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MINNESOTA GEOLOGICAL SURVEY
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SCIENTIFIC TEST DRILLING, 1989–1992: DESCRIPTIONS AND INTERPRETATIONS PERTINENT TO THE BEDROCK GEOLOGY AND QUATERNARY HYDROGEOLOGY OF SOUTHWESTERN MINNESOTA

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Minnesota Geological Survey
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INTRODUCTION

In 1980 the Minnesota Geological Survey (MGS) started a program of scientific test drilling designed to acquire a better understanding of the complex Precambrian bedrock of Minnesota. A research approach that combined selective test drilling with geophysical surveying of the Precambrian terrane was dictated by the fact that the Precambrian rocks are covered by substantial thicknesses of quaternary glaciogenic sediment in most places and therefore are not amenable to standard outcrop mapping techniques. This circular is the seventh to report basic results from the drilling program. It contains data from 20 holes drilled for three separate studies undertaken in southwestern Minnesota in 1989-92 (Fig. 1).

The drilling for two of the three projects reported here was closely coordinated with geophysical surveys, and the selection of drilling targets was guided by geophysics to the maximum extent practicable. The third study, consisting of the single hole PR-90-1, was somewhat abnormal in that drilling was targeted on a topographic rather than a geophysical feature (see discussion below for details). Apart from this one exception, our standard procedure was to formulate regional interpretations of the buried Precambrian geology from the geophysical data and then drill to verify, modify, or otherwise constrain the geophysical interpretation. Earlier applications of this approach have contributed to regional-scale geologic maps of the Penokean orogen (Early Proterozoic) in east-central Minnesota (Southwick and others, 1988) and an Archean greenstone belt in north-central Minnesota (Jirsa and Boerboom, 1990; Jirsa, 1990; Jirsa and others, 1991). The data tabulated in this circular will eventually contribute to a new geologic map for southwestern Minnesota.

The geophysical backbone of the drilling program is the detailed aeromagnetic survey begun in 1979 with funding from the Legislature as recommended by the Legislative Commission on Minnesota Resources. The drilling in southwestern Minnesota was targeted on aeromagnetic features displayed in a survey block compiled from privately funded data acquired in 1979 and state-funded data acquired in 1987-1988 (Chandler, 1989). Target selection was based on direct inspection of the contoured anomaly maps and various computer-enhanced derivative maps constructed from the digital aeromagnetic data. Gravity data and their derivatives (Ervin and others, 1980) also contributed materially to the site-selection process.

Because the primary objective of this drilling project was to attain an enhanced understanding of regional geological features in the Precambrian basement, we have drilled on geophysical anomalies of relatively large dimensions. Our intent has been to characterize the major rock units responsible for the first-order geophysical patterns of the region and develop geologic maps that show the most fundamental rock units and structural elements with reasonable precision. Petrographic and geochemical studies on recovered bedrock samples further characterize rock units and aid in their geophysical interpretation.

Secondary but very important objectives of the drilling were to acquire subsurface data on the stratigraphy, composition, and thickness of the Upper Cretaceous sedimentary rocks that overlie Precambrian rocks in much of western Minnesota, and also to obtain subsurface data on the Quaternary surficial deposits in the region. The Cretaceous strata are of interest because they have attributes indicative of environments in which sedimentary manganese deposition may have been favored (Cannon and Force, 1983; Frakes and Bolton, 1984; Bolton and Frakes, 1985; Force and Cannon, 1988; Setterholm, 1989). The Quaternary materials contain most of the exploitable ground water in southwestern Minnesota, and a proper three-dimensional understanding of their hydrogeologic parameters is essential to wise ground-water management. The data obtained on Quaternary materials in this study will contribute to ongoing hydrogeologic investigations by the MGS, the Minnesota Department of Natural Resources, and the U.S. Geological Survey.

Logistics and Drilling Methods

Insofar as possible the drilling for this project was done on state land or within the right-of-way of public roads to avoid infringing on private property or disturbing area residents with mud and noise. In some cases, however, it was necessary to drill on private land where the geophysical target contained no public land or was not adjacent to a public roadway, or where there were no suitable places for situating the drill rig along public roads. Where drilling was done on private land, the landowners granted permission in advance and retained title to all mineral rights.

Conventional rotary-drilling equipment was used to penetrate the unconsolidated overburden, which consists of the Quaternary surficial deposits, local erosional remnants of Upper Cretaceous marine and terrigenous strata, and a pre-Upper Cretaceous saprolitic regolith developed on Precambrian rocks. A hole 6.75 inches (17.15 cm) in diameter was drilled through these materials and then cased with steel pipe to the top of sound rock. A rotary core barrel of size HQ (core diameter 2.5 inches or 6.35 cm) was then employed inside the casing for core drilling into Precambrian rock. Most commonly 10 feet (3 m) of core was drilled per site, but larger or smaller amounts were obtained where drilling conditions or scientific considerations so dictated. The holes ranged in total depth from 64 to 742 ft (19.5 to 226.2 m); in a typical hole all but 10 feet (3 m) of the drilled interval is poorly consolidated material that was penetrated with standard tricone tools. Drilling was done by the Ben Ervin Well Company of Olivia, Minnesota.

Mudline cuttings from the unconsolidated overburden were continuously monitored and described by the drill-site geologist, and representative samples were collected of 5-foot (1.5 m) intervals. The unconsolidated interval of most holes was logged by down-hole geophysical methods to further refine the stratigraphy penetrated.

The short drill cores of Precambrian rock were logged visually in the field and later in greater detail at the offices of the Minnesota Geological Survey. After petrographic study, samples were selected for geochemical analysis. All cores and overburden samples are available for public examination at the MGS offices.

Project Focus and Rationale

The results of three administratively distinct drilling projects are summarized in this report. Holes identified with the prefix YB were drilled in 1989 with funds appropriated by the Legislature to the MGS, on the recommendation of the Legislative Commission on Minnesota Resources (LCMR), for the conduct of the statewide aeromagnetic survey and follow-up investigations. Major aeromagnetic lineaments having the attributes of regional shear zones were the primary focus. Holes identified with the prefix SWG were drilling in 1991 and 1992, also with funding recommended by LCMR. This project, however, was designed specifically to examine geophysical anomalies that have attributes potentially ascribable to greenstone-belt stratigraphic assemblages. The intent was to determine the existence and extent of greenstone-belt rocks in a terrane that heretofore had been interpreted to contain mostly high-grade quartzofeldspathic gneiss. The single hole PR-90-1 was drilled in 1990 with funds from a combination of sources, including the Legislative State Special appropriation to MGS. It was drilled to characterize the sediments and bedrock in an isolated, circular geomorphic depression in Rock County that has been interpreted variously and equivocally as a glacial kettle, as a bedrock-controlled structural basin, as a periglacial eolian "blowout," and as a meteorite impact structure.

SYNOPSIS OF RESULTS

Regional geophysical boundaries within the Minnesota River Valley subprovince

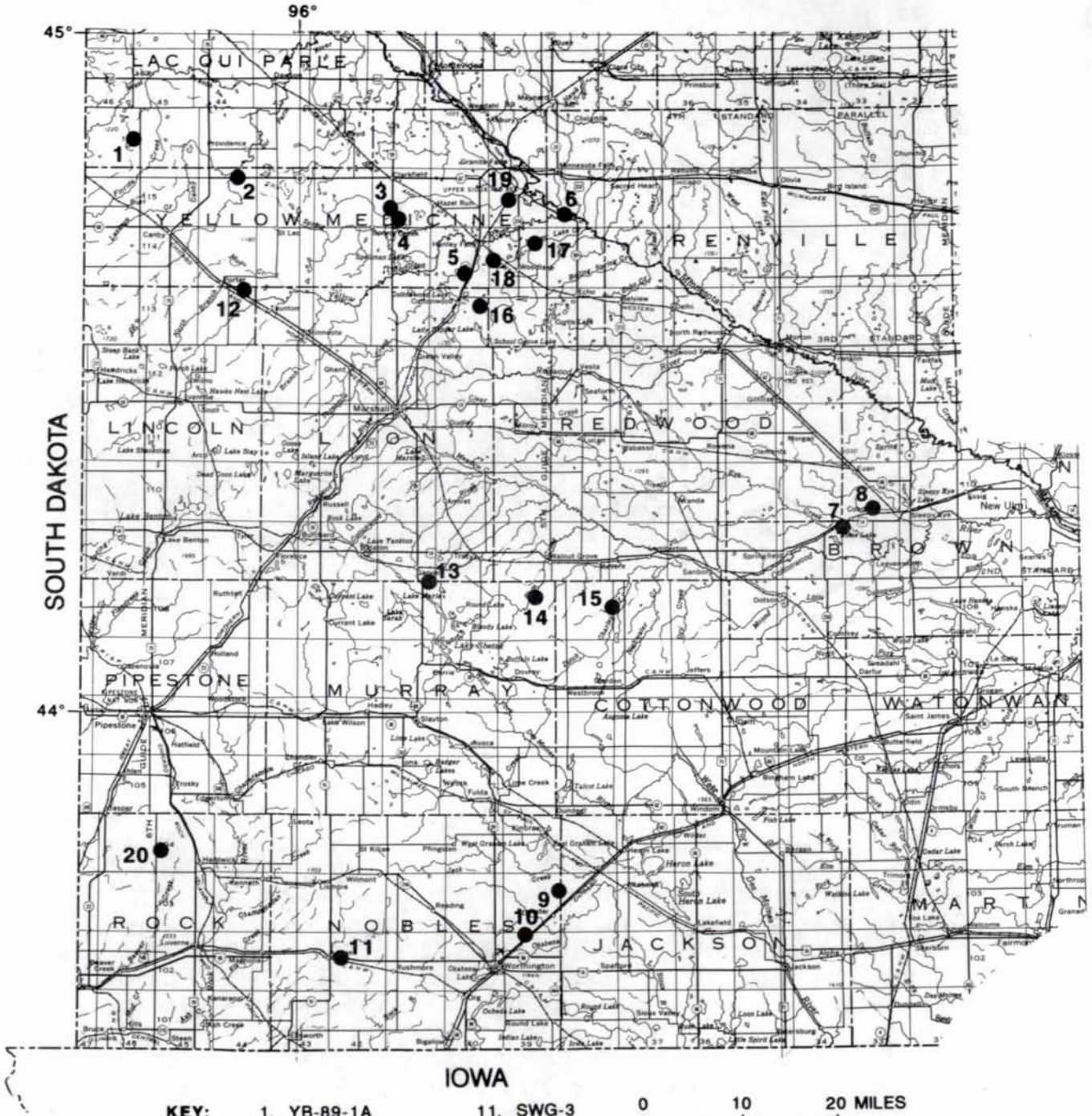
It has become clear in recent years that the Minnesota River Valley subprovince of the Superior Province of the Canadian Shield (terminology of Card, 1990) is a tectonic entity of considerable complexity and diversity. It consists predominantly of quartzofeldspathic gneiss and migmatite of Middle and Late Archean age that were intruded by substantial volumes of Late Archean granitoid rocks (Himmelberg, 1968; Grant, 1972; Goldich and others, 1980a, b; Goldich and Wooden, 1980; Wooden and others, 1980), but it is not a simple, uniform nugget of ancient cratonic gneiss (Southwick and others, 1989; Chandler and Southwick, 1990). Rather, the subprovince is composed of four geophysically distinct blocks that are bounded by prominent ENE-trending linear zones of elongate geophysical anomalies (Schaap, 1989). The informal terminology applied to these blocks and their bounding geophysical lineaments is explained in Figure 2.

The outcrop belt along the Minnesota River is the primary source of detailed information on rocks and structures within the Minnesota River Valley subprovince. Away from the river there are a few widely scattered, isolated bedrock exposures, but for all practical purposes the problem of deciphering the bedrock geology away from the river rests on geophysical methods and drilling for its solution. Even the outcrop belt in the Minnesota River Valley has distinct limitations. Although there are reasonably good river transects of the Morton and Montevideo blocks, and a less satisfactory transect of the Benson block, there are no river exposures of rocks in either the Appleton or Yellow Medicine geophysical lineaments.

Previously reported drilling results (Southwick and others, 1990) confirm the geophysical inference that the Appleton lineament is a major shear zone, but leave unanswered the questions of when and in what sense the shearing occurred. The results reported here establish that the Yellow Medicine geophysical lineament also is a major zone of shearing; it appears to have played a role in localizing the emplacement of Archean leucogranite sheets, and to have been episodically reactivated in Proterozoic and Phanerozoic time. A full discussion of the significance and history of the Yellow Medicine shear zone is beyond the scope of this report, and will be developed elsewhere. The key finding from drilling is the direct confirmation of sheared rock within the geophysically defined boundary zone between the Morton and Montevideo blocks.

Neither the Jeffers block nor its boundary with the Morton block is transected by the Minnesota River; there are no outcrops of either feature. Three drill holes described in this report encountered gneissic rocks from the Jeffers block, and a fourth was targeted on the bounding Brown County lineament. The gneisses of the Jeffers block are not obviously different from the gneisses in other blocks of the Minnesota River Valley subprovince in rock type, mesoscopic structure, or metamorphic grade. Isotopic and geochemical differences may well exist, but as yet the analytical work required to confirm them has not gone beyond the earliest reconnaissance stage (Southwick, 1993, in press). The single sample from the Brown County lineament zone (drill hole YB-89-9) is a texturally inhomogeneous, weakly gneissose leucogranite; it shows no evidence of a shearing history, which implies that the geophysical boundary may be a lithologic contact instead of a fault zone. The Brown County lineament, though distinct, is less well defined geophysically than the Appleton and Yellow Medicine lineaments.

Two-dimensional potential-field models (both aeromagnetic and gravity) across the Appleton, Yellow Medicine, and Brown County lineaments strongly imply that these features are the surface traces of northward-dipping planar zones or thin sheets (Schaap, 1989). This geometry is consistent with that inferred from seismic reflection for the Great Lakes tectonic zone (Gibbs and others, 1984), the northern boundary of the subprovince as a whole. Although critical age data are



KEY:

1. YB-89-1A	11. SWG-3
2. YB-89-2A	12. SWG-4
3. YB-89-3	13. SWG-5
4. YB-89-4	14. SWG-6
5. YB-89-6	15. SWG-7
6. YB-89-7	16. SWG-8
7. YB-89-8	17. SWG-9
8. YB-89-9	18. SWG-10
9. SWG-1	19. SWG-11
10. SWG-2	20. PR-90-1

0 10 20 MILES

0 10 20 30 KILOMETERS

Figure 1. Index map of southwestern Minnesota showing the approximate locations of scientific test holes discussed in this report.

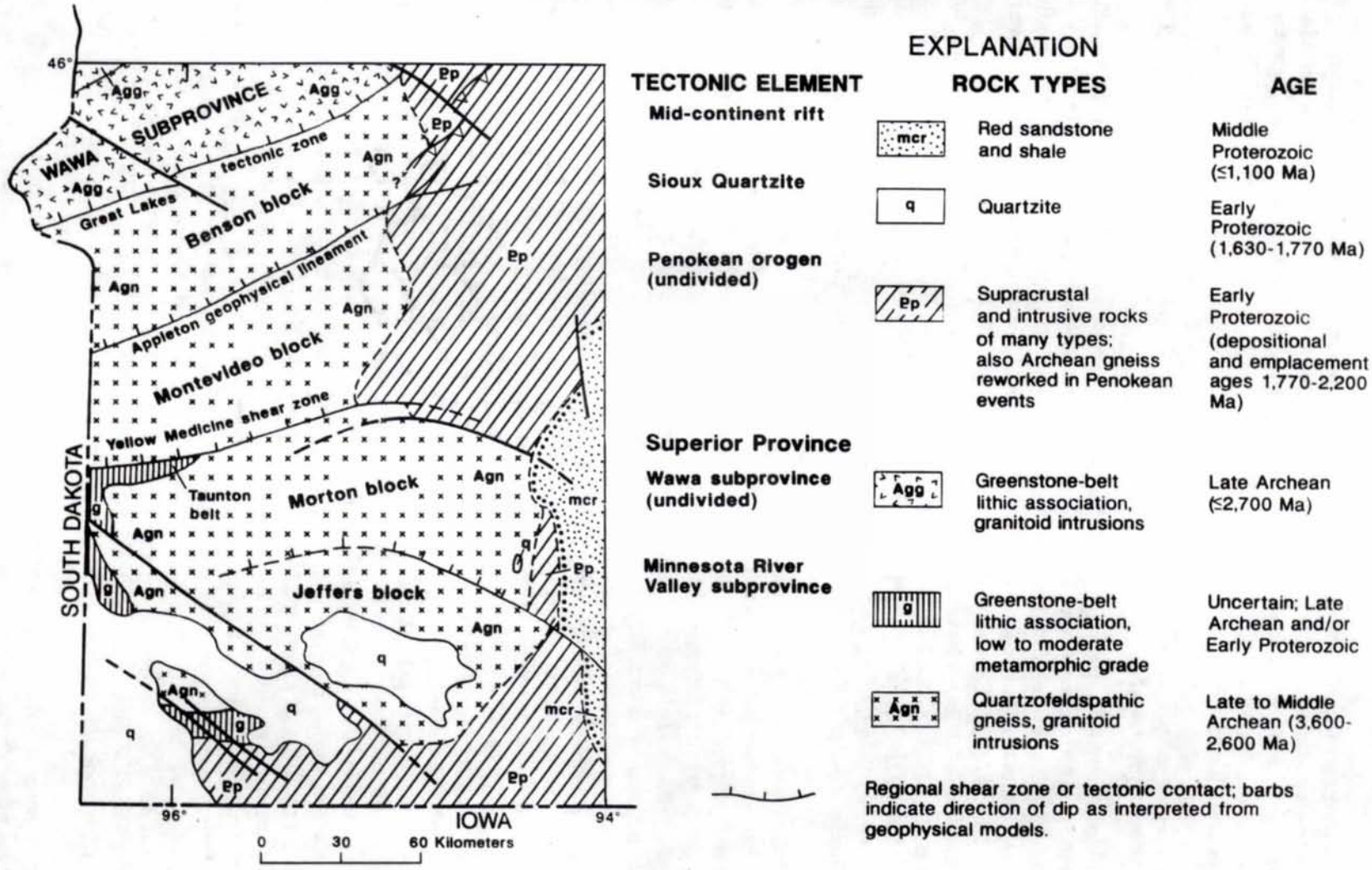


Figure 2. Tectonic sketch map of Precambrian terranes in southwestern Minnesota showing the major tectonic elements discussed in the text. Note especially the Taunton belt and the Yellow Medicine shear zone, informally named elements defined in this report. Map modified from Chandler and Southwick (1990).

lacking and direct structural comparisons are impossible because of the Quaternary cover, the fact that the geometry of the major internal shear zones of the Minnesota River Valley subprovince is congruent with that of the subprovince boundary zone suggests a common tectonic origin for the internal and bounding shears. Once formed, these crustal breaks were episodically reactivated in Proterozoic and Phanerozoic time.

Greenstone-belt sequences around and within the gneiss terrane of the Minnesota River Valley subprovince

Geophysical anomaly patterns suggestive of "greenstone-belt" lithostratigraphic sequences (Table 1) form a discontinuous girdle that flanks the gneissic core of the Minnesota River Valley subprovince on the south and southwest (Figs. 2 and 3). The Precambrian rocks responsible for these geophysical anomalies are partially covered by the Sioux Quartzite, and also by marine sedimentary rocks of Late Cretaceous age and glacial deposits of Quaternary age. As a consequence, the girdling anomaly belts have not received much exploration interest, despite the long-recognized possibility, based on older geophysical surveys (Philbin and Gilbert, 1966; U.S. Geological Survey, 1970; Ervin and others, 1980), of their association with metavolcanic sequences. One hole drilled into a girdling anomaly (SWG-3 on Fig. 1) encountered an actinolite- and epidote-bearing metadiabase in which ophitic texture and relict igneous minerals are preserved; this low-grade rock closely resembles the weakly metamorphosed subvolcanic sills that are common components of mafic volcanic sequences in other Archean subprovinces (e.g. Schulz, 1980) and also in Early Proterozoic volcanic sequences in the Penokean orogen (Southwick and Morey, 1991). This single datum strengthens the inference that the east-west anomaly belt through Nobles County may reflect a metavolcanic sequence, but it does not constitute unassailable proof.

Another linear belt of spatially correlative aeromagnetic and gravity highs trends approximately east-west across southern Yellow Medicine, northern Lincoln, and northern Lyon Counties between the South Dakota border and the Minnesota River (Figs. 2 and 3). For ease of discussion and reference, this anomaly belt is here named informally the Taunton belt, for the small town of Taunton in Lyon County. The Taunton belt is internal to the Minnesota River Valley subprovince; it lies along the north edge of the Morton block, immediately south of the Yellow Medicine shear zone. Five holes into the Taunton belt intersected mafic and ultramafic rocks that range in composition from andesite to peridotite and in metamorphic grade from greenschist to lower amphibolite facies.

Three of the five recovered drill samples are metamorphic rocks that possess deformation fabrics, and two are altered intrusive rocks that lack evidence of penetrative deformation. In the deformed group are a serpentinite derived from dunite or harzburgite (hole SWG-8) and two fine-grained mafic rocks that now lack definitive primary textures and consist entirely of metamorphic minerals. Protoliths of these are inferred on geochemical grounds (Table 2) to have been hornblende andesite or equivalent tuffaceous rock (hole SWG-4), and picritic basalt (hole SWG-9).

In the undeformed group are a diabase extensively converted to actinolite (hole YB-89-6) and a uralitized quartz-bearing gabbro (hole SWG-10). The hanging wall of the diabase is slaty iron-formation that has been decomposed to secondary oxides and clay by deep weathering. The geologic nature of the contact between iron-formation and diabase is unknown because it occurs within the saprolite profile in the drill hole and was not well sampled. It is likely, however, that the diabase is the younger rock and is intrusive into a deformed, dipping layer of iron-formation.

The diabase of hole YB-89-6 and the gabbro of hole SWG-10 both contain strongly zoned plagioclase phenocrysts, strongly zoned "groundmass" plagioclase that is less calcic than the phenocrysts, and large quantities of skeletal Fe-Ti oxide. Neither is foliated or lineated, despite

Table 1 — Generalized geological attributes of Archean greenstone belts in the Superior Province.

Characteristic rock types

Volcanic rocks

Basalt and kindred compositions, mainly as massive or pillowed flows and associated subvolcanic sills

- komatiite
- Mg - tholeiite
- tholeiite
- calc-alkalic basalt

Intermediate and felsic compositions, mainly as fragmental rocks (agglomerate, breccia, tuff-breccia, tuff)

- andesite
- dacite

Sedimentary rocks

Volcanic-derived epiclastic materials, most commonly of dacitic provenance and in rhythmically bedded turbidite sequences

- lithic graywacke
- shale

Iron-formation

Stratigraphy

Volcanic rocks typically are organized into one or more mafic-to-felsic sequences or cycles. Sedimentary rocks of felsic provenance are abundant in the upper parts of some cycles. Iron-formation may occur at any stratigraphic level but is most abundant near the transition from mafic to felsic volcanism. Unconformities of various scales are common.

Structure

Early recumbent folds, nappes, thrusts typically refolded one or more times under metamorphic conditions; present attitudes of bedding, other planar elements tend to be steep. Faults of several generations.

Tectonic interpretation

Volcanic rocks represent sea-floor, sea-mount, and oceanic island-arc magma systems. Turbidite sequences are indicative of submarine-fan and fan-valley environments in forearc, back-arc, and trench settings. Structures are consistent with tectonic amalgamation and deformation at convergent, transpressional plate margins.

Mineral deposits

Major deposits of gold, copper, lead, and zinc occur in Canadian greenstone belts. The larger gold deposits are in vein systems controlled by shear zones and faults; the larger base-metal deposits are within bodies of massive sulfide associated with sea-floor volcanic successions.

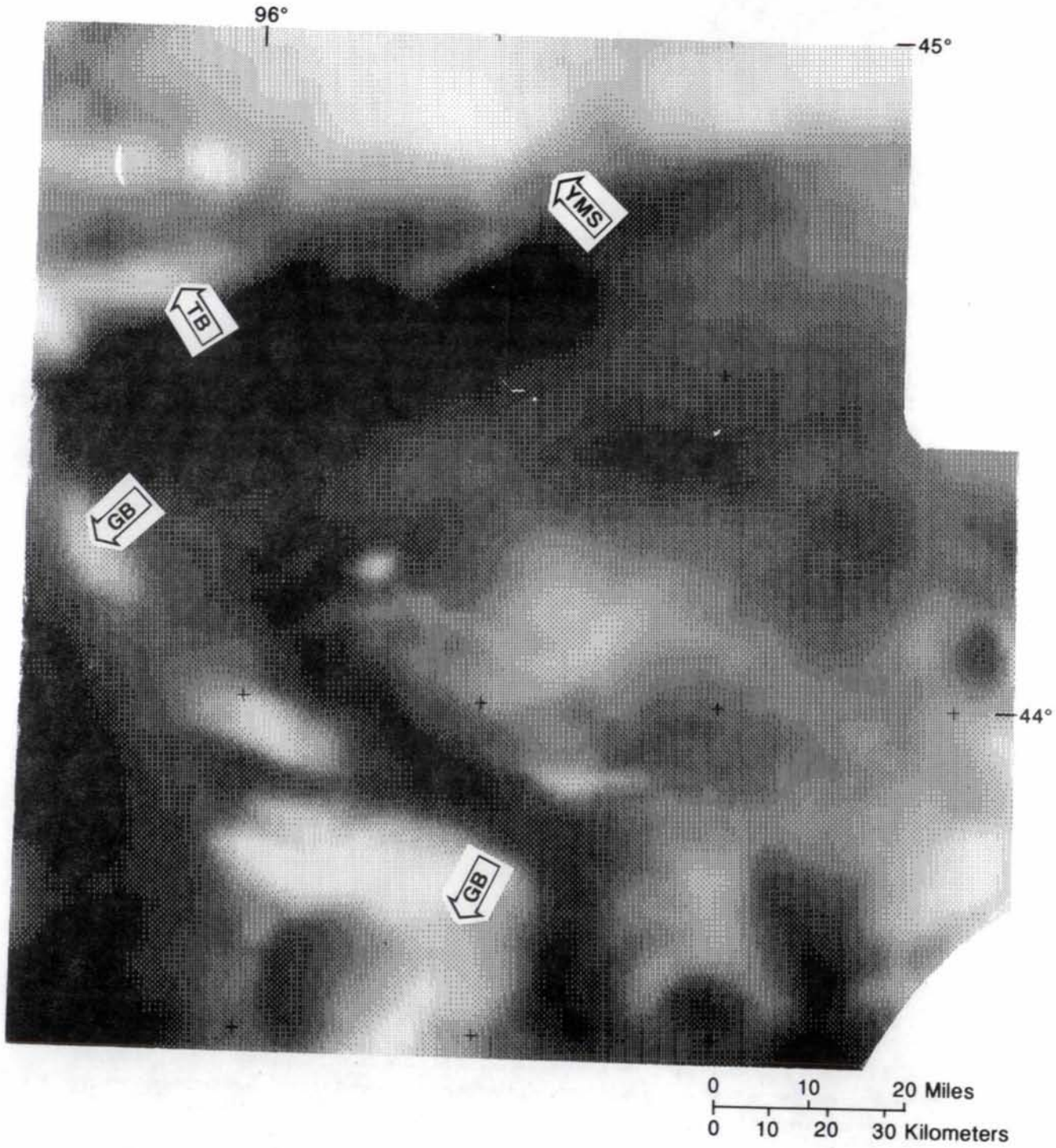
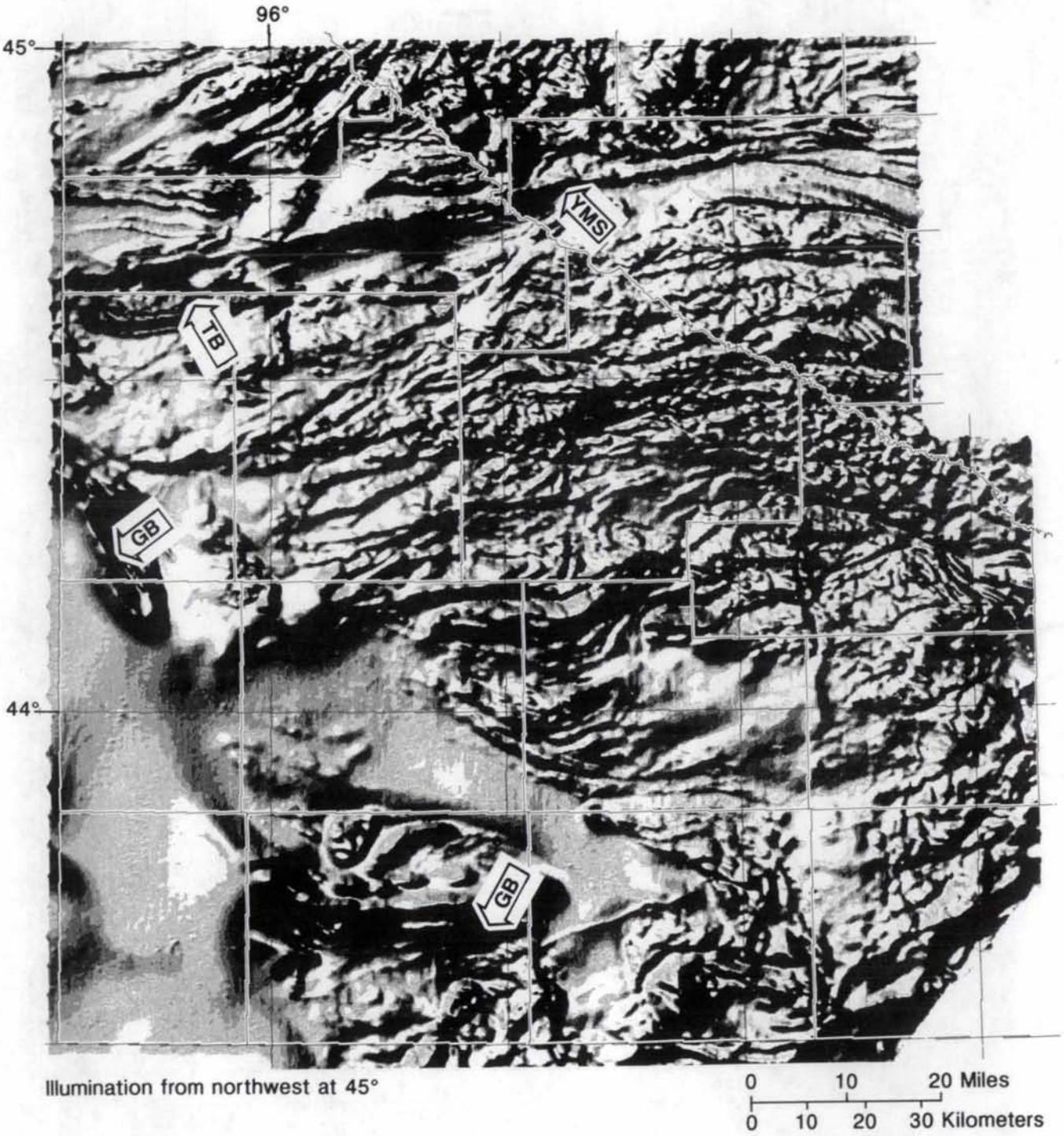


Figure 3. Geophysical images of southwestern Minnesota.

A. Gray-scale image of the Bouguer gravity anomaly in southwestern Minnesota; approximate range is from -5 (light) to -65 (dark) mgal.



B. Shaded-relief aeromagnetic image of southwestern Minnesota adapted from Chandler (1991); false illumination is from the northwest. See Figure 1 for county names and geographic locations. The Yellow Medicine shear zone (YMS), the Taunton belt (TB), and other belts of greenstone affinity (GB) are indicated by bold arrows.

Table 2 — Major- and minor-element geochemistry of mafic and ultramafic rocks sampled by drilling.

	1	2	3	4	5	6	7	8	9	10	11
	St Leo gb	Taun-Ctwd md	Cobden gb	Adrian md	Adrian md	Taun andesite	Garvin	Ctwd peridotit	Ctwd peridotit	Wd Lk mb	Han falls mgb
	YB89-2A	YB89-6	YB89-8	SWG3-733	SWG3-738	SWG4-272	SWG5-659	SWG8-102	SWG8-116	SWG9-315	SWG10-242
SiO2 (wt. %)	45.4	50	52.9	51.1	51	55.1	50.1	39.5	37.9	46.7	48.4
TiO2	4.56	1.48	0.58	0.27	0.24	1.64	1.03	0.13	0.14	0.84	1.78
Al2O3	15.6	13.5	17.7	17.7	20.7	13.3	16.6	3.35	3.23	7.74	13.5
Fe2O3	4.92	2.68	3.87	1.61	1.1	2.94	1.77	5.4	5.24	2.94	3.22
FeO	9.8	11.2	4.7	4.4	3.5	10.6	9.3	3.5	4.6	12.6	11.8
MnO	0.17	0.45	0.14	0.12	0.1	0.19	0.23	0.14	0.19	0.36	0.24
MgO	4.88	5.99	5.73	7.21	5.65	3.32	3.71	33	35.7	11.7	5.72
CaO	9.82	9.63	9.31	12	12.1	4.06	11	1.18	0.35	11.1	8.93
Na2O	2.59	2.34	3.49	2.55	2.58	3.11	3.33	0.01	<.01	0.58	1.69
K2O	0.27	0.31	0.48	0.6	0.85	2.27	0.29	<.01	<.01	0.35	0.68
P2O5	0.52	0.15	0.23	0.04	0.04	0.2	0.09	0.02	0.02	0.08	0.18
CO2						0.18	0.69	0.69	0.35	0.04	0.09
H2O	0.7	1.9	0.8	2.2	1.6	1.2	0.7	10.1	10	1.2	1.5
S											
SUM	99.23	99.63	99.93	99.80	99.46	98.11	98.84	97.02	97.72	96.23	97.73
FeOt	14.23	13.61	8.18	5.85	4.49	13.25	10.89	8.36	9.32	15.25	14.70
FeOt/MgO	2.92	2.27	1.43	0.81	0.79	3.99	2.94	0.25	0.26	1.30	2.57
Mg#(atomic)	37.96	43.98	55.54	68.74	69.18	30.90	37.80	87.57	87.24	57.79	40.98
Rb (ppm)	8	14	17	29	19	75	14	31	11	19	17
Sr	397	123	885	193	208	181	38	<10	<10	30	121
Ba	139	166	329	124	159	684	24	66	86	77	103
Nb	18	17	10	8	7	44	13	<10	11	18	28
Zr	56	107	32	40	37	211	63	<10	22	60	118
Y	13	27	13	10	18	29	24	<10	11	<10	23
Cr	18	158	123	86	57	60	273	2670	3430	1110	183
Ni	29	66	47	137	104	31	135	1840	1750	404	79
Cu	60	82	8	144	3	108	142	42	25	71	76
Zn	94	120	91	57	53	132	86	78	87	150	116
V	313	333	156	130	89	250	289	70	69	220	403
Rb/Sr	0.0202	0.1138	0.0192	0.1503	0.0913	0.4144	0.3684	?	?	0.6333	0.1405
CIPW norm	YB89-2A	YB89-6	YB89-8	SWG3-733	SWG3-738	SWG4-272	SWG5-659	SWG8-102	SWG8-116	SWG9-315	SWG10-242
Q	2.71	3.12	3.51	0	0	9.55	0	0	0	0	4.91
or	1.62	1.87	2.87	3.63	5.13	13.87	1.76	0.06	0.06	2.18	4.18
ab	22.24	20.26	29.85	22.11	22.31	27.21	28.92	0.1	0.09	5.17	14.88
an	30.59	26.01	31.55	35.94	43.32	16.16	30.26	6.64	1.85	18.4	28.34
C	0	0	0	0	0	0	0	1.42	3.01	0	0
diwo	6.43	9.13	5.69	10.35	7.41	1.39	10.49	0	0	16.29	6.9
dien	3.91	4.26	3.92	7.01	4.98	0.51	4.16	0	0	9.25	3.17
difs	2.16	4.78	1.3	2.55	1.88	0.9	6.45	0	0	6.35	3.67
hyen	8.42	11.01	10.5	11.05	8.96	8.04	4.58	45.19	36.58	21.16	11.65
hyfs	4.65	12.36	3.49	4.02	3.38	14.27	7.11	1.11	1.34	14.51	13.51
olfo	0	0	0	0.24	0.31	0	0.52	35.12	46.11	0.19	0
olfa	0	0	0	0.1	0.13	0	0.89	0.95	1.86	0.14	0
mt	7.24	3.98	5.67	2.39	1.63	4.41	2.63	9.08	8.75	4.49	4.86
il	8.79	2.88	1.11	0.53	0.47	3.22	2.01	0.29	0.31	1.68	3.52
ap	1.25	0.36	0.55	0.1	0.1	0.49	0.22	0.05	0.05	0.2	0.44

NOTE: All constituents except ferrous iron and H2O were determined by X-ray fluorescence methods. Analyses performed by XRAL Laboratories, Don Mills, Ontario.

considerable development of secondary actinolitic hornblende and epidote. These shared petrographic attributes and the geochemical similarity of the two rocks (Table 2) suggest that they are part of the same magmatic system. Moreover, their petrographic and chemical characteristics are strikingly similar to those of the larger dikes in the Early Proterozoic Kenora-Kabetogama dike swarm of northern Minnesota and Ontario (Southwick and Day, 1983; Southwick and Halls, 1987) and to the high-Ti tholeiite dikes of the Granite Falls area (Hanson and Himmelberg, 1967; Manzer, 1978). Thus, a Proterozoic age is tentatively inferred for the undeformed gabbro and diabase in the Taunton belt. Although these rocks resemble known dike rocks in petrographic and chemical attributes, the geophysical anomalies associated with them are more suggestive of plug-like than dike-like morphology.

The diverse rock types in the Taunton belt, the position of the belt in the middle of a predominantly gneissic terrane, the lower metamorphic grade of rocks in the belt as compared to their gneissic surroundings, and the spatial association of the belt with the Yellow Medicine shear zone collectively suggest several tectonic possibilities. The Taunton belt could be (1) the erosional remnant of a deformed Late Archean volcanic-hypabyssal sequence that lies above a deformed unconformity on older Archean gneiss; (2) the erosional remnant of an Early Proterozoic (Penokean?) volcanic-hypabyssal sequence that rests unconformably on Archean basement; (3) a remnant of allochthonous (obducted?) Late Archean oceanic or arc-related crust preserved in a Late Archean suture zone; or (4) a far-travelled Penokean thrust slice emplaced onto Archean cratonic foreland and preserved in a post-Penokean half-graben. It obviously will require substantially more geophysical, geochronologic, and geologic data than are now availabe to choose among these and perhaps other interpretations. Nevertheless, the Taunton belt would appear to be an intriguing speculative target for mineral exploration simply on the basis of the diverse tectonic environments already inferred (Sawkins, 1990), and it deserves further investigations of its composition, structure, age, and mineral potential.

The Garvin anomaly

The Garvin anomaly is a prominent football-shaped feature of the gravity and magnetic fields that is centered about 5 km (3 mi) southeast of the village of Garvin in southern Lyon County (Fig. 4). Its size and oval shape suggest that it is related to some sort of igneous intrusion within the Jeffers block of the Minnesota River Valley subprovince. The anomaly is somewhat unusual, however, in that it is delimited by a weak magnetic low that is spatially congruent with a strong gravitational high. This striking inverse correlation is especially clear in the first vertical derivative of the magnetic field and the second vertical derivative of the Bouguer gravity field. The inferred combination of low or moderate magnetic susceptibility with high density is not characteristic of common igneous rock types, and raises the question as to what the geological source of the Garvin anomaly might be.

Drill hole SWG-5 was sited near the center of the Garvin anomaly, but deliberately away from a centrally located magnetic high about a km (.6 mi) in diameter (Figs. 4A, B) that was interpreted as a minor feature not typical of the anomaly as a whole. Instead of encountering the predicted igneous rock, the drill penetrated a fine-grained metamorphic hornfels (grain size 0.1-0.2 mm) that is bedded on the scale of a meter or less and appears therefore to have had a sedimentary or tuffaceous protolith. Most beds consist of subequal amounts of olive-green hornblende and untwinned intermediate to calcic plagioclase, together with a rather consistent small amount (ca. 5%) of calcite; the beds are distinguished from one another by small variations in the modal ratio of hornblende to plagioclase. Interbedded with these rocks of essentially mafic composition are scattered thin layers of calc-silicate marble. The marble consists predominantly of calcite, but contains in addition variable amounts of orange-red grossular, diopside, plagioclase, scapolite,

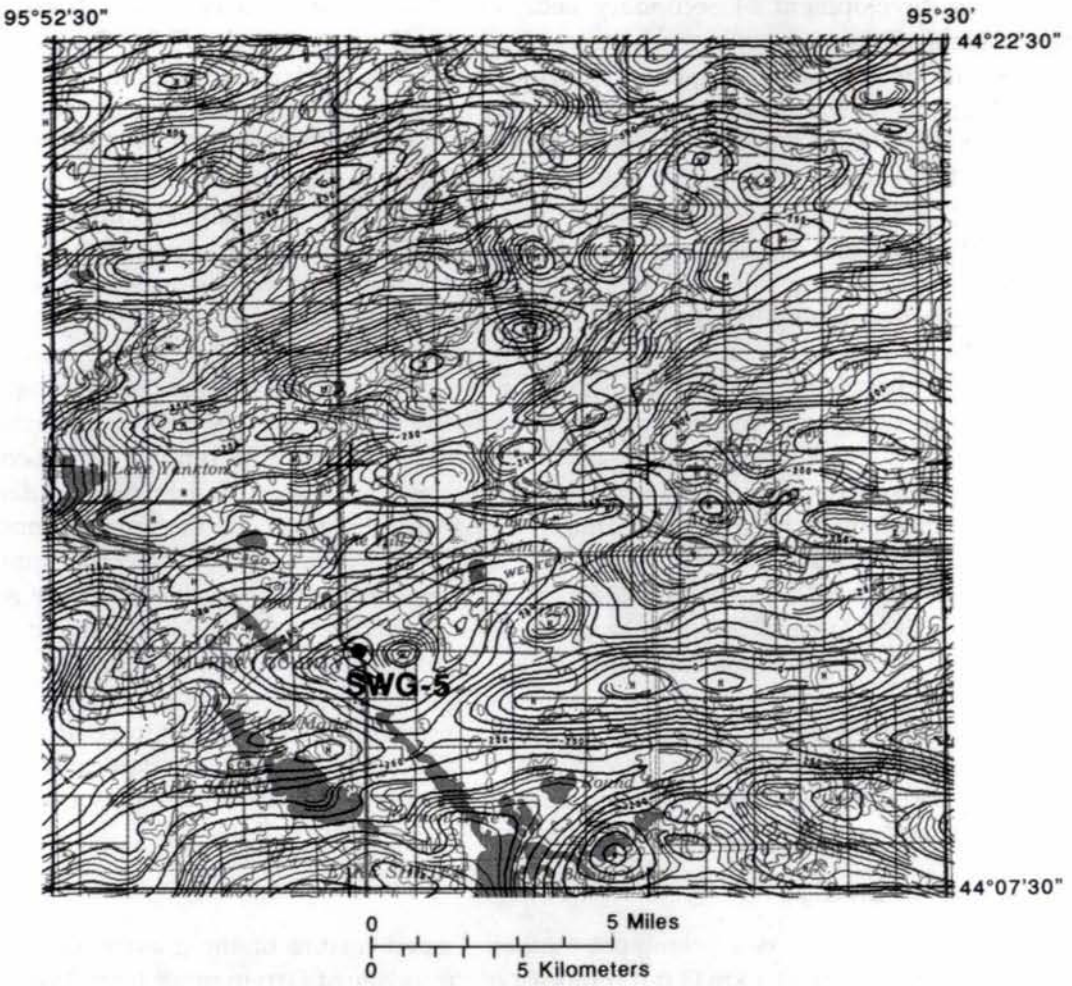
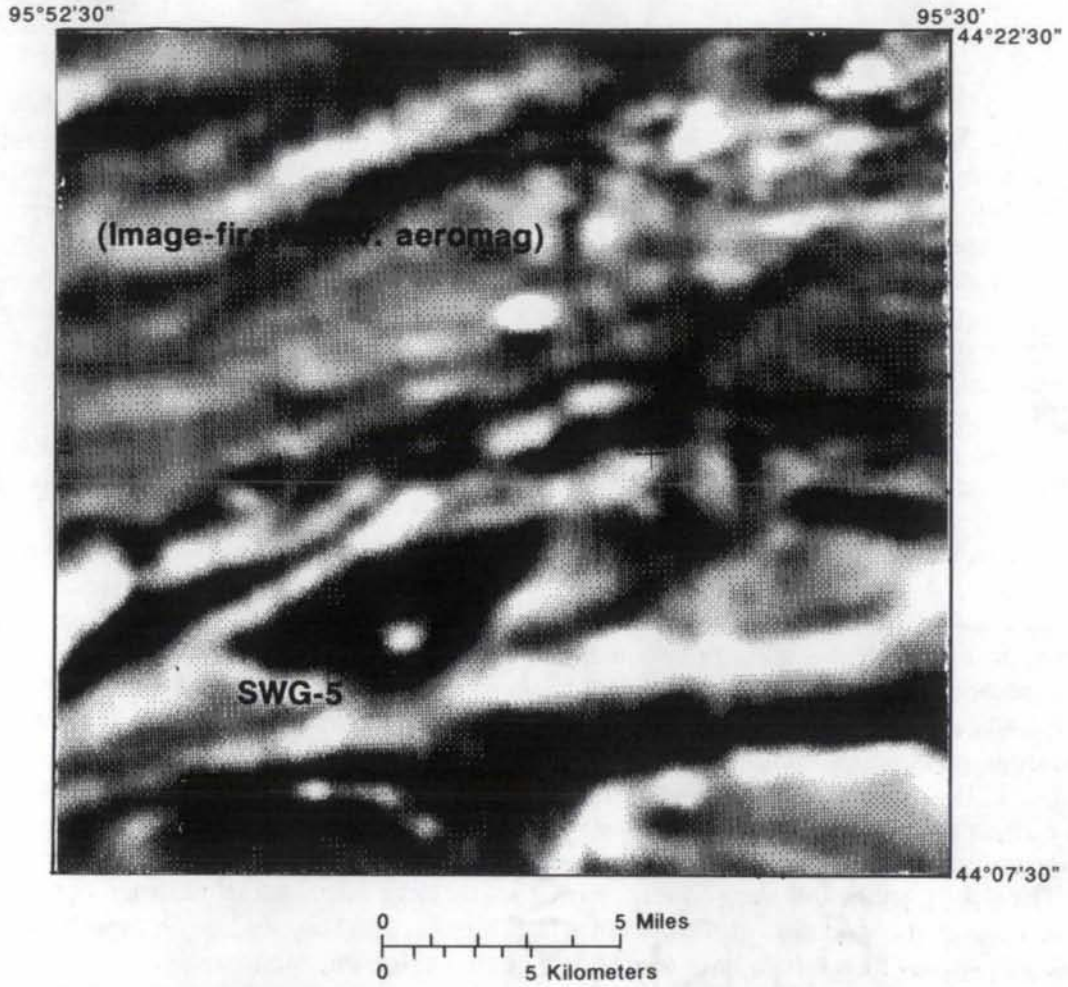


Figure 4 . Geophysical images of the Garvin area.

A. Aeromagnetic anomaly map of the Garvin area; magnetic intensity contours at 10-nT intervals. The Garvin anomaly is the ovoid, northeast-trending low in which drill hole SWG-5 is located. Note the sharp, circular magnetic high within the main anomaly. Map adapted from Chandler (1989).

B. Gray-scale image of the first vertical derivative of the aeromagnetic map of the Garvin area. The Garvin anomaly stands out as a pronounced low. Approximate range: +500 (light) to -200 (dark) nT/km.

C. Gray-scale image of the second derivative of the Bouguer gravity field in the Garvin area. The Garvin anomaly stands out as a pronounced high. Approximate range: +1.5 (light) to -1.5 (dark) mgal/km2.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95°30'
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SWG-5
44°07'30"
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5 Miles
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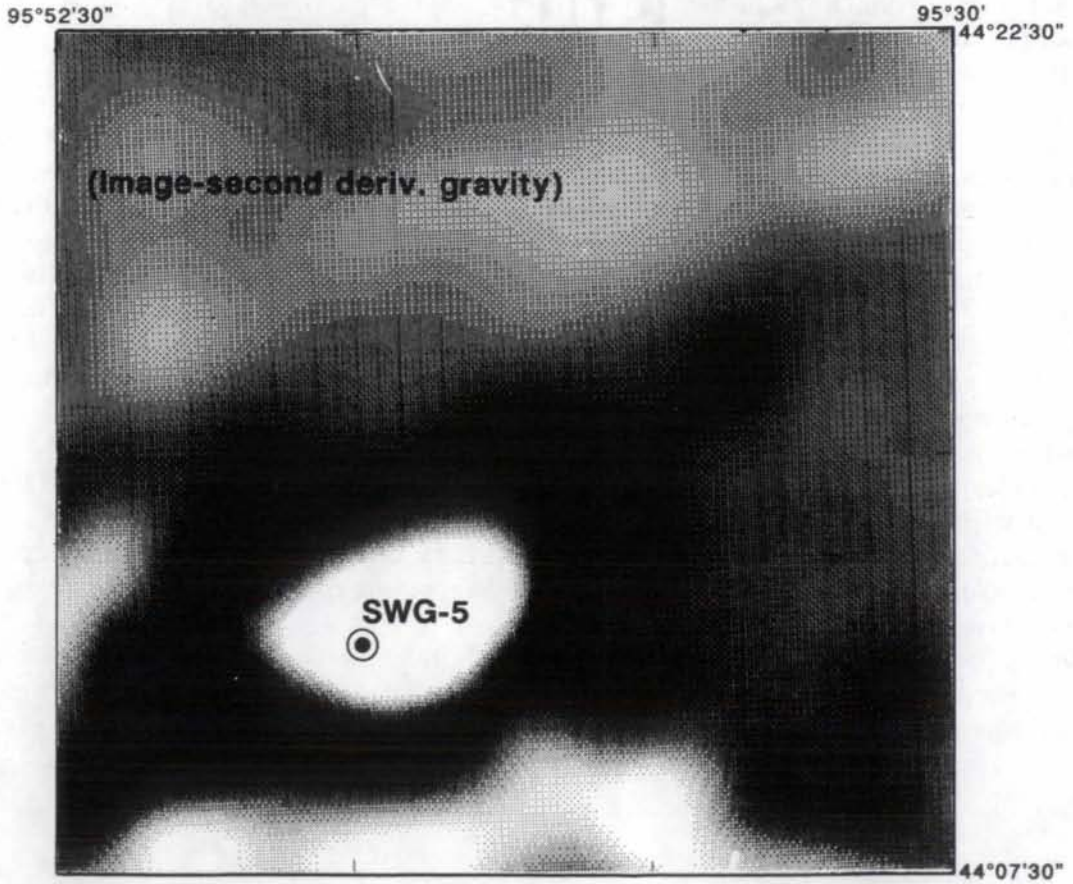
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SWG-5
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vesuvianite, hornblende, and sphene and therefore has the mineralogical attributes of a skarn (Meinert, 1992). Although the interbedded association of carbonate-bearing amphibolite and silicate-bearing marble could be derived from interstratified dolomitic shale, marl, and perhaps calcareous tuff (Gindy, 1951; Ferry, 1976), the presence of the typical skarn minerals scapolite, grossularite, and vesuvianite implies open-system metamorphic conditions and casts considerable doubt on the assignment of a protolith. Neither calcareous shale nor skarn has been described previously from the Minnesota River Valley subprovince or any other Archean subprovince in Minnesota. Sequences of interbedded calcareous shale and marble are known within several Early Proterozoic sedimentary units in the Penokean orogen (Southwick and Morey, 1991; Morey and Southwick, in prep), but to our knowledge no skarn assemblages have been reported.

Structurally, the bedding in the hornfels-marble sequence dips about 80 degrees, and a subtle but pervasive LS foliation dips about 65 degrees in the same sense. The regional geophysical strike in the vicinity of the Garvin anomaly is approximately 070 to 080 degrees, so it is likely that bedding and foliation in the hornfels-marble sequence strike northeast. Numerous thin veins are quasi-conformable to bedding and foliation. These typically are a few centimeters thick, boudinaged, and deformed into highly asymmetrical tight folds that plunge steeply. Some of the folds in veins approach sheath-fold morphology.

The mineralogy and internal zonation of the deformed veins are rather unusual. The innermost zone typically contains one of three mineral assemblages: (1) calcite + plagioclase, (2) calcite + plagioclase + phlogopitic biotite, or (3) phlogopitic biotite + plagioclase. In each of these the plagioclase is heavily degraded to clinozoisite and sericite. If a vein has a calcite-bearing central zone (i.e. either assemblage (1) or (2)), the next zone outward is composed of one of the assemblages phlogopitic biotite + altered plagioclase, phlogopitic biotite + garnet, or phlogopitic biotite alone. The sieved, subhedral megacrysts of garnet are as large as 10 mm in diameter and may be nearly as large as the thickness of the vein in which they occur. They enclose all other core-zone minerals and appear therefore to have formed late in the paragenetic sequence.

The biotite-bearing zones in the interior parts of veins are overlain by zones that contain hornblende. Hornblende joins phlogopitic biotite and altered plagioclase in the innermost hornblendic zone; this assemblage is succeeded outward by a marginal selvedge of monomineralic hornblende. The hornblende selvedge is in sharp contact with hornfels host rock that contains perfectly fresh, unaltered plagioclase and hornblende as principal phases.

The composition and arrangement of mineral zones in the veins are highly suggestive of metasomatic reactions between a streaming fluid phase and the confining wall rock. Although considerable detailed work on phase chemistry and the relevant theory of chemical diffusion and metasomatic transport (e.g. Fisher, 1978; Jamtveit and others, 1992) would be required to fully understand the system, it appears that the fluid phase was aqueous, with elevated concentrations of CO_2 and alkalis, especially potassium. Such a fluid might have emanated from a magmatic body located not far below the level reached by drill hole SWG-5; in other words, the drill may have penetrated metamorphosed and veined roof rock above the postulated pluton, or a roof pendant within it. One can speculate that this concealed pluton was responsible for contact metamorphism of the sampled hornfels, for the introduction of volatile components required for the growth of scapolite and vesuvianite in marble beds and/or skarn veins, for the potassic veins, and for the combination of potential-field anomalies already discussed. A pluton of lamproitic affinity (Mitchell and Bergman, 1991) might possess the requisite combination of geochemical and physical properties.

We emphasize that the inference of lamproite within the Garvin anomaly is based on incomplete and indirect evidence, and must be viewed as a speculative hypothesis. Nevertheless, the possibility is great enough to warrant further investigations, including more drilling. This is

especially true in light of the association of economic diamond deposits with lamproites in other cratonic terranes (see Mitchell and Bergman, 1991, p. 371-384, for a useful review) and the association of various metal deposits (W, Cu, Pb, Zn, Mo, Ag, Au, U, and Sn, among others) with skarns (Meinert, 1992).

The Marsh: An enigmatic circular feature in Rock County

"The Marsh" is the local name applied to a circular depression and former lake bed located about 5 km (3 mi) southeast of Jasper in Rock County (Fig. 5). The depression is about 3 km (about 2 mi) in diameter and has about 10 m (33 ft) of topographic closure; its floor is a flat plain developed on horizontally bedded lake clay of Quaternary age, and its topographic rim is underlain by Quaternary glacial deposits of several kinds. Superficially, the depression resembles the thousands of other kettle lakes and potholes that dot the glacial landscapes of the northern plains, but it possesses some attributes that set it apart from the ordinary glacial kettle.

Peculiar features of the Marsh are:

(1) Its isolation and uniqueness in the region. The Marsh lies outside the Bemis moraine (Wright, 1972; Matsch, 1972) in an area covered by glacial deposits of pre-Wisconsinan age. There are no lakes or former lakes of comparable morphology preserved anywhere else beyond the limits of the Wisconsinan glaciation in southwestern Minnesota or nearby parts of adjacent states.

(2) Its hilltop location. The Marsh is a depression that is situated on the top of a broad, high drainage divide. Stream valleys radiate away from the outer slope of the low rim of hills that encloses the circular depression.

(3) The thinness of the Quaternary section in the immediate vicinity. Bedrock outcrops of Sioux Quartzite are relatively abundant west and southwest of the Marsh, and less abundant on the other sides. The Quaternary section is less than 15 m (50 ft) thick in most places; it is 16 m (53 ft) thick at drill site PR-90-1 within the Marsh. As a rule, glacial kettles form in stagnant ice regimes where fluvial processes are active, and kettles therefore are usually embedded in thick aprons of glacial outwash. The glacial sediments are thin in northern Rock County, and do not include much outwash material. Sand and gravel layers compose less than 30 percent of the Quaternary section penetrated by drill hole PR-90-1, and the greater part of that thickness consists of older lacustrine deposits.

The remarkably circular shape of the Marsh and its seeming uniqueness in the region have stimulated the speculation from time to time that it might be a meteorite-impact structure. This idea surfaced most recently in the late 1980s in the aftermath of media publicity surrounding the identification of the Manson structure in Iowa as a Late Cretaceous impact phenomenon (Anderson, 1988; Hartung and Anderson, 1988). The Manson structure is located about 200 km (124 mi) southeast of the Marsh. It is a circular area about 30 km (about 19 mi) in diameter of strongly disturbed Phanerozoic and Pecambrian rock in which microstructural features indicative of hypervelocity shock deformation are widespread. Because large meteorites commonly break up into several fragments as they enter the earth's atmosphere, it is not unreasonable to postulate that a fragment of the Manson meteorite struck the earth in northern Rock County, Minnesota, where it produced a crater in Sioux Quartzite that was deeply eroded in post-Cretaceous time, later covered by Quaternary glacial deposits, and eventually occupied by a lake.

Clearly, this speculative hypothesis of impact origin cannot be taken seriously without direct evidence of hypervelocity impact phenomena in the Sioux Quartzite directly beneath, or very near the perimeter of, the circular feature in Rock County. Indicative structures would include shatter cones, veins of impact breccia or shock-induced glassy melt, and microscopic shock-dislocation lamellae in quartz (French, 1968; Stöffler, 1971; Alexopolous and others, 1988; Officer and Carter,

1991). The principal reason for drilling hole PR-90-1 was to obtain rock from beneath the Marsh that could be examined closely for these shock-related structures.

Neither the drill core nor nearby outcrops of the Sioux Quartzite contain structures or textures that can be ascribed unequivocally to shock metamorphism. Some of the quartz grains in these samples do contain one or more sets of planar strain lamellae that are significantly more prominent and clearly defined than those found anywhere else in the vicinity (Fig. 6), but the observed lamellae in quartz lack certain of the definitive geometric and crystallographic attributes associated with a shock-metamorphic origin (Alexopolous and others, 1988), and therefore they must have formed in response to ordinary terrestrial processes. It does seem clear, however, that the Sioux Quartzite has undergone a strain history of greater intensity in the immediate vicinity of the Marsh than it has in neighboring areas, and there is no obvious explanation for this difference. Research will continue on this puzzling problem.

Despite the field work and drilling undertaken thus far, we still do not have a straightforward explanation for the isolated circular lake bed in northern Rock County. Our present view is that an impact origin is not sustained by the observable data, although some sort of anomalous preglacial strain history is indicated by the quartz lamellae in the Sioux Quartzite. The lake bed is not a conventional glacial kettle, as discussed above, but it probably had some sort of glacial geomorphic origin. A new geologic map of the Quaternary deposits of southwestern Minnesota is currently in preparation, and the regional insights gained from systematic regional mapping may eventually provide a genetic explanation for the Marsh.

Deeply buried glacial gravels: their potential as aquifers and some exploration criteria for their discovery and extension

Historically, southwestern Minnesota has depended on ground water for most of its domestic, agricultural, and municipal water needs. Much of that water was, and still is, recovered from shallow wells (typically in the depth range of 25 to 200 ft or 8 to 61 m) that are finished in deposits of unconsolidated sand and gravel. The near-surface sand and gravel bodies most commonly used as sources of water were deposited by glacial meltwater streams toward the end of Pleistocene glaciation.

Some of the most prolific and heavily pumped glacial sand bodies in southwestern Minnesota are situated only a few feet beneath the present land surface. Thus they are poorly protected from surface infiltration and are vulnerable to contamination from agricultural, municipal, and domestic sources. Moreover, because of their shallow location and long, narrow, valley-controlled morphology, these near-surface aquifers contain water that is derived very directly from local rainfall. Consequently, they are subject to diminished yield during times of drought. These factors have prompted the consideration of alternative water sources, including imported surface water from the Missouri River.

Within the pile of glacial debris that now covers the bedrock of southwestern Minnesota, there is a complex vertical repetition of glacial tills, deposited during periods of glacier growth and stability, and meltwater deposits that formed during periods of glacier retreat. The meltwater deposits, which consist primarily of sand and gravel, are not as a rule blanket-like deposits of wide areal extent; most of them are branching networks of former stream channels of varying size and continuity. The larger, more continuous systems of buried meltwater channel deposits are potential aquifers that to date have not been used much in southwestern Minnesota.

Channel sands that are buried at a depth of more than 80 m (260 ft) generally are well protected from surface contamination and are relatively immune to short-term fluctuations in yield. They are not, however, easy to find. If deeply buried meltwater deposits are to become economically viable sources of ground water, geological and geophysical criteria must be developed

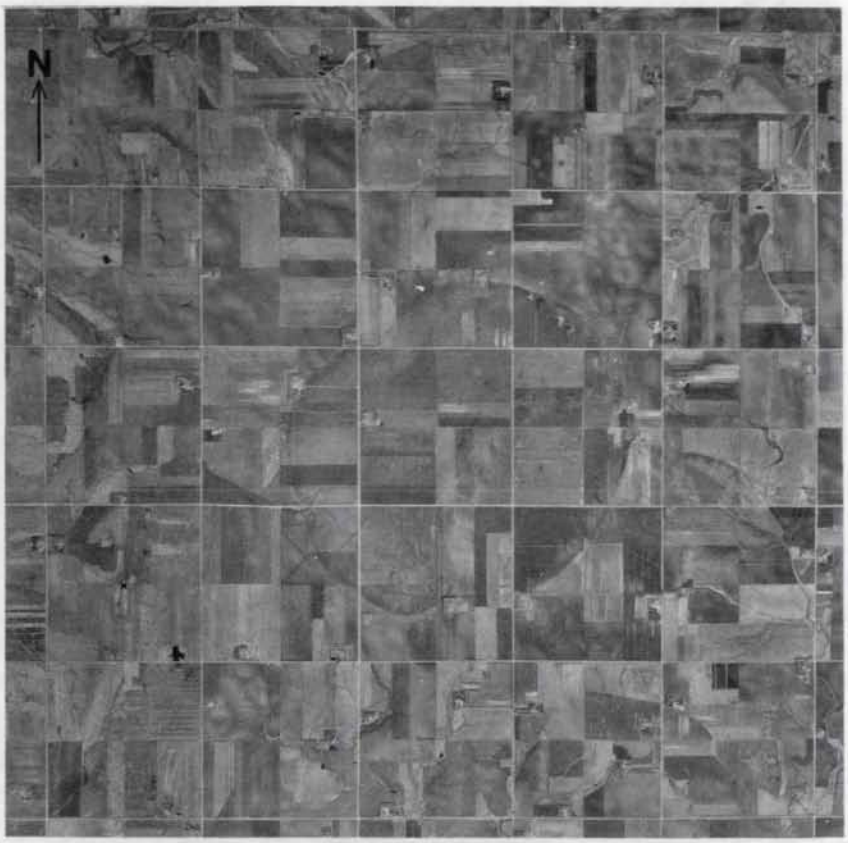


Figure 5. Aerial photograph of the circular lake bed in Rock County where hole PR-90-1 was drilled. Scale is given by the gridwork of section-line roads spaced one mile (1.6 km) apart.

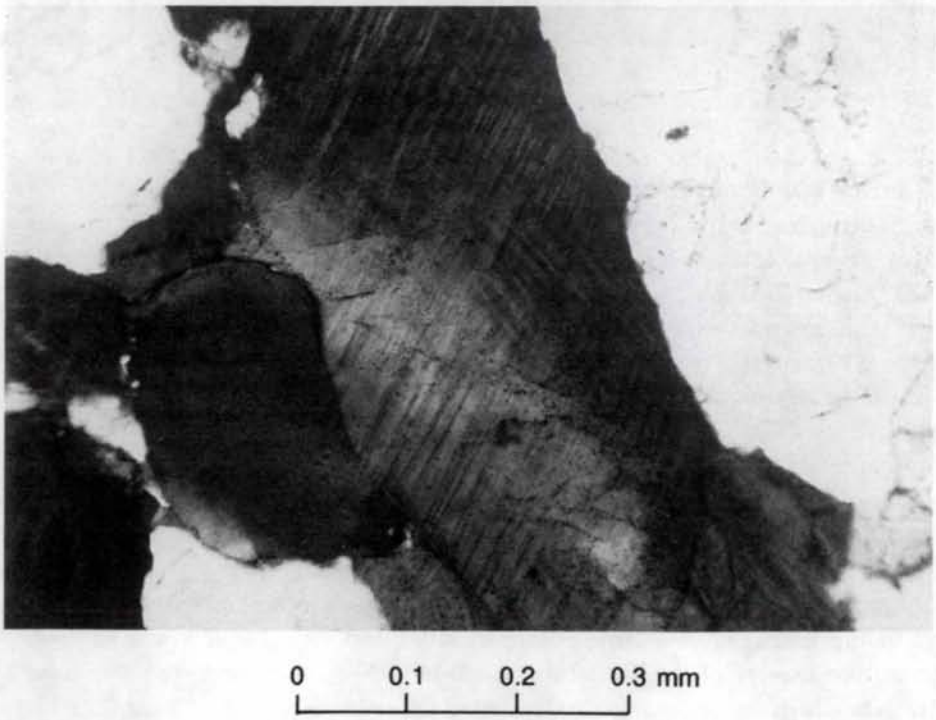


Figure 6. Photomicrograph of large, well-developed strain lamellae in quartz from drill core PR-90-1.

that can pinpoint their subsurface position in three dimensions. Also required are hydrologic pumping tests to quantify their yield, storage, and recharge characteristics, together with chemical studies to determine the quality of the water they contain. The costs of exploring for and developing ground water from deeply buried glacial deposits are up-front capital risks that ultimately must be weighed against the long-term costs of importing water from outside the region, or mitigating the quality of ground water from shallower aquifers that are already known.

Geological information relevant to these concerns has come from several drill holes discussed in this report. Two holes intersected thick sections of glacially derived sand and gravel along the north side of the Sioux Ridge in northern Murray (SWG-5), and western Cottonwood (SWG-7) Counties. These results, coupled with data from the same geological setting in southern Lincoln County and in adjacent South Dakota (Hansen, 1986; Hamilton, 1989; Hammond, 1991), strongly suggest that glacial meltwater channels formed repeatedly along the north side of the erosionally persistent bedrock high that is cored by the Sioux Quartzite (Fig. 7). An exploration strategy for deep ground water that is based on this hypothesis would involve (1) locating the buried northern margin of the Sioux Quartzite by geophysical methods, and (2) drilling a series of deep test wells (approximately 400 to 500 ft (120 to 150 m) deep on the average) just to the north of the quartzite margin. Follow-up hydrologic pumping tests and water-quality assessments would of course be required for full aquifer evaluation.

Farther north, in Yellow Medicine County, drill holes YB-89-4, YB-89-6, SWG-9, SWG-10, and SWG-11 intersected another set of thick and laterally persistent sand bodies at depths of about 150 to 300 ft (46 to 91 m), or about half the depth of those found along the Sioux Ridge. Here also the structure of the bedrock may have controlled the distribution of glacial meltwater channels, although this is not absolutely certain. The holes which encountered potential aquifer sands are in and near the Yellow Medicine shear zone (Fig. 2), where the rock is likely to be more severely fractured and therefore less resistant to erosion than in surrounding areas. The shear zone may have stood low in the paleolandscape, and served therefore to localize streams of glacial

Figure 7 (facing page). Schematic cross sections of the southwest margin of the Des Moines lobe glacier during stagnation and melting.

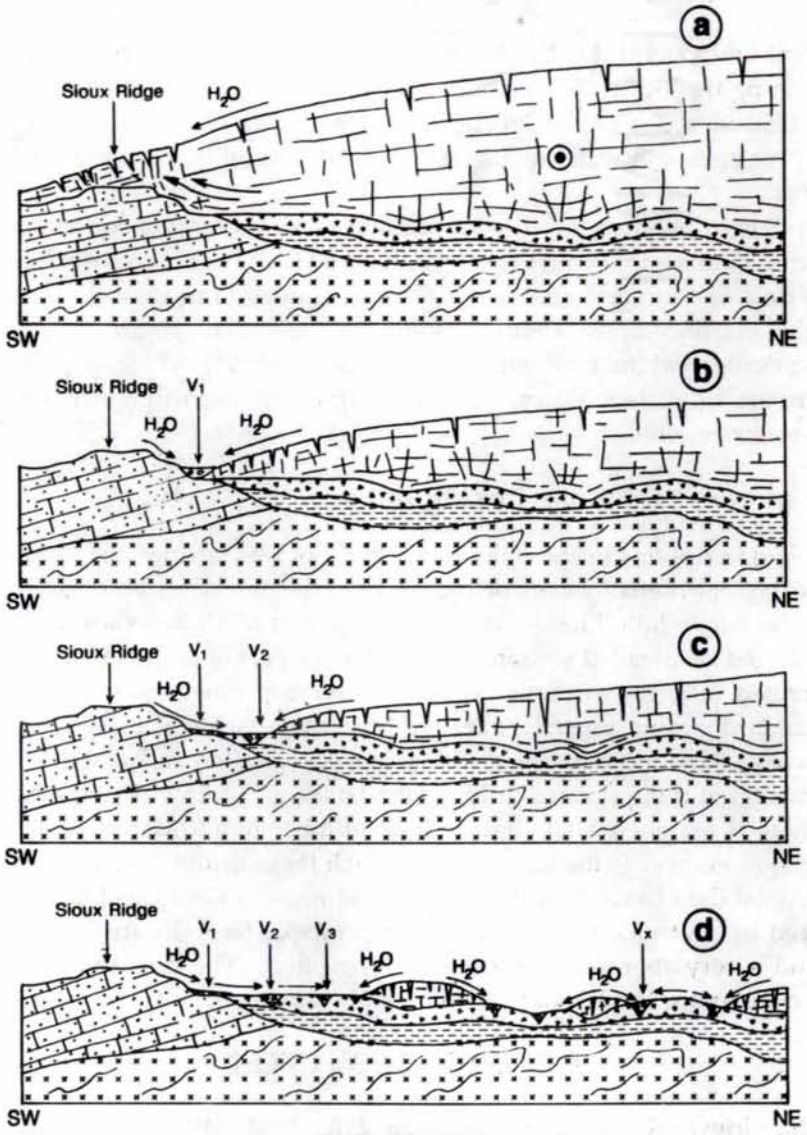
A. Glacier melting and thinning; Sioux Ridge still ice-covered. Ice is flowing southeastward (toward viewer as indicated by bullet symbol) and spreading laterally; at some stage it ceases to flow and stagnates.

B. Glacier stagnant and melting; valley (V1) exists between exposed quartzite of Sioux Ridge (on SW) and the ice margin (on NE). Meltwater drains toward this valley and flows more or less parallel to the decaying glacier margin. The valley fills with sand and gravel.

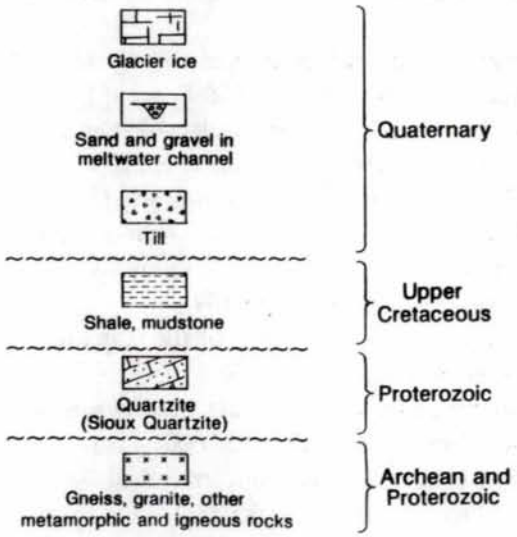
C. Glacier has melted back so as to expose till or soft shale (Cretaceous) at the ice margin. Meltwater streams excavate ice-margin valleys (V2) and fill them with sand and gravel.

D. Glacier all but melted; many valleys (V3....Vx) form and fill with sediment carried by transitory meltwater streams.

Subsequent cycles of glaciation and retreat will tend to produce new sediment-filled valleys in approximately the same positions as V1 and V2 because Sioux Ridge is a long-lived positive feature of the landscape. Drill hole SWG-5 is interpreted to have penetrated a plexus of ice-margin paleovalley deposits that formed near Sioux Ridge in the setting illustrated for V1 and V2.



EXPLANATION



meltwater. To test and extend this hypothesis as a water exploration strategy would require (1) geophysically refining the location of the buried shear zone, and (2) drilling a series of moderately deep test holes (250 to 400 ft (75 to 120 m) on the average) along its trace. In this case also, hydrologic pumping tests and water-quality assessments would be required for full evaluation of the aquifer system.

The drilling data at hand are clear evidence that sand and gravel bodies having the textural and stratigraphic attributes of potential aquifers do occur in the deeper subsurface of southwestern Minnesota. The data also suggest geologically based strategies for ground-water exploration and evaluation in the region. Some thought should be given to conducting the research and development work needed to evaluate properly the viability of deep ground water as an alternative to importing surface water, or to the continued use of environmentally vulnerable shallow ground-water systems.

Organization of the Drill Hole Descriptions

The drill-hole descriptions in the following section of this circular are arranged by project as identified by the project prefix. Holes of the YB-89 series are described first, holes of the SWG series next, and the single hole PR-90-1 last. The locations of all holes are plotted on a regional index map (Fig. 1) and on detailed section maps that are a part of each hole description. Locations are further described in terms of the abbreviated township-range-section system that has been adopted as a standard coding procedure by the Minnesota Geological Survey and several other Minnesota agencies. Readers unfamiliar with this system (often called the ABCD system) may find a full explanation of it in previous drilling circulars (e.g. Southwick and others, 1990).

Each drill hole is assigned a six-digit unique number in addition to its project-coded field number. The unique number is the identifier by which these drilling records are entered into and retrieved from digital data bases maintained by the Minnesota Geological Survey. In general, the information stored in electronic form is limited to principal facts (location, diameter, depth, etc.) for each hole, and a very abbreviated lithologic description. The descriptive and analytical data supplied in this circular are much more extensive and complete than those stored digitally.

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Field number YB-89-1A

Date finished 9/16/89

MGS unique number 242824

MGS lab number 2911

LOCATION (see map at right)

T–R–S 116 – 46 W – 24 ABABAB

County Lac Qui Parle

Quadrangle Gary SE (116D)

HOLE PARAMETERS (feet)

Surface elevation 1171+/-5

Total depth 335

Elevation, top of Precambrian rock 873

Core interval 325-335

Hole azimuth: plunge: vert

Core recovered 100%

Granite, medium-grained, pink and gray, biotite-bearing, weakly lineated.

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-11	Sand, fine-grained
11-33	Till, silt-loam, calcareous, shale-bearing; larger clasts are predominantly limestone and dolomite. Color medium-gray; oxidized to tan and brown in top 14'.
33-42	Sand, fine-grained; contains lignitic wood fragments.
42-54	Till, clay-loam, calcareous, gray. Fragments of Cretaceous fossils and concretions in coarse fraction.
54-65	Mixed sequence of silt interbedded with thin units of silty, sandy till. Probably a stagnant-ice deposit.
65-81	Till, clay-loam, calcareous, stiff; gray at top, grading downward to brown.
81-117	Sand and gravel, poorly sorted, composed predominantly of carbonate detritus; interval 104-108' is silty clay or possibly a thin unit of till.
117-166	Till, clay-loam, very calcareous, light gray; many thin layers of sand in basal 5 feet.
166-188	Till, clay-loam, calcareous, stiff, very compact; light- to medium-gray.
188-225	Sand and gravel; much of material is of granule size. Basal foot or two is coarse gravel.
	CRETACEOUS SEDIMENTARY ROCKS
225-254	Shale, non-calcareous, waxy, brittle, dark gray.
254-280	Shale, calcareous, high-gamma, dark gray with white specks.
280-294	Shale and marl, very calcareous, organic-rich, dark gray-brown; abundant fish scales, shelly debris.
294-298	Sandstone, quartzose, friable; quartz grains very angular.
	SAPROLITE ON PRECAMBRIAN ROCK
298-325	Clay, white to green, with much residual quartz; grades downward into partly decomposed rock.
	PRECAMBRIAN CRYSTALLINE ROCK
325-335	Granite, medium-grained, pink and gray.

PETROGRAPHIC DESCRIPTION OF CORE: YB-89-1A

This rock is a medium-grained, pale pink , homogeneous two-mica granite. Although it is essentially massive, the granite possesses a very weak linear fabric that plunges about 30 degrees.

The granite is allotriomorphic granular in texture and consists of grains that range in size between 0.5 and 2 mm. Grain boundaries are seriate and sutured; minor recrystallization has occurred along quartz-feldspar contacts. Quartz grains are strained and divided into subgrains that are reoriented only slightly. Twin planes and perthite lamellae in microcline show minor strain displacements. Plagioclase is unstrained and preserves normal compositional zoning.

Modally the granite consists of essential quartz (25%), perthitic microcline (35%), plagioclase (30%), biotite (8%), and muscovite (1-2%). Patches of granophyre are common along quartz-microcline contacts. Accessory minerals are epidote, allanite, apatite, zircon (prismatic crystals that are distinctly zoned), and Fe-Ti oxides.

CHEMICAL DATA: none.

Field number YB-89-2A

Date finished 9/20/89

MGS unique number 242825

MGS lab number 2912

LOCATION (see map at right)

T–R–S 115 – 44 W – 12 BCBBCB

County Yellow Medicine

Quadrangle Providence (115D)

HOLE PARAMETERS (feet)

Surface elevation 1105+/-5

Total depth 89

Elevation, top of Precambrian rock 1033

Core interval 78-89

Hole azimuth: plunge: vert

Core recovered 100%

Gabbro, medium- to coarse-grained, massive

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-3	Soil, calcareous, loamy, dark gray-brown.
3-6	Loess, chiefly silt and sandy silt, strongly calcareous, ashen gray.
6-35	Till, loamy to clay-rich, calcareous; larger clasts are mostly limestone and dolomite. Oxidized to yellow-brown above 17' depth; medium gray below.
35-49	Coarse sand interbedded with gravel; cobbly coarse gravel in depth interval 45-49'.
49-57	Till, calcareous, shale-rich, stiff, dark gray; very few clasts larger than granule size.
57-60	Gravel, medium- to coarse-grained; thin interbeds of sand, silt, clay.
	CRETACEOUS SEDIMENTARY ROCKS
60-72	Clay, blue-gray to green-gray, noncalcareous. Interpreted as clay shale that contains much saprolitic material derived from the underlying weathered zone.
	PRECAMBRIAN CRYSTALLINE ROCK
72-89	Gabbro, medium-grained; slightly weathered to green-gray color in topmost 2 feet; otherwise dark gray to black.

PETROGRAPHIC DESCRIPTION OF CORE: YB-89-2A

This rock is a medium-grained two-pyroxene gabbro (grain size 0.5-3.0 mm) that occurs toward the edge of an oval aeromagnetic high about 7 km in length. Exploration drilling (private) nearer the center of the anomaly encountered an olivine gabbro that is more primitive in composition than the present sample, but is probably related to it genetically. Both drill samples are pristine igneous rocks; this is provisionally taken as evidence of a Proterozoic age for the gabbro intrusion, but of course is not definitive proof.

Most of gabbro YB-89-2A displays a granular texture in which the mafic mineral grains tend to be smaller than the associated plagioclase grains. Locally, however, igneous hornblende forms oikocrysts as large as 5 mm across that contain inclusions of plagioclase, pyroxene, and opaque phases. Plagioclase (unzoned labradorite), orthopyroxene, and clinopyroxene are interpreted to have crystallized in equilibrium and at an early stage. Reaction rims of olive-green to brown-green magmatic hornblende surround many pyroxene crystals and crystal clusters, and locally have coalesced into the large oikocrysts previously mentioned. Pyroxene crystals that lack rims of igneous hornblende are fringed by a fibrous uralitic amphibole that is interpreted as deuteric. Russet-brown biotite proxies for igneous hornblende near granules of Fe-Ti oxide.

Accessory Fe-Ti oxide and apatite are both fairly abundant. The oxide phase occurs mainly as anhedral, equant grains associated with interstitial biotite and hornblende, and makes up at least 1% of the bulk rock.

CHEMICAL DATA: Table 2, column 1 -- Gabbro, depth 84 feet.

Field number YB-89-3

Date finished 9/06/89

MGS unique number 242826

MGS lab number 2908

LOCATION (see map at right)

T–R–S 115 – 41 W – 28 CBBBCC

County Yellow Medicine

Quadrangle Normania (99A)

HOLE PARAMETERS (feet)

Surface elevation 1062+/-5

Total depth 150

Elevation, top of Precambrian rock 931

Core interval 140-150

Hole azimuth: plunge: vert

Core recovered 100%

Biotite-hornblende quartz diorite, weakly to moderately foliated

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-87	Till, loamy, very calcareous, shale-bearing; pebbles, boulders of limestone, dolomite, granitoid rocks, various kinds of metamorphic rocks. Unit is dark gray except for topmost 17' where it is oxidized to hues of tan and brown.
87-88	Sand and gravel, poorly sorted.
88-107	Till, very similar to that in depth interval 0-87'.
107-108	Sand
108-131	Till, loamy, calcareous, shale-bearing, somewhat stiffer than overlying tills; cobbles are predominantly red granite and a variety of fine-grained to aphanitic, dark-colored igneous and metamorphic rocks.
	PRECAMBRIAN CRYSTALLINE ROCK
131-150	Biotite-hornblende quartz diorite, weakly to moderately foliated; slightly weathered throughout cored interval. The saprolitic zone is absent and presumably was eroded.

PETROGRAPHIC DESCRIPTION OF CORE: YB-89-3

This rock is a medium-grained, weakly foliated quartz diorite. It is allotriomorphic granular in texture and composed of grains that are about 1 mm in diameter. Mild deformation is indicated by undulose to polygonally recrystallized quartz and slight bending of biotite and plagioclase.

Modally the quartz diorite consists of essential plagioclase (58%), quartz (12%), hornblende (13%), and biotite (10%). The accessory minerals apatite (2%) and Fe-Ti oxide (5%) are uncommonly abundant. Other trace minerals are epidote, allanite (zoned), zircon, and sphene; the latter typically forms rims around oxide grains. Biotite, Fe-Ti oxide, and epidote are spatially associated and tend to be intestitial with respect to plagioclase and hornblende. Traces of myrmekite occur along quartz-plagioclase contacts.

CHEMICAL DATA: none

Field number YB-89-4

Date finished 9/09/89

MGS unique number 242828

MGS lab number 2909

LOCATION (see map at right)

T–R–S 115 – 41 W – 34 BBCCCC

County Yellow Medicine

Quadrangle Normania (99A)

HOLE PARAMETERS (feet)

Surface elevation 1057+/-5

Total depth 395

Elevation, top of Precambrian rock 831

Core interval 385-395

Hole azimuth: plunge: vert

Core recovered 100%

Mylonite gneiss derived from granitoid protolith; somewhat weathered.

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-8	Soil, organic, black. Probably includes some spoil from nearby drainage ditch.
8-15	Till, clay-loam, calcareous, plastic, light- to medium-gray. Top 2 feet may be loess.
15-17	Silt; contains abundant fragments of hard, black, carbonized wood.
17-24	Sand and gravel, poorly sorted; predominant pebble types are carbonate rocks, shale. Much carbonized wood as in overlying silt.
24-78	Till, clay-loam, calcareous, compact and sticky, medium-gray.
78-91	Sand, fine- to medium-grained.
91-106	Till, clay-loam, calcareous, compact and sticky; medium-gray. Depth interval 99-103' contains thin, sandy layers.
106-107	Sand
107-136	Till, loamy, calcareous, abundant limestone and dolomite pebbles of all sizes. Medium to dark gray.
136-226	Sand, fine- to coarse-grained, interbedded with pea-gravel.
	SAPROLITE ON PRECAMBRIAN ROCK
226-350	Clay, gritty because of residual quartz, white to pale blue-green. Residual feldspar toward base.
350-384	Grus composed of residual quartz and feldspar plus variable amounts of clay. Grades downward into hard rock.
	PRECAMBRIAN CRYSTALLINE ROCK
384-395	Mylonite gneiss derived from granitoid protolith; see detailed discussion below.

PETROGRAPHIC DESCRIPTION OF CORE: YB-89-4

This rock is a mylonite gneiss developed from a medium- to coarse-grained granitoid rock. The mylonitic fabric dips 50-55 degrees and varies abruptly in appearance and intensity as a function of lithologic variation and the mechanical partitioning of shear strain. Prior to shearing, the rock was a biotite quartz diorite transected by many dikes and veins of pegmatitic leucogranite.

Mylonitic microstructures are best developed in the leucogranite part of the rock. Grains originally as large as 5 mm in diameter have been variably reduced, recrystallized, and otherwise deformed by ductile to semibrittle shear. The quartz shows all degrees of conversion to ribbon-quartz aggregates; microcline crystals are optically strained, recrystallized at their margins, and flattened; plagioclase crystals are bent, microfaulted along crystallographic planes, and marginally recrystallized; biotite is kinked, displaced on cleavage, and extensively retrograded to hydrobiotite and chlorite. The plagioclase is heavily sericitized. Similar phenomena are less well developed in the quartz diorite part of the rock, which is finer grained than the leucogranite and poorer in easily deformed quartz and microcline.

CHEMICAL DATA: none.

Field number YB-89-6

Date finished 9/14/89

MGS unique number 242829

MGS lab number 2910

LOCATION (see map at right)

T–R–S 114 – 40 W – 27 DADADB

County Yellow Medicine

Quadrangle Wood Lake NW (98B)

HOLE PARAMETERS (feet)

Surface elevation 1050+/-5

Total depth 392

Elevation, top of Precambrian rock 835

Core interval 382-392

Hole azimuth: plunge: vert

Core recovered 98%

Metadiabase, actinolite-bearing, fine- to medium-grained (see discussion below)

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-2	Soil, loamy, organic, black.
2-48	Till, clay-loam to loam, calcareous, pebbly, medium-gray; top 16' is oxidized to yellow-tan.
48-60	Sand and gravel; abundant limestone, dolomite, and shale clasts; also abundant fragments of black, carbonized wood. Depth interval 56-58' is stiff silty clay.
60-150	Till, clay-loam to loam, calcareous, pebbly to rocky, gray; larger clasts are carbonate and granitoid rocks. Depth interval 89-94' contains several thin layers of sandy till.
150-211	Sand, fine- to coarse-grained, and gravel, pebbly to cobbly.
211-215	Clay and grit, rusty red-brown; interpreted as material reworked from subjacent weathering profile.
	SAPROLITE ON PRECAMBRIAN ROCK
215-253	Iron-formation and/or ferruginous slate, splintery, partly weathered, red, brown, and black; admixed with variable amount of yellow-brown to red-brown clay. Quartz vein at depth 240'.
253-381	Clay, smooth, without rock fragments; frequent color changes among hues of red, brown, gray, blue-green, and green; grades abruptly into hard, fractured rock in basal 3 feet.
	PRECAMBRIAN CRYSTALLINE ROCK
381-392	Recovered core (first sound rock) is metadiabase, actinolite-bearing, fine- to medium-grained. It is interpreted as a sill or dike intruded into iron-formation and allied rocks that are deeply weathered in the hanging wall of the intrusion.

PETROGRAPHIC DESCRIPTION OF CORE: YB-89-6

This rock is a coarse metadiabase or fine metagabbro that occurs beneath iron-formation and presumably intrudes it. The diabase contains plagioclase phenocrysts as long as 8 mm in a groundmass that consists predominantly of secondary actinolite but is neither foliated nor lineated.

The plagioclase of the groundmass and phenocrysts is stongly zoned and extensively replaced by iron-poor epidote. The calcic cores of unreplaced plagioclase crystals are cloudy and brown, owing to the presence of extremely small inclusions of an unidentified high-relief mineral. All primary mafic silicate phases are replaced by granular to fibrous actinolite which has obliterated original crystal shapes and partly obscured original textures. Quartz occupies the angular interstices among plagioclase laths; small patches of myrmekite are common along quartz-plagioclase contacts. Small, somewhat skeletal, octahedral grains of an opaque Fe-Ti oxide constitute as much as 8% of the rock by volume and appear to be late paragenetically.

Certain petrographic attributes of this diabase resemble those of the less altered gabbro sampled in drill hole SWG-10, and the two rocks are very similar geochemically. See the text of this report for further details of interpretation.

CHEMICAL DATA: Table 2, column 2 -- Metadiabase, depth 382 feet.

Field number YB-89-7

Date finished 9/25/89

MGS unique number 242827

MGS lab number 2913

LOCATION (see map at right)

T–R–S 115 – 38 W – 29 DBCCBA

County Yellow Medicine

Quadrangle Lone Tree Lake (97B)

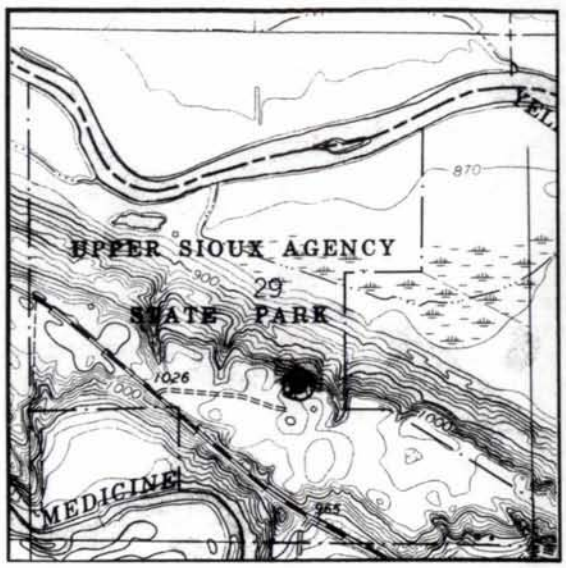
HOLE PARAMETERS (feet)

Surface elevation 1040+/-5

Total depth 436

Elevation, top of Precambrian rock 844

Core interval 425-436



Hole azimuth: plunge: vert

Core recovered 95%

Biotite-muscovite leucogranite and pegmatite, variably but pervasively sheared.

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-9	Silt, loam; some admixture of sand grains, granules in lower half. Color dark brown to yellow-brown. Unit interpreted as loess and associated windblown material.
9-24	Till, calcareous, clay-rich to loamy, yellow-brown.
24-30	Sand and gravel, subangular, composed prdominantly of carbonate rocks. Sequence coarsens downward.
30-41	Till, calcareous, clay-rich to loamy with abundant carbonate pebbles, yellow-brown.
41-46	Sand, coarse-grained, and pea-gravel.
46-116	Till, calcareous, generally loamy but with clay-rich and sandy intervals; larger clasts mainly carbonate, aphanitic basaltic rocks, and granitoid rocks. Color medium-gray; topmost 6' oxidized to yellow-brown.
116-121	Sand and gravel.
121-130	Till, clay-rich,stiff, gray. Boulder-cobble lag at base.
130-141	Gravel and sand
	CRETACEOUS SEDIMENTARY ROCKS
141-179	Clay and soft clay shale, non-calcareous, blue-gray.
179-196	Clayey siltstone, soft, friable, dark gray. Contains abundant lignite fragments.
	SAPROLITE ON PRECAMBRIAN ROCK
196-202	Clay, white to pale blue-green.
202-399	Clay, blue-green; contains residual grains of quartz throughout. Residual muscovite appears at depth 280'; K-feldspar at 355'; biotite at 370'. Grades downward into grus.
399-425	Grus composed of residual silicate minerals plus variable amounts of clay.
	PRECAMBRIAN CRYSTALLINE ROCK
425-436	Biotite-muscovite leucogranite and pegmatite, variably sheared.

PETROGRAPHIC DESCRIPTION OF CORE: YB-89-7

This rock is a pegmatitic two-mica leucogranite in which the texture grades abruptly and irregularly from pegmatitic to granitic. Curving foliation surfaces anastomose around and among coarse crystals and impart to the rock a rough gneissosity that dips about 50 to 65 degrees. This quasi-planar fabric is largely due to semibrittle shear. Although it would be misleading to class the whole rock as a mylonite, the foliae are narrow bands or layers in which mylonitic microstructures are well developed. Such zones of concentrated shear strain are separated by rock volumes of variable thickness in which the manifestations of shear are slight or absent.

The most typical leucogranite is an allotriomorphic granular rock made up of crystals that range between 2 and 5 mm in size. Megacrysts of perthitic microcline about 20-30 mm in size are unevenly distibuted and constitute the greater part of the rock in the pegmatitic zones. The normal, non-pegmatitic leucogranite contains subequal amounts of quartz, sodic plagioclase, and perthitic microcline together with a few percent of biotite and muscovite. The muscovite occurs as individual flakes, as intergrowths with biotite, and as intergrowths with K-feldspar, quartz, and fibrolitic sillimanite. It may be inferred from the latter intergrowth assemblage that the rock locally reached the P-T conditions required for the breakdown of muscovite to anhydrous phases. Apatite and blue tourmaline are the accessory minerals.

Within the shear zones the quartz shows all gradations from moderately domainal to ribbon structure. Plagioclase twin lamellae are bent, kinked, and microfaulted. Perthitic exsolution lamellae in microcline are kinked and have a regular en echelon orientation with respect to strain twinning in the host. In addition, the tips of perthite exsolution lamellae tend to be bent sigmoidally, which suggests that the lamellae were elongating under conditions of shear.

CHEMICAL DATA: none.

Field number YB-89-8

Date finished 10/04/89

MGS unique number 247182

MGS lab number 3020

LOCATION (see map at right)

T–R–S 109 – 34 W – 1 DAAAAD

County Brown

Quadrangle Evan (78D)

HOLE PARAMETERS (feet)

Surface elevation 1026+/-2

Total depth 129

Elevation, top of Precambrian rock 910

Core interval 118-129

Hole azimuth: plunge: vert

Core recovered 95%

Gabbro, medium-grained

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-4	Soil, clay-rich, black.
4-22	Till, loamy, calcareous, shale-bearing, medium-gray to olive-gray. Oxidized to ochre and tan hues in upper 12'.
22-29	Sand and gravel; grains, pebbles are mainly carbonate, chert, and black, aphanitic, basaltic rock.
29-44	Till, clay-rich to loamy; coarsens with depth. Till is calcareous and shale-bearing; the larger clasts are mostly dolomite and basaltic rocks, but include a small fraction that are red sandstone and red felsite of Superior provenance.
44-77	Sand, coarse sand, and gravel that is composed overwhelmingly of dolomite clasts.
	CRETACEOUS SEDIMENTARY ROCKS
77-99	Clay, greatly variable in color from bed to bed, interstratified with thin beds of silty clay and poorly sorted clayey silty sand. Interpreted as material reworked from subjacent or nearby saprolitic weathering profile.
	SAPROLITE ON PRECAMBRIAN ROCK
99-116	Clay, blue-green; grades abruptly to fractured, hard rock at base.
	PRECAMBRIAN CRYSTALLINE ROCK
116-129	Gabbro, medium-grained, dark green-gray to black.

PETROGRAPHIC DESCRIPTION OF CORE: YB-89-8

This rock is a two-pyroxene hornblende gabbro, medium- to fine-grained, that has a pronounced igneous lamination. The flow fabric is carried by oriented plagioclase laths of aspect ratio 1:3 that average about 1 mm in length. Orthopyroxene and clinopyroxene crystals are approximately equant and generally are smaller than 0.5 mm in diameter. Oikocrysts of igneous hornblende are as large as 3 mm in size and enclose smaller crystals of plagioclase, both pyroxenes, and Fe-Ti oxide.

The plagioclase is of two types. One type forms strongly zoned crystals that are a little larger and more equant than the crystals of the unzoned second type. The zoned plagioclase crystals are corroded and embayed by unzoned plagioclase, which suggests that the zoned crystals were small xenocrysts out of equilibrium with the host magma. The clinopyroxene and orthopyroxene appear to have crystallized in equilibrium with each other and the unzoned variety of plagioclase; hornblende forms reaction rims around both pyroxene types and these rims locally have coalesced into oikocrysts. Dark reddish-brown biotite locally proxies for hornblende in the vicinity of paragenetically late Fe-Ti oxides. Apatite is a moderately abundant accessory mineral.

CHEMICAL DATA: Table 2, column 3 -- Gabbro, depth 122 feet.

Field number YB-89-9

Date finished 10/03/89

MGS unique number 247183

MGS lab number 3026

LOCATION (see map at right)

T–R–S 110 – 33 W – 35 BABBBB

County Brown

Quadrangle Evan (78D)

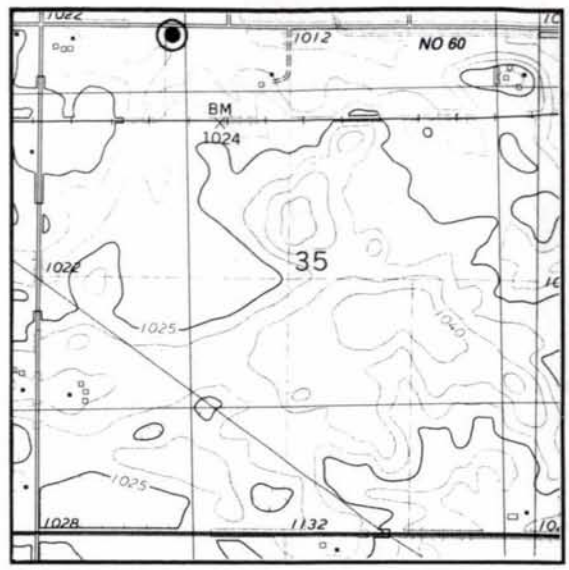
HOLE PARAMETERS (feet)

Surface elevation 1013+/-2

Total depth 245

Elevation, top of Precambrian rock 887

Core interval 235-245



Hole azimuth: plunge: vert

Core recovered 95%

Biotite-muscovite leucogranite, medium-grained to pegmatitic; many nebulitic schlieren.

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-3	Topsoil, black, organic
3-6	Clay, smooth but stiff, dark gray. Possibly a lacustrine deposit.
6-52	Till, calcareous; texture of matrix varies abruptly from clay-rich to loamy to sandy in a manner that suggests the deposit is layered internally, perhaps by shear. The predominant clast types are limestone, dolomite, aphanitic basaltic rocks, and granitoids.
52-83	Till, feebly calcareous, gray-brown to brown, loamy, stiff; abundant small pebbles of red to brown felsite and siltstone; also basaltic rocks. Abundant wood chips immediately above base.
83-99	Till, gray-brown to medium-gray, calcareous, loamy; abundant carbonate clasts. Abundant wood chips immediately above base.
99-126	Silt, fine sand, and clay, interbedded; stiff clay layer in interval 109-113' may be lacustrine. Much wood, including large logs, encountered just above base.
	CRETACEOUS SEDIMENTARY ROCKS
126-136	Clay, white to pale gray, interbedded with coarse grained, angular quartz sand in interval 132-136'.
	SAPROLITE ON PRECAMBRIAN ROCK
136-221	Clay, pale greenish-gray; residual quartz veins common throughout. Residual K-feldspar appears at depth 145'; horses of hard rock occur at depth 177' and become more abundant downward.
	PRECAMBRIAN CRYSTALLINE ROCK
221-245	Biotite-muscovite leucogranite, nebulitic and texturally inhomogeneous.

PETROGRAPHIC DESCRIPTION OF CORE: YB-89-9

This rock is a medium- to coarse-grained pale pink granite that contains many vaguely bounded layers and pods of a grayer, more schistose and biotite-rich paleosome. Overall, the rock has the physical appearance of a nebulitic migmatite or the inclusion-choked marginal facies of a mesozonal granite pluton. The streaky biotitic pods and schlieren define a crude foliation that dips about 25-30 degrees; this is cut by a steeper, weaker grain foliation that strikes oblique to the schlieric layering and dips about 75 degrees in the same sense.

The clean granite fraction of the rock is allotriomorphic granular in texture and is composed of grains in the 1 to 4 mm size range. Small megacrysts of microcline (approximately 8 mm in size) are widely scattered. Grain boundaries are sutured and moderately embayed. The quartz is undulose and locally divided into subgrains. Otherwise there are no grain-scale indications of strain.

Modally the granite consists of weakly zoned plagioclase (30%), quartz (30%), slightly perthitic microcline (35%), red-brown biotite (5%), and traces of primary muscovite. The accessory assemblage includes metamict zircon, xenotime, monazite, and Fe-Ti oxides. Biotite is variably altered to chlorite + opaques + muscovite + rutile + adularia.

The schlieren are similar to the granite in texture and mineral assemblage, but contain more biotite and less microcline.

CHEMICAL DATA: none.

Field number SWG-1

Date finished 09/24/91

MGS unique number 247029

MGS lab number 3216

LOCATION (see map at right)

T–R–S 103 – 39 W – 12 DAAAAA

County Nobles

Quadrangle Brewster (18-B)

HOLE PARAMETERS (feet)

Surface elevation 1452+/- 5

Total depth 190

Elevation, top of Precambrian rock 1275

Core interval 187-190

Hole azimuth: plunge: vert

Core recovered 100%

Sioux Quartzite: Medium-grained quartz arenite, pale pink, cross-laminated, completely lithified

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-7	Topsoil, black, soft, slightly calcareous
7-56	Till, clay-rich, calcareous; grades downward in color from yellow-buff at top through greenish gray to medium blue-gray at depth of 17 feet; is medium-gray from 17 feet to base. Sand lens at depth 19.5-20 feet.
56-59	Sand, coarse, calcareous, with lenses of medium-grained gravel that is rich in carbonate and granitoid pebbles.
59-62	Till, clay-rich, calcareous, medium blue-gray.
62-102	Till, loamy to somewhat sandy, calcareous; contains much chert in coarse fraction. Topmost 9 feet oxidized to yellow-brown color; remainder of unit is streaky or variegated in shades of yellow-brown and gray.
102-108	Sand, medium to coarse, interbedded with gravel and minor amounts of blue-gray clay and silt. Gravel consists mainly of chert and carbonate clasts.
108-126	Till, clay-rich, calcareous, very compact and stiff.
126-177	Till, loamy to slightly sandy; texture somewhat variable throughout unit. Sandier intervals are greenish- or yellowish-gray whereas loamy or clay-rich intervals are medium-gray or blue-gray. Sandy material predominates in basal 20 feet. Till is calcareous and contains abundant clasts of Sioux Quartzite.
	PRECAMBRIAN CRYSTALLINE ROCK (Sioux Quartzite)
177-190	Quartzite, hard, pale pink. Sharp, unweathered contact with overlying glacial deposits.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-1

The detrital framework of the quartzite consists overwhelmingly of subrounded quartz grains between 0.5 and 1.0 mm in size. Unstrained to weakly undulose unit grains of quartz are predominant; some of these are n-cycle grains that show abraided epitaxial quartz overgrowths. Other grain types constitute less than 1% of the total framework; these include polygonally recrystallized quartzite and chert, unrecrystallized hematitic chert and lean iron-formation, and mortar-textured "metamorphic" quartz. Trace minerals include tourmaline, monazite, rutile, sphene, and a blue, polysynthetically twinned, high-relief phase tentatively identified as corundum.

The principal cementing material is a complex, fine-grained, intimately intergrown assemblage of quartz, kaolinite, pyrophyllite, diaspore, hematite, and an unconfirmed phase tentatively identified as adularia. It is virtually certain that these minerals are the products of digenetic reactions among primary detrital components and pore fluids, but the details of the reactions (the reactants, intensive variables, and rates) cannot be established from the surviving petrographic evidence.

This quartzite has undergone little if any post-depositional strain. A minority of the unit quartz grains display undulose extinction; strain lamellae are virtually absent.

CHEMICAL DATA: none

Field number SWG-2

Date finished 10/04/91

MGS unique number 247037

MGS lab number 3217

LOCATION (see map at right)

T–R–S 102 – 39 W – 4 BBBBBB

County Nobles

Quadrangle Worthington North (19A)

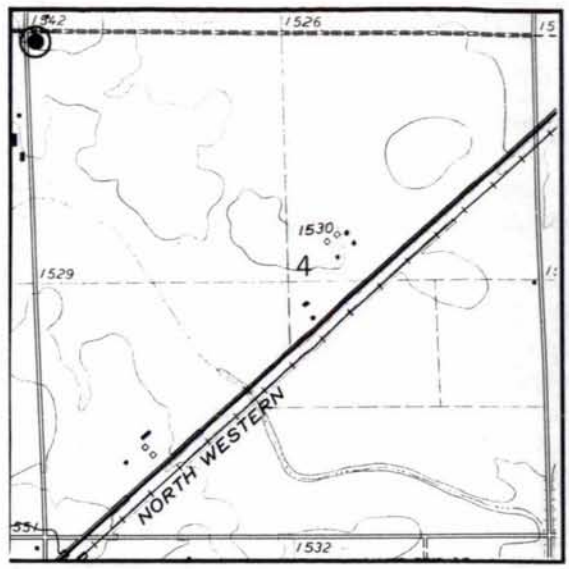
HOLE PARAMETERS (feet)

Surface elevation 1545 +/- 5

Total depth 650

Elevation, top of Precambrian rock 930

Core interval 638-650



Hole azimuth: plunge: vert

Core recovered 92%

Sioux Quartzite, originally coarse-grained quartz arenite with thin interbeds and lenses of pea-gravel

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-57	Till, clay-rich to loamy, calcareous; thin layers or lenses are somewhat sandy. Topmost 7 feet is oxidized to buff-tan color; remainder of unit is medium-gray to blue-gray.
57-68	Sand, coarse, interbedded with gravel. Gravel contains abundant limestone pebbles, smaller proportions of granitoid and mafic pebbles.
68-138	Till, pebbly-sandy clay-loam, calcareous, medium-gray.
138-142	Gravel, limestone-rich; interbeds of coarse carbonate sand.
142-178	Till, pebbly-sandy clay-loam, calcareous, medium- to dark gray.
178-199	Gravel and coarse sand, carbonate-rich, buff, water-bearing; small boulders at base.
199-222	Till, sandy clay-loam, calcareous; more clay-rich (less sand) below topmost few feet. Depth interval 199-210 feet is somewhat oxidized and olive-green in color; below 210' the till is dark greenish-gray.
222-224	Sand, fine sand and silt.
224-261	Till, clay-loam, generally poor in pebble and cobble size grades. Color is dark gray.
261-272	Gravel with interbeds of coarse to fine sand and silt; pebble fraction consists of carbonate, various metamorphic rocks, granitoids, shale, and pyrite nodules. Basal foot or two contains large cobbles, boulders.
272-280	Till, clay-rich, calcareous, poor in large clasts. Dark gray.
280-375	Clay, brown to brown-gray, interbedded with silt and fine sand. May be a lacustrine sequence.
375-402	Till, fine-sandy to clay-loam, feebly calcareous, poor in large clasts. Dark gray.
402-427	Till, clay-rich to sandy, possibly grading into and admixed with weathered shale near base. Oxidized to gray-green in topmost 4 feet; remainder of unit is dark gray.

CRETACEOUS SEDIMENTARY ROCKS

427-444	Shale, clay-rich and sticky, in part decomposed, dark gray.
444-496	Shale, dark gray, soft; many thin interbeds of better indurated brown-gray siltstone and very fine-grained sandstone.
496-558	Shale, dark gray, plastic; thin interbeds of lignite; poorly defined zones rich in calcareous fossils or fossil debris.
558-576	Siltstone and fine sandstone, brown to gray; interbeds of shale throughout.
576-608	Shale, clay-rich, variegated color in shades of light- to medium-gray and blue-gray; thin interbeds of lignite and fine-grained white sand.
608-626	Sand, fine- to coarse-grained, quartz-rich, white to pale pink, kaolinitic. May include some untransported regolith derived from Sioux Quartzite near base.

PRECAMBRIAN CRYSTALLINE ROCK (Sioux Quartzite)

626-631	Quartzite, hard, pink, interspersed with intervals of sandy, decomposedquartzite.
631-650	Unweathered quartzite.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-2

The quartzite in this core is cross-bedded and cross-laminated. Many individuals cross beds of decimeter thickness or greater are normally graded from pea-gravel at the base to very fine sand and silt at the top, and their framework elements are commonly bimodal in texture. The framework in the basal part of such a graded bed is about 75% quartz sand that is subangular to subrounded and between 0.1 and 1.0 mm in diameter, and about 25% oversize granules between 5 and 12 mm in diameter. The granules diminish upward in amount and disappear entirely near the middle of the bed. The preponderance of framework grains in the topmost 2-4 cm of a typical bed are between 0.05 and 0.3 mm in diameter, but scattered among them are oversize grains of coarse sand as large as 2 mm.

The vast majority of quartz clasts exhibit strain phenomena such as undulose extinction, polygonal recrystallization, and mortar or ribbon textures. Unstrained unit grains are relatively rare. Other clast types include chert, granular iron-formation, and recrystallized siliceous rhyolite. Grains interpreted as former detrital biotite consist of chlorite and white mica intergrown with parallel laminae of Fe-Ti oxides. Trace minerals include zircon, monazite, rutile, and rounded granules of maghemite.

The matrix material in the quartzite is an intergrown assemblage of quartz, diaspore, kaolinite, pyrophyllite, hematite, and an unverified phase tentatively identified as adularia. This diagenetic mineral assemblage is especially abundant in the silty upper parts of graded units.

CHEMICAL DATA: none

Field number SWG-3

MGS unique number 247039

MGS lab number 3224

LOCATION (see map at right)

T–R–S 102 – 42 W – 18 ABABAC

County Nobles

Quadrangle Adrian (20-B)

HOLE PARAMETERS (feet)

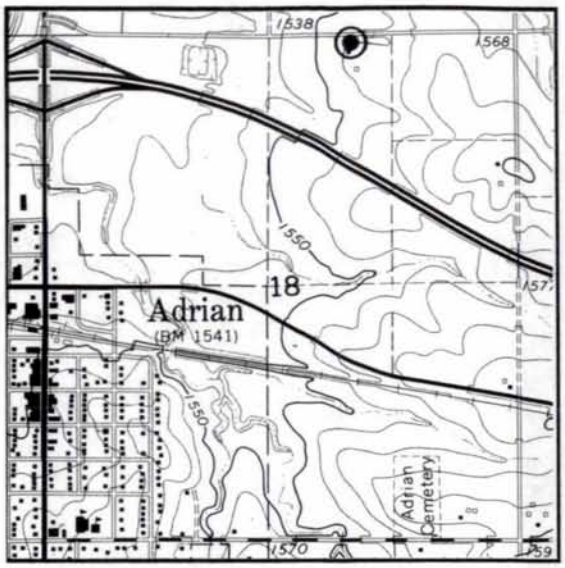
Surface elevation 1560 +/- 5

Total depth 741

Elevation, top of Precambrian rock 854

Core interval 730-741

Date finished 10/15/91



Hole azimuth: plunge: vert

Core recovered 100%

Hornblende-bearing gabbro or diorite, in part diabasic; extensively altered to actinolite, epidote.

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-2	Topsoil, dark gray to black, soft, slightly calcareous.
2-10	Sand, poorly washed, fine- to coarse-grained, brown, calcareous; much admixed clay and silt.
10-46	Till, loamy to sandy, very calcareous; more clay-rich below depth 15'. Abundant chert clasts in size fraction >1.5 cm. Oxidized to tan and brown above depth 35'; otherwise blue-gray.
46-94	Till, similar to above, but distinctly sandier. Topmost 6' oxidized to yellow-green, yellow-brown; otherwise blue-gray. Thinly interbedded clay-rich and sand-rich layers in basal 2'.
94-158	Till, loamy to sandy above depth 98', clay-rich and plastic below. Moderately calcareous; abundant cobbles and boulders. Oxidized or partly oxidized to yellow-brown above depth 138'; otherwise medium-gray to blue-gray. Basal foot is sand or sandy till.
158-190	Till, generally clay-rich, calcareous, similar to overlying unit. Oxidized or partly oxidized to yellow-brown and olive above depth 178'; otherwise blue-gray.
190-261	Till, clay-rich, moderately calcareous; similar to overlying two units. Oxidized to yellow-brown and olive in interval 190-238' depth; otherwise blue-gray to medium dark-gray.
261-346	Till, clay-rich, moderately calcareous. Oxidized to yellow-brown and yellow-green above depth 275'; otherwise blue-gray to medium-gray. Layers of lignitic clay, noncalcareous, dark brown to black, in depth interval 280-310'. Till below depth 310' is notably more rocky than that above, and may be a separate depositional unit.

CRETACEOUS SEDIMENTARY ROCKS

346-410	Clay, green, light green and white, non-calcareous; interbedded with fine- to medium-grained white sand. Contains abundant small pyrite nodules, gypsum crystals, and gypsum rosettes.
410-417	Clay and sand as above, with abundant fragments of fossil ammonites and lignitic wood.
417-480	Shale, clay-rich, non-calcareous, chalky white above depth 425', gray to dark gray below.
480-485	Sandstone, poorly lithified, fine-grained, with thin interbeds of shale.
485-506	Shale, gray to pale blue-gray, fossiliferous, soft.
506-539	Shale as above, interbedded with thin layers of poorly indurated siltstone and fine-grained sandstone.
539-550	Shale, gray, very rich in shelly fossils: lower part also contains much carbonized fossil wood.
550-676	Shale, fossiliferous, gray to light gray with some dark gray beds; the latter are better lithifed than the predominant light-gray shale.
676-700	Sandstone, fine-grained, white to variegated, variably lithified; interbedded on fine scale with variegated shale.

SAPROLITE ON PRECAMBRIAN ROCK

700-719	Clay of highly variable color from white through orange to brick-red; very plastic.
719-729	Clay, green to brown-green to red; in part soft, in part hard and waxy. Mixed with dark green rock chips near base.

PRECAMBRIAN CRYSTALLINE ROCK

729-741	Metagabbro and metadiabase, fine- to medium-grained; faintly layered in terms of modal composition and grain size.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-3

Prior to low-grade metamorphism and weak deformation, this rock was an ophitic to subophitic, amphibole-bearing diabase and gabbro. It exhibits a subtle layering that is due to the combined effects of modal and textural variations; finer-grained diabase layers contain a higher proportion of mafic minerals than the coarser-grained gabbroic layers into which they grade. The tendency toward ophitic texture and the variable grain size are suggestive of a hypabyssal cooling history.

On average, the primary, igneous mineralogy of the rock consists of about 50-55% intermediate plagioclase, 40-45% mafic silicate phases, and 2-5% oxides and accessory minerals. The primary minerals are replaced to varying degrees by a secondary, metamorphic assemblage that is dominated by actinolite together with smaller amounts of epidote, clinozoisite, secondary plagioclase, calcite, and leucoxene. In places, the bulk of the rock is replaced by a virtually monomineralic mass of felted actinolite.

Because the variable but ubiquitous secondary alteration has particularly affected the primary silicate minerals, it is difficult to establish the relative proportions of the primary mafic silicates with any degree of precision. The primary assemblage consisted of orthopyroxene, clinopyroxene, a colorless orthoamphibole, and a pale green clinoamphibole. The pyroxenes appear to have been present in all of the rocks examined (either as residual cores or textural pseudomorphs) whereas the primary amphiboles were seemingly more restricted.

The opaque assemblage consists of Fe-Ti oxide granules that typically are rimmed by sphene, and disseminated pyrite.

The deformation associated with low-grade metamorphism is manifested by (1) brittle cracking and microfaulting of primary plagioclase grains, and (2) the tendency toward parallel orientation of actinolite blades in secondary actinolite aggregates. The rough foliation of secondary actinolite deflects around "harder" plagioclase grains in a manner suggestive of development in response to shear.

CHEMICAL DATA: Table 2, column 4 -- metadiabase, depth 733 feet
Table 2, column 5 -- metadiadase, depth 738 feet

Field number SWG-4

Date finished 8/26/92

MGS unique number 247590

MGS lab number 3372

LOCATION (see map at right)

T–R–S 113 – 44 W – 1 CCDCC

County Lincoln

Quadrangle Taunton (100D)

HOLE PARAMETERS (feet)

Surface elevation 1171+/-2

Total depth 279

Elevation, top of Precambrian rock 968

Core interval 268-279

Hole azimuth: plunge: vert

Core recovered 99%

Hornblende schist, fractured and somewhat weathered; derived from andesite or andesite tuff

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-4	Organic soil and Recent alluvium on flood plain. Clay-rich, very plastic; dark gray.
4-54	Interbedded clay and sand; beds range in thickness from less than a foot to approximately 10 feet. The clay layers range in color from blue-green to neutral pale gray and in consistency from plastic to stiff; they are feebly calcareous. The sand layers consist mainly of carbonate-rich fine-grained sand and silt; minor interbeds are coarse sand and gravel. Abundant fossil wood at base of section. Unit interpreted to be of fluvial origin.
54-63	Till, clay-rich, calcareous; abundant shale and lignite fragments. Pale gray at top; grades to dark gray at base.
63-88	Sand, mostly fine-grained, calcareous, buff to gray. Contains fossil snails (juvenile forms) and much woody and lignitic chaff. Lower half of interval contains many thin beds of pale gray clay intercalated with the fine sand. Unit interpreted to be of fluvial origin.
	CRETACEOUS SEDIMENTARY ROCKS
88-94	Clay or partly decomposed shale, blue-green to medium green-gray, non-calcareous, very stiff.
94-101	Sandstone, fine-grained, buff to tan. Moderately well indurated in topmost 2 feet; otherwise very friable.
101-119	Soft claystone or shale, blue-green, with many thin interbeds of fine-grained, tan, friable sandstone.
119-144	Claystone or shale, non-calcareous, blue-green to gray.
144-152	Shale, clay-rich, variegated; color ranges from blue-green to brown to medium gray in beds or zones that are no more than a foot thick.
152-199	Shale, clay-rich, fissile, of variable consistency from plastic to stiff; green-gray above depth 170' and medium to dark gray below.
	SAPROLITE ON PRECAMBRIAN ROCK
199-259	Clay, intense blue-green, with zones or veins of brittle limonite; residual rock chips appear at depth 215' and increase irregularly in abundance as a function of depth.
	PRECAMBRIAN CRYSTALLINE ROCK
259-279	Hornblende schist, fine-grained, foliated, dark greenish-gray to black, heavily fractured and veined. See following sections for further details.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-4

This rock is a fine- to medium-grained hornblende schist that displays a weak compositional layering (probable bedding; dips about 70 degrees) and a prominent S-L foliation (dips about 85 degrees in same sense as layering). The foliation is composed locally of curving, anastomosing segments suggestive of a shear-generated S-C fabric.

Texturally the rock is granoblastic and microporphyroblastic. The groundmass is a fine-grained mosaic (0.1 mm grain size) composed most commonly of untwinned plagioclase (35-40%), biotite (60-65%), and minor quartz (ca. 2-3%); hornblende replaces about a third of the groundmass biotite in some layers. Highly sieved hornblende microporphyroblasts (0.2-0.3 mm grain size) are thickly set in the biotitic groundmass and account for about 50% of the bulk rock. The S-L foliation is carried by the preferred orientation of the hornblende megacrysts and to a lesser degree by the orientation of groundmass biotite.

Localized shear zones and associated retrograde metamorphism are prominent features of the lowermost third of the interval cored. In this region the rock consists of a great many small, streamlined volumes of granoblastic schist that are separated from one another by narrow shear zones filled with secondary hydrous phases. The principal minerals in the shears are chlorite and tremolite; associated with them are smaller amounts of epidote, calcite, granular plagioclase, and Fe-Ti oxides in the form of large, prominent euhedra. The unretrograded schist in this part of the core is notably richer in granular magnetite than that elsewhere.

Chemical data (Table 2), the fine grain size, and the layering of this rock suggest that it was derived from an andesitic, supracrustal protolith.

CHEMICAL DATA: Table 2, column 6, hornblende-biotite schist (meta-andesite ?), depth 272 feet.

Field number SWG-5

Date finished 9/03/92

MGS unique number 247591

MGS lab number 3373

LOCATION (see map at right)

T–R–S 108 – 41 W – 3 AAAAAA

County Murray

Quadrangle Tracy West (62B)

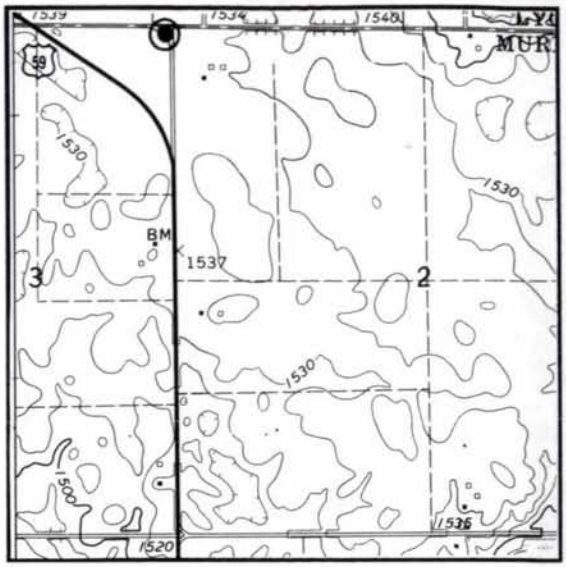
HOLE PARAMETERS (feet)

Surface elevation 1535+/-2

Total depth 670

Elevation, top of Precambrian rock 901

Core interval 659-670



Hole azimuth: plunge: vert

Core recovered 100%

Hornblende hornfels interbedded with calc-silicate skarn

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-6	Organic soil and soft clay, brown-gray.
6-75	Till, loamy, calcareous, pebbly; abundant pebbles of limestone, chert; smaller amounts of red porphyry, shale. Oxidized to buff and brown-gray in depth interval 6-32'; otherwise medium gray.
75-87	Till, loamy to sandy-loamy, calcareous, less shale than above; color buff (at top) grading downward to olive-gray.
87-105	Sand, mostly coarse-grained, interbedded with gravel. Gravel fraction is rich in carbonate rocks, granitoid rocks, felsic to intermediate porphyry, and chert. Basal foot of unit is coarse gravel in which the pebbles are coated with calcite and limonite.
105-130	Till, loamy-sandy to sandy, very calcareous, olive-gray to medium gray. Abundant small pebbles of basaltic rock types.
130-159	Gravel, carbonate-rich, subangular; pebble population similar to that in unit in depth interval 87-105'. Excellent aquifer potential.
159-170	Till, loamy, calcareous, shale-poor, medium gray.
170-192	Till, loamy to clay-rich, calcareous, shale-rich; color is distinctly green- to olive-gray. Color change at top of unit is sharp and corresponds with an abrupt change in drilling rate (moderate above; very slow below). Unit resembles Kandiyohi till of Meyer (1988).
192-211	Till, sandy, feebly calcareous; small fraction of coarse clasts consists of Superior-type red porphyry and red sandstone. Till matrix is ochre to red-brown.
211-232	Till, loamy, calcareous, shale-rich, olive-gray.
232-256	Till, somewhat sandy, calcareous, shale-bearing; matrix in top 8' is odd shade of pale greenish-brown and more clay-rich than in rest of unit. Sandy-loamy till below depth 240' is variegated in shades of ochre and brown.
256-263	Sand and gravel; much carbonate detritus.
263-332	Till, loamy, sparingly calcareous, shale-bearing. Interval 263-272 is ochre to brown-gray, stiff and dry; interval 272-290 is somewhat sandy, neutral gray, moderately soft; interval 290-332 is clay-rich, shale-rich, dark gray, moderately stiff. Internal contacts are gradational.
332-405	Gravel and fine- to coarse-grained sand. Abundant pebbles, cobbles of chert, quartzite, basaltic rocks; less abundant carbonate, granitoid rocks. Much lignite and wood debris in interval 355-356'. Interval 355-392' is chiefly fine sand; interval 392-405' is chiefly coarse gravel (clasts 3-5 cm) with interbeds of pea-gravel and coarse sand. Unit has excellent aquifer potential.

405-420	Clay, sparingly calcareous, medium-gray, plastic, smooth; lacustrine deposit or very clay-rich till.
420-422	Sand, fine-grained.
422-439	Till, calcareous, loamy-clayey, shale-rich, dark gray.
439-445	Sand and gravel; much lignite and woody debris in upper part.
445-491	Till, shale-rich, calcareous, loamy, stiff: olive-gray at top to dark gray at base.
491-495	Gravelly sand; fines downward to sandy silt at base.

CRETACEOUS SEDIMENTARY ROCKS

495-623	Shale, dark gray except in top 9' where it is green-gray. Soft and structureless in greenish weathered zone; otherwise weakly lithified and fissile. Thin beds of better lithified brown siltstone are widely spaced between 545' and 611'. Thin beds of fine-grained, white, friable sandstone occur interbedded with dark shale below depth 616'.
623-634	Sandstone, friable, fine- to medium-grained, quartz-rich, kaolinitic, white to pink; interbedded on fine scale with white to pink kaolinitic claystone.

SAPROLITE ON PRECAMBRIAN ROCK

634-639	Duricrust (?), oolitic to pisolitic, very hard, cherty, brick-red to pale gray. Detailed mineralogy yet to be determined.
639-657	Clay, soft, plastic; white in depth interval 639-647', pale green to dark green between 647 and 657'. Abrupt contact with unweathered rock at base.

PRECAMBRIAN CRYSTALLINE ROCK

657-670	Hornblende hornfels, fine-grained, dark green, with interbeds of calc-silicate marble (skarn) and complex veins of probable pneumatolitic origin. See discussion of Garvin anomaly in text of this report for details.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-5

Considerable detail on the structure, mineral composition, and geological setting of drill core SWG-5 is presented in the main body of this report in the section on the Garvin anomaly, and it will not be repeated here. This description covers (1) the hornblende hornfels that constitutes the major part of the core, (2) the thin beds of calc-silicate marble that are intercalated with the hornblende hornfels, and (3) the metasomatic veins that traverse the hornblende hornfels and are provisionally interpreted to have emanated from an intrusive body not penetrated by the drill.

(1) hornblende hornfels

The hornfels is a finely granoblastic rock (grain size 0.1-0.2 mm) that is composed of intermediate plagioclase (50%), hornblende (45%), and calcite (4.5%); very small, equant grains of magnetite and somewhat larger grains of sphene are scattered throughout. Slight variations in the ratio of hornblende to plagioclase account for the faint layering of the rock that is observable megascopically.

(2) calc-silicate marble (layers of thickness 10-20 cm)

The marble is composed predominantly of medium- to coarse-grained calcite that is intergrown in a patchy, irregular manner with individual grains and multi-grain aggregates of silicate minerals. Both the texture and the mineral composition of the rock are heterogeneous on a centimeter scale. The most abundant silicate phases are diopside, garnet (tiny orange-red grains that presumably are enriched in the grossularite component), calcic plagioclase, scapolite, quartz, and hornblende; vesuvianite occurs as a reaction rim between scapolite and calcite and also forms planar domains within scapolite crystals that resemble exsolution intergrowths. Large, subhedral grains of sphene and smaller, equant grains of magnetite are scattered unevenly throughout the rock.

(3) metasomatic veins (thickness on the scale of 5 to 20 mm)

The veins exhibit a complex and intricate pattern of center-to-wall mineral zonation that is described rather fully in the text of this report. In summary, the zones nearest the walls are enriched in hornblende and the zones at the center are enriched in calcite and phlogopitic biotite. Large, highly sieved garnets locally have nucleated in the centers of veins and grown to diameters approaching the width of the vein in which they occur.

CHEMICAL DATA: Table 2, column 7 -- Hornblende hornfels, depth 659 feet.

Field number SWG-6

Date finished 9/11/92

MGS unique number 247592

MGS lab number 3374

LOCATION (see map at right)

T–R–S 108 – 39 W – 14 BBACAB

County Murray

Quadrangle Walnut Grove (61B)

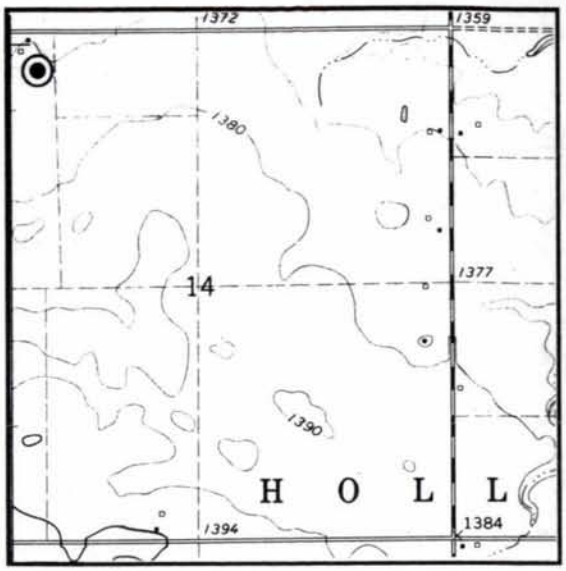
HOLE PARAMETERS (feet)

Surface elevation 1375+/-5

Total depth 702

Elevation, top of Precambrian rock 816

Core interval no core



Hole azimuth: plunge: vert

Core recovered chips only

Granitoid gneiss, approximately of granodiorite composition

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-4	Organic black soil
4-59	Till, clay-rich, calcareous; majority of coarse clasts are carbonate. Oxidized interval between 4 and 27' depth is buff to gray-brown; remainder of unit is medium gray.
59-67	Sand, poorly sorted, calcareous; thin interbeds of gravel.
67-103	Till, loamy, calcareous, medium-gray to olive-gray; pebbles, cobbles mostly carbonate above 90' depth, of diverse rock types below. Shale content sharply higher below 90' depth.
103-114	Till, loamy to sandy, calcareous, shale-poor, ochre to olive matrix. More cobbles, boulders than in overlying tills; boulders are mostly limestone, dolomite, and granitoid rocks. Sharp upper and lower contacts.
114-137	Till, clay-rich, calcareous, shale-bearing, medium to dark gray. Many thin sandy layers (<1 foot) in lower half of unit.
137-164	Till, clay-rich, sparingly calcareous, shale-rich. Very compact and dry; stiff, slow-drilling.
	CRETACEOUS SEDIMENTARY ROCKS
164-304	Shale, non-calcareous, fissile, medium to dark gray. Slightly weathered material in top 12' is green-gray and somewhat softer than the rest of the unit.
304-352	Shale, non-calcareous, fissile, medium to dark gray. Differentiated from the overlying unit by the presence of many thin interbeds of non-calcareous siltstone, medium-gray to brown.
352-360	Shale, silty, very calcareous, dark brown.
360-395	Shale, non-calcareous, brown to dark gray, intimately interbedded with thin layers of siltstone, fine-grained sandstone.
395-396	Sideritic nodules in sideritic mudstone.
396-419	Shale, non-calcareous, fissile, dark gray; many thin interbeds of gray silty shale and layers of sideritic concretions.
419-452	Thin-bedded mudstone and fine-grained sandstone; sandstone is poorly sorted, buff to gray.
452-471	Mudstone.

471-522	Thin-bedded, variable sequence composed of fine-grained, poorly sorted sandstone, siltstone, mudstone, and claystone.
522-556	Shale, fissile, non-calcareous, highly variable color in shades of gray, green-gray, and maroon.
556-559	Sandstone, quartzose, medium- to coarse-grained.
	SAPROLITE ON PRECAMBRIAN ROCK
559-630	Kaolinitic clay, white, with scattered grains of residual quartz.
630-655	Clay, green to blue-green, with variable amounts of residual quartz.
655-698	Clay, green-gray, grading downward into grus as amounts of residual quartz and K-feldspar increase.
	PRECAMBRIAN CRYSTALLINE ROCK
698-702	Granitoid gneiss, pink to gray, composed of biotite, quartz, K-feldspar, plagioclase.

PETROGRAPHIC DESCRIPTION OF ROCK CUTTINGS: SWG-6

The sample material recovered from the Precambrian intersection in this hole consists of cuttings that are 2 cm or smaller in size. Therefore the following description is restricted to small-scale features of the rock.

The largest fraction of the cuttings sample is a medium-grained granite gneiss composed of quartz, plagioclase, and microcline in subequal amounts together with a few percent of biotite. A second, less abundant granitoid rock type contains a few percent hornblende in addition to biotite, and it is likely that it is interlayered on the mesoscale with the hornblende-absent rock. Texturally, both rock types exhibit a bimodal size distribution in which the larger grains (2-5 mm) are plagioclase and microcline and the smaller grains (0.2-0.5 mm) are mostly quartz, microcline, myrmekite, and granophyre. Grain boundaries are embayed and sutured.

Only apatite and Fe-Ti oxides were noted as accessory minerals.

CHEMICAL DATA: none

Field number SWG-7

Date finished 9/16/92

MGS unique number 247593

MGS lab number 3375

LOCATION (see map at right)

T–R–S 108 – 38 W – 24 DBBBBB

County Cottonwood

Quadrangle Lamberton (61A)

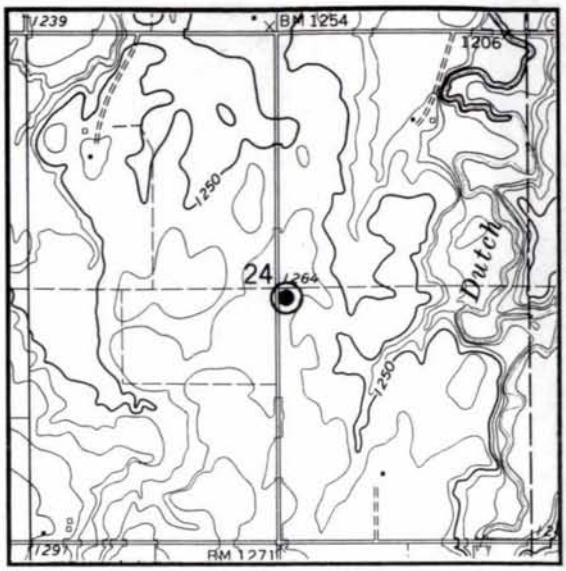
HOLE PARAMETERS (feet)

Surface elevation 1264+/-5

Total depth 469

Elevation, top of Precambrian rock 889

Core interval 458-469



Hole azimuth: plunge: vert

Core recovered 100%

Quartz diorite gneiss, mesocratic, with amphibolite inclusions

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-5	Soil, black, clayey, organic-rich.
5-32	Till, calcareous, clay-rich; oxidized to light brown above 16' depth; otherwise blue-gray to gray. Larger clasts mostly carbonate, granitoid rocks.
32-45	Sand, silt, clay, interbedded; minor gravel. Sand, gravel are composed mainly of carbonate.
45-65	Till, calcareous, clay-rich, blue-gray to gray; Larger clasts mostly carbonate and granitoid rocks.
65-164	Interbedded sand, fine sand, silt, clay; dominant component is fine sand.
164-183	Thin-bedded clay and silt. May be lacustrine deposit.
183-193	Till, clayey to sandy, calcareous, blue-gray.
	CRETACEOUS SEDIMENTARY ROCKS
193-199	Clay shale, non-calcareous, dark gray; contains fossil ammonites.
199-236	Thin-bedded sequence of siltstone, mudstone, fine-grained sandstone; some lignitic beds.
236-249	Shale, medium to dark gray.
249-306	Thin- to medium-bedded sequence of siltstone, fine-grained sandstone, mudstone; major component is siltstone. Many horizons of nodular siderite concretions.
306-316	Shale and mudstone, clay-rich, plastic, medium-gray.
316-332	Sandstone, quartzose, medium- to coarse-grained; minor interbeds of siltstone, mudstone.
332-352	Shale, very stiff and compact.
352-357	Sandstone-dominated unit similar to that in depth interval 316-332'.
357-375	Clay shale, kaolin-rich and variegated in color; thin interbeds of quartzose sandstone. Interpreted as reworked saprolitic material.
	SAPROLITE ON PRECAMBRIAN ROCK
375-420	Clay, light green to various shades of pink and red; minor residual quartz.
420-458	Clay, green, grading downward into grus as residual quartz, feldspar become more abundant. Gradational lower contact with granitod rock.

PRECAMBRIAN CRYSTALLINE ROCK

458-469 Quartz diorite gneiss, mesocratic, moderately well foliated; contains inclusions of amphibolite.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-7

This is a medium-grained, gneissose granitoid rock that has the modal composition of an alkali-poor biotite- hornblende granodiorite. It possesses a weak modal layering that is parallel to a strong planar fabric defined by aligned biotite and hornblende grains; these elements dip about 25 degrees. Scattered throughout the rock are small quartz-feldspar clots about 2-3 cm in length and indistinctly bounded pods of pegmatite a few cm thick. Both are flattened parallel to foliation. The core terminates in a fine-grained amphibolite that is cut by many slickensided, chlorite-coated slips and is severely weathered; the amphibolite is provisionally interpreted as a large xenolith.

The gneissose granodiorite is allotriomorphic granular in texture and has an average grain size between 1 and 2 mm. The quartz grains have been recrystallized and annealed into polycrystalline aggregates; otherwise, there is little evidence at the grain scale of deformation or metamorphism. The recovered core is somewhat weathered; the weathering has caused the replacement of hornblende by an aggregate of chlorite, calcite, and montmorillonitic clay and the partial replacement of biotite by chlorite and montmorillonitic clay.

Modally the rock contains essential plagioclase (50%), quartz (30%), microcline (10%), biotite (5%), and hornblende (5%), the latter two weathered in the present sample as described above. The accessory minerals include apatite, sphene, allanite, zircon, and Fe-Ti oxides.

CHEMICAL DATA: none.

Field number SWG-8

Date finished 9/17/92

MGS unique number 247594

MGS lab number 3376

LOCATION (see map at right)

T–R–S 113 – 40 W – 11 DCCCCC

County Lyon

Quadrangle Cottonwood (98C)

HOLE PARAMETERS (feet)

Surface elevation 1065+/-5

Total depth 116

Elevation, top of Precambrian rock 991

Core interval 94-116

Hole azimuth: plunge: vert

Core recovered 95%

Serpentinized peridotite, coarse-grained

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-1	Soil, black, organic-rich
1-21	Till, clay-rich to loamy, calcareous, shale-bearing; pebbles, cobbles of limestone, dolomite, aphanitic basaltic rocks, granitoid rocks. Color blue-gray, oxidized to light brown in top 15'.
21-25	Sand, fine-grained.
25-74	Till, blue-gray to medium-gray, very similar to that in depth interval 16-21'.
	SAPROLITE ON PRECAMBRIAN ROCK
74-77	Laterite or material approaching laterite; red-brown, oolitic to pisolitic. Overlies or is intermingled with hard, fine-grained, green rock.
77-90	Clay, yellow to green-gray; mixed with hard rock in varying proportions.
	PRECAMBRIAN CRYSTALLINE ROCK
90-116	Serpentinized peridotite, coarse-grained; marginally weathered to depth of 106'; fresh below.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-8

This is a serpentinized peridotite that prior to serpentinization consisted almost exclusively of olivine. There are no primary minerals other than olivine surviving in the rock, and there are no textures that indicate the former presence of other primary minerals. The protolith therefore was a dunite. The original olivine grains were as long as 2 cm and were preferentially aligned into a grain-shape foliation that is visible megascopically in the serpentinized rock. This primary olivine fabric dips steeply (ca. 80-90 degrees) and is cut by other planar elements that formed during the serpentinization process and later. Residual kernels of primary olivine are scattered unevenly throughout the rock; locally they are replaced wholly or in part by brown mixed-layer clays ("iddingsite").

By far the greatest volume of the present rock (90% or more) consists of serpentine. Most of it is very fine-grained and has adopted the "mesh-texture" arrangement of cross-fiber veinlets and platy intramesh volumes that typifies serpentine pseudomorphs of olivine. Locally there are coarser blades and sprays of recrystallized antigorite. As usual, much dusty magnetite is intimately associated with the mesh-textured serpentine.

Long blades and sprays of anthophyllite and talc have grown across and through the mesh-textured serpentine and appear therefore to be later minerals in the paragenetic sequence. They are interpreted to indicate prograde metamorphism of the serpentinized rock. The small amount of secondary forsterite noted locally also is consistent with a prograde event.

Retrograde events of two types are indicated by petrographic observations. The earlier of these may have been an autometamorphic cooling wherein talc and Mg-chlorite formed at the expense of anthophyllite.The second was a late-stage event that involved brittle fracturing and faulting of the rock mass and the introduction of calcite-quartz veins. Much fine-grained talc and carbonate replace serpentine in the immediate vicinity of the vein arrays, and brucite or brucite plus Mg-chlorite replace serpentine or serpentine plus anthophyllite at somewhat greater distances.

Minor minerals not mentioned in the foregoing discussion include hematite and an opaque phase tentatively identified as chromite.

CHEMICAL DATA: Table 2, column 8 -- Serpentinized peridotite, depth 102 feet.
Table 2, column 9 -- Serpentinized peridotite, depth 116 feet.

Field number SWG-9

MGS unique number 247589

MGS lab number 3349

LOCATION (see map at right)

T–R–S 114 – 39 W – 11 DDCDDD

County Yellow Medicine

Quadrangle Wood Lake (98A)

HOLE PARAMETERS (feet)

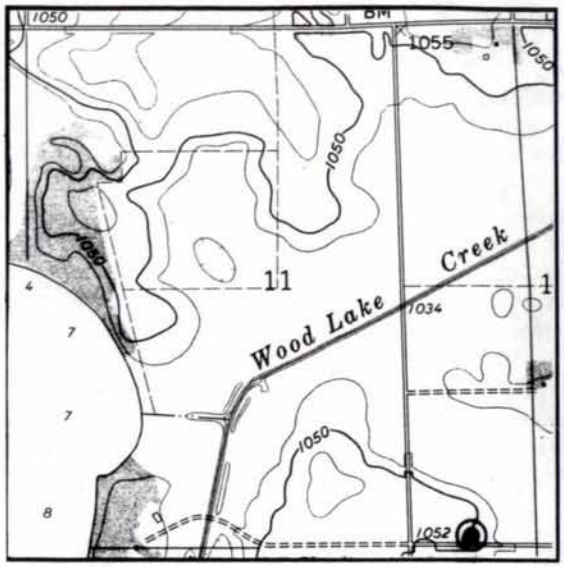
Surface elevation 1050+/-5

Total depth 322

Elevation, top of Precambrian rock 783

Core interval 314-322

Date finished 10/06/92



Hole azimuth: plunge: vert

Core recovered 80%

Actinolite schist, fine-grained, fractured; derived from basalt or related mafic rock

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-3	Soil, dark gray, organic
3-32	Till, clayey to loamy, calcareous, shale-bearing. Larger clasts are chiefly carbonate and aphanitic, basaltic rocks; granitoids are less abundant. Color blue-gray to dark-gray; upper 24' oxidized to light brown.
32-33	Pebbly sand composed predominantly of yellow-buff carbonate.
33-83	Till, loamy-sandy, calcareous, shale-rich, dark gray; similar to unit in depth interval 3-32'.
83-97	Silt and fine, poorly sorted sand.
97-134	Till, clay-rich, calcareous; coarse clast composition similar to till units above. Color distinctly green-gray in interval 97-105'; dark gray below 105' depth. Wood fragments in interval 103-105'.
134-164	Clay, stiff and smooth, strongly calcareous. Interpreted provisionally as lacustrine sequence.
164-167	Pebbles, cobbles, and light brown clay.
	CRETACEOUS SEDIMENTARY ROCKS
167-185	Clay, various colors, non-calcareous; distinct thin beds of siltstone, silty shale, siderite nodules.
185-191	Siltstone and fine sandstone, friable.
191-225	Shale or mudstone, soft, non-calcareous, brown and gray.
225-228	Lignite.
228-262	Shale and claystone, thin-bedded; colors range from black to very pale gray.
262-267	Sandstone, quartzose, friable, medium- to coarse-grained; grains angular.
	SAPROLITE ON PRECAMBRIAN ROCK
267-307	Clay, white, red-brown, and green; residual quartz veins. Grades downward into hard rock.
	PRECAMBRIAN CRYSTALLINE ROCK
307-322	Actinolite schist, fine-grained, fractured.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-9

The rock is a fine-grained amphibole-rich schist that exhibits a subtle layering or streakiness manifested by slight variations in grain size and color. This vague layering , which dips about 85 degrees, is intersected by a spaced schistosity (crenulation cleavage) that dips 70-75 degrees in the same sense. Quartz-feldspar veinlets 1-5 mm in thickness are cut and crinkled by the crenulation cleavage. Hairline-thin, post-schistosity veinlets of chlorite and pink carbonate are abundant but lack systematic orientation; many of these are slickensided and clearly were sites of small-scale fault displacement that followed vein filling. Thicker intervals of the core that are enriched in secondary chlorite are badly disintegrated. These chloritized zones are shot through with slickensided slip surfaces, and therefore appear to be fault-related.

The rock away from the chloritized zones consists predominantly of actinolite or actinolitic hornblende in bladed crystals from 0.2 to 0.7 mm long. Spaced foliation domains about 0.05 mm thick and 0.5 mm apart contain well oriented amphibole grains that are somewhat smaller in size than those in the intervening microlithons. The amphibole in the microlithon domains lacks a preferred orientation; the fabric is random or nearly so. In addition to the predominant amphibole, the rock contains fine-grained Fe-Ti oxides (2-3%) and Ca-poor epidote (2% or less).

Chemical data (Table 2) indicate that the protolith for this schist was a mafic igneous rock of quite primitive composition (SiO_2 = 46.7%; Mg# = 58; Cr = 1100 ppm). Primary textures and structures are lacking that might resolve extrusive versus intrusive origin.

CHEMICAL DATA: Table 2, column 10 -- Actinolite schist (basaltic or gabbroic protolith) depth 315 feet.

Field number SWG-10

Date finished 10/08/92

MGS unique number 247595

MGS lab number 3377

LOCATION (see map at right)

T–R–S 114 – 39 W – 19 DCBCC

County Yellow Medicine

Quadrangle Wood Lake (98A)

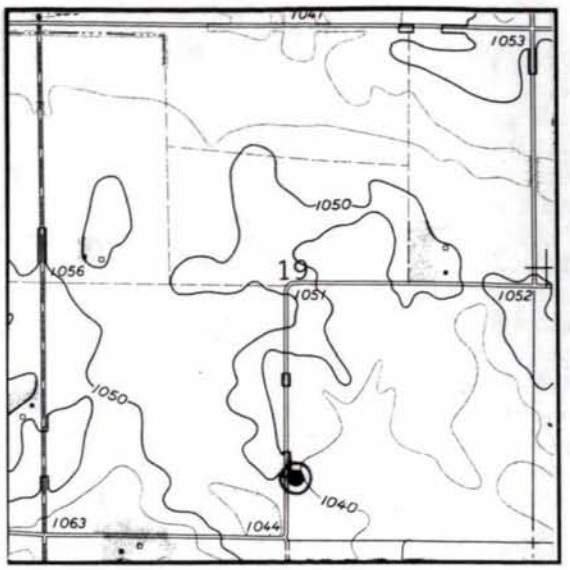
HOLE PARAMETERS (feet)

Surface elevation 1045+/-3

Total depth 246

Elevation, top of Precambrian rock 844

Core interval 235-246



Hole azimuth: plunge: vert

Core recovered 98%

Hornblende gabbro, sparingly porphyritic, somewhat altered; interior of Proterozoic dike or plug

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-2	Soil, organic-rich, black.
2-60	Till, clayey to loamy, calcareous, shale-bearing. Larger clasts predominantly carbonates and aphanitic, basaltic rock; granitoid rocks less abundant. Color blue-gray to medium-gray; oxidized to light brown in upper 20'.
60-92	Silt, fine-grained sand; minor interbeds of clay.
92-123	Sand and gravel, locally coarse. This and the overlying unit together represent a major outwash deposit.
123-155	Till, clay-rich, shale-poor, calcareous, blue-gray; clast composition similar to uppermost till unit.
155-178	Sand and gravel, locally coarse.
178-183	Till, clay-rich, shale-poor, calcareous, blue-gray. Similar to till in depth interval 123-155'.
183-202	Sand and gravel, locally coarse.
	SAPROLITE ON PRECAMBRIAN ROCK
202-233	Clay, brown and green; grades downward to uniform deep blue-green. Quartz vein at depth 213'. Grades abruptly into hard rock through depth interval 224-233'.
	PRECAMBRIAN CRYSTALLINE ROCK
233-246	Hornblende gabbro, medium-grained, sparingly plagioclase-phyric.

PETROGRAPHIC DESCRIPTION OF CORE: SWG-10

This rock is a medium-grained, hornblende- and quartz- bearing gabbro that resembles the coarse interior parts of large Proterozoic dikes found elsewhere in Minnesota and nearby Ontario. See the text of this report for a further interpretation. The gabbro in the recovered core is cut by a plethora of chloritized, slickensided brittle shears and by epidote-quartz veins of several sizes and types. The rock adjacent to the fracture zones and vein arrays is intensely chloritized and punky.

The gabbro contains a scattering of cm-size phenocrysts and glomeroporphyritic clots of strongly zoned calcic plagioclase. The inner zones of the phenocrysts are euhedral, thin, and oscillatory in composition within the labradorite range. Many of the calcic cores are cloudy and brown, owing to the presence of very small inclusions of an unidentified high-relief mineral. Surrounding these euhedral cores are broad, gradationally zoned rims that merge with the intermediate plagioclase of the gabbro host.

In addition to plagioclase that is zoned in the andesine-oligoclase range, the gabbro proper contains compositionally zoned blue-green hornblende, some crystals of which have cores of colorless amphibole that is intergrown with remnants of clinopyroxene. Quartz, sodic plagioclase, biotite, and myrmekite are interstitial to the zoned plagioclase and hornblende. Secondary uralitic hornblende fringes most of the primary hornblende crystals and is interpreted to be of deuteric origin. Epidote of several textures and compositions is widespread in the rock and probably formed at several different times. Large, skeletal plates of ilmenite and long needles of apatite constitute the accessory mineral assemblage. These grew across all other minerals and therefore appear to have formed late in the paragenetic sequence.

CHEMICAL DATA: Table 2, column 11 -- Gabbro, depth 242 feet.

Field number SWG-11

Date finished 10/09/92

MGS unique number 247596

MGS lab number 3378

LOCATION (see map at right)

T–R–S 115 – 39 W – 20 DCCD

County Yellow Medicine

Quadrangle Wood Lake (98A)

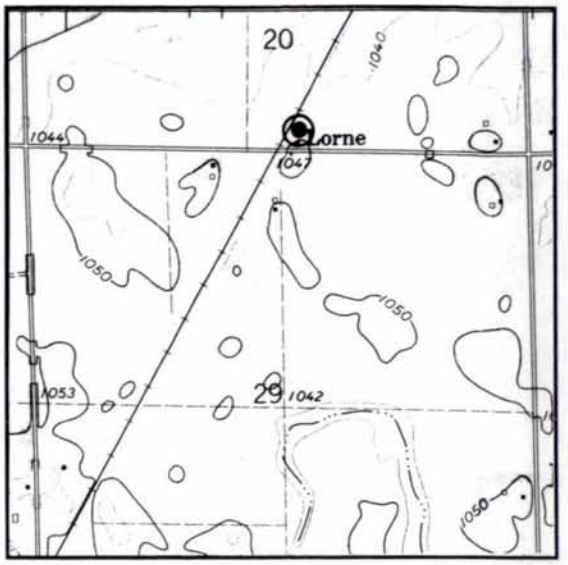
HOLE PARAMETERS (feet)

Surface elevation 1044+/-3

Total depth 168

Elevation, top of Precambrian rock Precamb. not reached

Core interval no core



Hole azimuth: plunge: vert

Core recovered none

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-5	Organic soil, black.
5-9	Clay, soft, very plastic, yellow-brown to ochre; interbedded with sand, poorly sorted, silty, fine- to medium-grained, very soft, brown.
9-37	Till, clayey to loamy, calcareous; abundant clasts of carbonate, tan chert. Oxidized to yellow-brown color above depth of 22'; medium-gray below.
37-39	Sand and sandy, silty clay, calcareous brown.
39-47	Till, similar to unit in depth interval 22-37'.
47-168	Downward-coarsening sequence of clay, silt, sand, and gravel that probably was deposited in a major meltwater channel. The interval between 47 and 65 feet is predominantly silt and fine-grained calcareous sand; that from 65 to 90 feet is predominantly medium to coarse sand, and that from 90 to 168 feet (EOH) is mainly coarse gravel. The coarse gravel consists mainly of pebbles of carbonate, chert, and assorted granitoid and metamorphic rocks; it also contains a small fraction of pebbles of Superior provenance such as red sandstone, red rhyolite porphyry, drusy red chert, and agate. The gravel is well rounded and well sorted in the size range between 2 and 10 cm. It has the physical potential to be a major source of ground water if recharge and water quality parameters are found to be acceptable.

Hole abandoned at depth 168' because of sidewall slumping of coarse gravel.

CHEMICAL DATA: none

Field number PR-90-1

Date finished 6/14/90

MGS unique number 247588

MGS lab number 3019

LOCATION (see map at right)

T–R–S 104 – 45 W – 18 CCCCCC

County Rock

Quadrangle Jasper SE (44D)

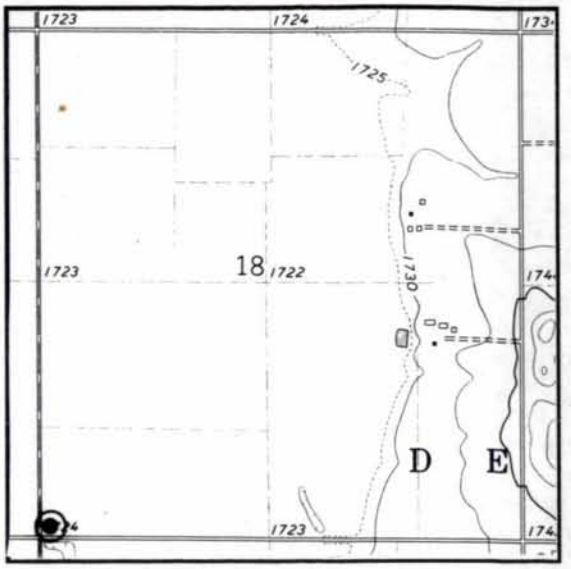
HOLE PARAMETERS (feet)

Surface elevation 1726+/-2

Total depth 64

Elevation, top of Precambrian rock 1673

Core interval 54-64



Hole azimuth: plunge:

Core recovered 100%

Sioux Quartzite; medium-grained orthoquartzite

ABBREVIATED LITHOLOGIC LOG (intervals recorded are depths in feet)

Interval	Description
	QUATERNARY DEPOSITS
0-4	Clay, dark gray, very plastic, organic-rich. Lake clay (disturbed) and ditch spoil.
4-9	Till, clay-rich, very calcareous, olive-gray to dark gray. Pebbles of chert, limestone, quartz, various granitoid and metamorphic rocks, agate; composition indicates Superior-lobe material extensively admixed with or diluted by material derived from the north or northwest.
9-18	Unit composed of clay, sand, and poorly sorted clayey gravelly sand in beds that range from <1 to about 3 feet in thickness.
18-26	Clay, smooth, plastic; probably a lacustrine deposit.
26-30	Thin-bedded sandy unit similar to depth interval 9-18'.
30-53	Till, clay-rich, weakly calcareous; many small pebbles of chert (yellow, tan, and black), black aphanitic rock (basalt or related rock type), buff dolomite, yellow sandstone, and pink quartzite (Sioux Quartzite). Upper 13' of unit is oxidized to yellow-tan; remainder is medium-gray to pinkish-gray.
	PRECAMBRIAN CRYSTALLINE ROCK
53-64	Quartzite, pale pink to pale salmon, medium-grained (Sioux Quartzite).

PETROGRAPHIC DESCRIPTION OF CORE: PR-90-1

This quartzite is composed predominantly of unit-quartz grains about 1 mm in diameter that are tightly cemented by secondary quartz. Less than 1% of the framework grains are material other than unit quartz, including chert, ferruginous chert, polygonally recrystallized metamorphic quartz, and ribbon quartz. Similarly, less than 1% of the cement consists of minerals other than quartz, including kaolinite, white mica, and dusty hematite. Zircon and rutile constitute the accessory mineral assemblage.

The framework quartz is moderately well rounded and very well sorted. Many grains (10% or more) have abraided epitaxial quartz overgrowths and therefore are multi-cyclic. Rutilated quartz grains are common, as are grains with aligned trails of fluid inclusions and lines of tiny opaques. Virtually all of the quartz in the rock shows undulose extinction. In addition, the quartz shows almost universal development of planar strain lamellae, either as a single set or as multiple, intersecting sets in two or more orientations. Lamellae occur in the quartz cement as well as in clastic framework grains, implying that the event responsible for the lamellae was post-lithification.

See the text of this report for further discussion of the geologic setting of this drill hole and the interpretational uncertainties raised by the occurrence of strain lamellae in the quartzite sample.

CHEMICAL DATA: none.