnetization was acquired after tipping (slow rate of cooling versus a more rapid rate of rotation). The mineral chemistry clearly indicates that the magnetite-ilmenite temperature-oxygen fugacity is subsolidus (around 600 °C), which is above the hematite and magnetite blocking temperatures. We conclude, therefore, that the NRM was acquired when the intrusion was in a subsolidus stage in its cooling history. Rotation of the body may have occurred during or very slightly after emplacement, but significant rotation did not occur after the body cooled below 500 °C.

Halls and Pesonen (1982, p. 181) addressed this in their analysis of rotational correction in paleomagnetic analysis of plutonic Keweenawan rock. If a rotational "correction based on the attitude of igneous lamination . . . is made [for the Mellen. gabbro], the [paleomagnetic] Mellen pole moves more than 30° off the apparent polar wander path to the east; this offset exceeds the large error associated with the Mellen pole." This difference can result in redefinition of the apparent polar wander path, and can lead to changes in relative stratigraphic and age position. Halls and Pesonen (l982, p. 182) conclude that unless a positive fold test is obtained, igneous layering should not be used in structural correction, and that the relative ages of the Duluth and Mellen bodies need reevaluation.

We concur with the Halls and Pesonen analysis and their conclusions. Their analysis was based in part on the slow cooling rate expected from large bodies such as the Duluth or Mellen suites. The Clam Lake body, on the other hand, is a small body, and thus cooled more rapidly; the paleomagnetic pole for the Clam Lake body should more adequately indicate the extent of structural correction that would be required, which is little in order to place the Clam Lake body on the apparent polar wander path for the Keweenawan.

Thus, significant rotation and evolution of the Keweenawan basin occurred in the middle Keweenawan during emplacement of plutonic bodies and during extrusion of lava, possibly as a result of depletion of shallow magmatic reservoirs, and consequent topographic adjustments.

REFERENCES CITED

Buddington, A. F., and Lindsley, D.H., 1964, Iron-titanium oxide minerals and genetic equivalents: Journal of Petrology, v. 5, p. 310-357.

DuBois , P.M. , 1962, Paleomagnetism and correlation of Keweenawan rocks: Geological Survey of Canada Bulletin 71, 75 p.

Ervin, C.P. , 1976, Reduction to the magnetic pole using a Fast Fourier Series algorithm: Computers and Geosciences, v. 2, p.211-217.

Ervin, C. P. 1977, Analysis of Clam Lake gravity and magnetic anomalies: Wisconsin Geological and Natural History Survey, Open-file Report WORF, 77-1, 8 p.

Ervin, C.P., and Hammer, S. 1974, Bouguer anomaly gravity map of Wisconsin: Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

Ervin, C.P., and Thompson, M.E., 1991, Principal facts for gravity stations in the Wisconsin Superior 1° x 2° map sheet: Wisconsin Geological and Natural History Survey Open-file Report OFR 1991-01, 1 computer diskette

Halls, H.C., and Pesonen, L. J. , 1982, Paleomagnetism of Keweenawan rocks, in Wold, R J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior Basin: Geological Survey of America Memoir 156, p. 173-201.

Karl, J.H., and Friedel, J.C., 1975, Maps Q0471 and Q0472, 1:24, 000 Aeromagnetic Series: Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

Keen, W.F and Swingen, R.A., 1981, Paleomagnetism of a Keweenawan age intrusive near Clam Lake, Wisconsin: Geophysical Research Letters v. 8, p. 579-582.

Klewin, K.W., 1987, The Petrology and Geochemistry of the Keweenawan Potato River intrusion, northern Wisconsin: Ph.D. dissertation, Northern Illinois University, 357 p.

Leighton M.W., 1954 Petrogenesis of a gabbro-granophyre complex in northern Wisconsin: Geological Society of America Bulletin, v 65, p. 401

Mudrey, M.G., Jr., and Brown, B.A., 1988, Summary of field mapping in the Superior map sheet: Wisconsin Geological a Natural History Survey Open-file Report 88-7, 37 p. , 1 plate.

Mudrey, M.G., Jr., Brown, B.A., and Greenberg, J.K., 1982, Bedrock geologic map of Wisconsin: Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

Mudrey, M.G., Jr., and Dickas, A.B., 1988, Midcontinent rift model based upon Gregory rift tectonic and sedimentation geometries: 34th Institute on Lake Superior Geology (Marquette) , Proceedings and Abstracts, v. 34, pt. 1, p. 73-75.

Olmsted, J.F., 1969, Petrology of the Mineral Lake intrusion, northwestern Wisconsin, in Isachsen, Y.W., ed., Origin of Anorthosites and Related Rocks: New York State Museum and Science Service Memoir 18, p. 1.49-161.

Sims, P.K., Peterman, Z.E., and Benedict, 1985, Geology and geochronology of granitoid and metamorphic rocks of Late Archean age in northwestern Wisconsin: U. S. Geological Survey Professional Paper 1292-C, p. c1-c17.

Stuhr, S.W., 1976, Geology of the Round Lake intrusion, Sawyer County, Wisconsin: M.S. thesis, University of Wisconsin-Madison, 148 p.

Tabet , D. E. , and Mangham, J . R., 1978, The geology of the eastern Mellen intrusive complex, Wisconsin: Wisconsin Geological and Natural History Survey Geoscience Wisconsin, v 3, p. 1-19.

Telford, W. M., Geldart, L. P., Sheriff, R.E ., and Keys , D. A., 1976, Applied Geophysics: Cambridge, Cambridge University Press, 860 p.

Weiblen, P.W., and Morey, G. B., 1980, A summary of the stratigraphy, petrology and structure of the Duluth Complex: American Journal of Science, v. 230-A, p. 88-133.

Wold, R.J., and Hinze, W.J., 1982, eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir, 156, 280 p.

Zietz, I., Karl, J.H., and Ostrom, M.E., 1977, Preliminary aeromagnetic map covering most of the exposed Precambrian terrane in Wisconsin, U.S. Geological Survey Miscellaneous Field Study MF-888.

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CERTIFICATE OF ANALYSIS

SAMPLE(S) FROM M.G. Mudrey,
Wisconsin Geo. Survey,
1815 University Avenue,
Madison, Wisconsin.
U.S.A.

REPORT No.
T 7460

Inv.#17671

SAMPLE(S) OF ROCK

MAJOR OXIDES IN %

Samples	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	BaO	LOI	Total
AS-105-155	21.20	8.15	43.34	5.61	5.79	0.95	0.24	13.10	0.27	0.03	0.00	0.00	98.68
AS-105-214	45.37	14.60	12.38	9.68	4.69	4.23	0.51	4.03	0.18	0.08	0.00	3.23	98.98
AS-105-230	7.08	4.69	64.44	1.45	4.77	0.02	0.27	18.74	0.37	0.05	0.00	0.00	101.88
AS-111-160	26.98	10.51	36.83	8.17	5.86	1.49	0.37	10.43	0.25	0.01	0.00	0.00	100.90
AS-111-259	46.59	11.91	19.58	8.43	4.62	2.71	0.63	4.60	0.21	0.46	0.02	0.82	100.58
AS-111-398	26.55	10.26	37.92	7.63	5.31	1.56	0.30	10.72	0.25	0.02	0.00	0.00	100.46

Note: Some totals are high because total Fe is expressed as Fe_2O_3 although some Fe would be present as FeO.

MINOR ELEMENTS IN PPM

Samples	Cd	Cr	Co	Cu	Ni	Mo	Pb	Sb	Zn	V
AS-105-155	<1	18	57	27	43	<1	18	78	228	<1
AS-105-214	4	50	100	13	52	<1	9	20	88	<1
AS-105-230	<1	39	288	42	42	<1	3	118	375	<1
AS-111-160	<1	59	213	32	46	<1	33	24	199	<1
AS-111-259	<1	66	108	528	58	<1	29	59	138	<1
AS-111-398	3	36	88	41	29	<1	58	256	180	<1

DATE October 9th, 1981 SIGNED [signature]

CTA