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A Limited Survey of Selected Kimberlite Indicator Minerals from Glaciofluvial Sediments Across Minnesota

By:
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Acknowledgments

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Kimberlite Indicator Minerals - Reconnaissance Survey

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PROJECT SUMMARY

A statewide reconnaissance-scale survey using 57 available overburden samples is being performed to search for kimberlite indicator minerals. The long range objective is to identify kimberlite bedrock sources to evaluate for diamond resources. The glaciofluvial samples are being analyzed by a contract laboratory. Three additional samples, spiked duplicates, were submitted for quality control. By using overburden samples available in the Drill Core Library or at the Minnesota Geological Survey, the funding could be applied fully to the sample processing and analysis, rather than to collecting.

SAMPLE SELECTION

The objective of sample site selection was to evaluate most of the major geologic terranes in the state, thus the samples are from 39 sites in 19 counties. Glaciofluvial materials were the preferred sample media because it represents more square miles of source area than till. Due to a lack of sample availability, four different sample types were necessary, as follows: 41 samples from 22 different Rotasonic drillholes, 8 samples from rotary drill cuttings, 6 samples from gravel pits, and 2 post-hole type (shallow auger) samples. This set of samples in no way represents completely the 19 county area, rather it is viewed as a screening phase to possibly point to priority areas.

SAMPLE ANALYSIS

A Canadian laboratory, Overburden Drilling Management (ODM), with recent kimberlite experience working with the Geological Survey of Canada on similar overburden samples, was the low bidder and was awarded the contract to process the samples. Basically, ODM separates the heavy minerals (+3.2 S.G.) from 10 kg samples (see flow sheet) and picks through the concentrates to count the following indicators - purple chrome pyrope garnet, orange megacrystic and eclogitic garnet, chromium-rich diopside, picroilmenite, and chromite. A scanning electron microscope is used to perform rapid semi-quantitative mineral analysis to improve the accuracy of the picking process. Microproble analyses of the probable kimberlite indicator minerals will be performed at Carleton University, Ottawa, under the supervision of ODM.

STATUS OF RESULTS

Following the first batch of heavy mineral separations, ODM identified many ilmenite grains that had surface textures indicative of kimberlitic ilmenites, and SEM compositions of (surficial analyses) that were unusual. Microprobe analyses were performed on hundreds of these grains to see if any fell into the kimberlitic-source composition range. Results indicate an unusual composition for ilmenite, but not likely a kimberlite source-rock.

From the 57 samples, a total of 35 probable kimberlite indicator minerals other than the above ilmenite, were identified within 21 samples. Microprobe analysis was completed. Nine indicator minerals within the kimberlite composition range (KIMs) were found. Photos of some of the grains are available at Hibbing for viewing.

Two reports are available. One is a discussion of the implications of the mineralogy of the

KIMs, written by Stuart Averill of Overburden Drilling Management Lab. The other, written by Dennis Martin, is a typical report on the survey itself, with discussion of the spatial distribution of the KIMs found.

QUALITY CONTROL

Three control samples were included in the batches. Each was a duplicate of another sample, and was spiked with KIM grains of the appropriate size. The KIMs were obtained from Mr. Glen Adams from Michigan kimberlites.

ODM recovered and identified KIMs in all three control samples. The recovery of the number of spiked KIM grains varied from sample to sample in this blind test. ODM subsequently wrote observations and comments about the quality control samples after they were told which samples were spiked.

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Introduction

The bedrock underlying almost all of Minnesota is covered by various types and thickness of overburden. Hence, there may be buried mineral deposits in the bedrock that remain undiscovered at this time. Diamonds are one such mineral deposit possibility. Large areas of bedrock underlying Minnesota are prospective because they fit the current ideas on criteria for the emplacement of diamonds. At least one company has been prospecting for diamonds in this state for about a decade. There is no public information to support any documented finds of diamonds in the state.

The rare types of bedrock host rocks for diamonds, called kimberlites and lamproites, bring diamonds and associated minerals from a depth of at least 150 kilometers to the bedrock surface in a volcanic eruption. These volcanic eruptions typically occur in a cluster called a field. A field of kimberlite eruptions typically includes 6 to 40 widely separated intrusive pipes not counting dikes (Kirkley, et al., 1991) made up of a range of related ultramafic compositions, scattered across an area of 60 miles or more in radius. The eruptions often are located along some large-scale structural feature of crustal extension that influenced the final intrusive emplacement.

Problem

The Precambrian bedrock terrane in much of Minnesota is permissive for emplacement of diamondiferous kimberlite intrusives, according to a comparison of the geologic setting of Minnesota with the discussion of Helmstaedt and Gurney (1995) regarding prospective areas. For example, the bedrock in Minnesota is composed of a stable Late Archean craton fused to a Middle Archean craton. The Precambrian rocks have a few recognizable dike swarms, indicative of crustal extension and crustal weakness. There are a few lengthy major fault zones, indicative of additional areas of crustal weakness. There are two areas of Paleozoic sedimentary platform rocks, larger in the southeast and smaller in the northwest, and the Transcontinental arch or shield area between them. Any or all of these features are supportive of the preservation of mantle-friendly-root-structures and the emplacement of diamondiferous kimberlite intrusions.

The problem is that the generally thick overburden cover in Minnesota prevents the direct examination of the bedrock for kimberlite pipes. Kimberlite pipes are small targets, with most diamond producing pipes being 12 to 75 acres in surface area (Kirkley, et al., 1991). The distribution and availability of bedrock samples from outcrops or drill core is inadequate to search for such small kimberlite bodies directly by examination of bedrock samples. Drilling to obtain bedrock samples is too expensive. Even a target as large as the cumulative area of a kimberlite field is still minuscule in comparison to the large prospective area in this state.

Another component of the problem is preservation from erosion of the economic zones - the uppermost portion - of a kimberlite pipe. The pipe may be destroyed by erosion over geologic time, such as 69 million years for an example cited by Kirkley, et al. (1991). It is difficult to predict or to describe statewide where such preservation would occur. One example of preservation is the presence of buried Cretaceous laterite in some parts of the state. However, there is a benefit to using geologically young glacial materials for sample media in that they are composed largely of clasts of the top of the present bedrock Hence, glaciofluvial materials represent real features in the bedrock, not some bedrock source that was eroded away in the geologic past.

Purpose and Scope

The purpose of this work is to prospect statewide at a reconnaissance level for diamonds, and publish the results for the public record. The strategy is to search indirectly by prospecting for associated rare minerals that may be indicators to a field of diamondiferous kimberlite bedrock sources. There are five rare heavy minerals associated with diamondiferous kimberlite, here labeled kimberlite indicator minerals (KIMs). The KIMs are present in diamondiferous kimberlite in ratios up to 100,000 times more common than diamond crystals themselves. Thus, the KIMs are useful pathfinders to diamondiferous kimberlite bedrock and provide more chance of success than searching solely for diamonds.

The long-term objective is to seek evidence of clasts (KIMs) eroded from a now-buried field of kimberlite intrusives in Minnesota's bedrock. Various processes of erosion tend to disperse the KIMs from the bedrock source location and deposit them in overburden materials both nearby and far away. This dispersal actually increases the probability of success at the reconnaissance level. The short term strategy applied here is to examine glaciofluvial materials, which are composed of clasts eroded from bedrock, for the presence of kimberlite indicator minerals. Glaciofluvial materials represent the mixture of clasts eroded from bedrock from broad areas, and hence make a good sample media for reconnaissance -scale work in the search for KIMs. It is recognized that the clasts, may have gone through multiple cycles of sedimentation.

Although the objective is to search statewide at a reconnaissance level, the scope was limited in the short term due to a small budget. The scope was therefore limited to existing samples, mostly from drill cores available in the Department of Natural Resources (DNR) Drill Core Library in order to apply all the available funds to sample processing and analysis. Thus, statewide coverage with an effective sample density was not possible. Large sample sizes were not feasible, due to the limited existing sample sizes within a stratigraphic unit and the requirement to preserve a 1/4 portion of the drill core.

Previous Work

This section focuses on kimberlite exploration data pertinent to Minnesota. The author is not aware of any public data specific to kimberlite exploration, such as in this survey. There have been numerous surveys that contain pertinent information regarding heavy minerals, in general, in glacial drift (e.g. Nelson, et al., 1992; or Martin, et al., 1988). There are also numerous drill cores, available for inspection in the DNR Drill Core Library, that are from private exploration programs. Some of these are presumed to have been targeted on geophysical features for kimberlite exploration.

There are three cases in Minnesota of reports of bedrock samples of possible kimberlite affinity (see Map 2). One sample is drill core from a hole sited on an aeromagnetic anomaly located in central Minnesota near Little Falls (Southwick and Chandler, 1987). The sample, while not a true kimberlite in composition, is described as a mica-bearing olivine pyroxenite of possible lamproite-kimberlite affinity (op. cit.). There are many other similar aeromagnetic anomalies in that area (op. cit.). Another drill core from southwestern Minnesota near Slayton contains altered rock that was speculated to indicate a possible lamproite intrusion nearby (Southwick et. al, 1993). The third is an ultramafic pipe that outcrops in the Minnesota River Valley near Franklin in southwestern Minnesota (Weiblen, 1989). The author is not aware of the verification of any samples of clearly kimberlite composition at any of these cases.

The survey results described in this report were described briefly by Averill (April, 1995), in keeping with the DNR's policy of prompt reporting of new data. That report was a brief description of each KIM found, and a discussion of the significance of the composition of each mineral in the broader context of exploration. Furthermore, that report was part of a contract for sample processing and analysis by ODM lab, that was intended to give an independent viewpoint. In comparison, this report places the key results in perspective in regard to the geologic setting in general and glacial stratigraphy in particular. All of the sample data, including HMC results, has been previously available in a series of open-file releases.

There were ten diamonds reportedly discovered in the time period 1880 to 1887 approximately 15 to 20 miles east of the Minnesota border in Plum Creek, Pierce County, Wisconsin (Cannon and Mudrey, 1981). This occurrence may be significant if it is related to a kimberlite field nearby, or if the diamonds were transported by glacial ice with a pathway from Minnesota. The glacial drift unit at this site is the Hersey member of the Pierce formation, a pre-late Wisconsinan unit with a northwestern provenance (Mickelson, et al., 1984).

A reconnaissance survey of KIMs in glacial drift was conducted in southwestern Manitoba (Thorleifson and Matilde, 1993), near the Minnesota border. The results include 55 KIMs from approximately 7920 kgs from 465 till samples and 195 sand samples. Lumping the two sample types together, the overall results can be generalized as a simple average of 1 KIM per 144 kg.

Geologic Setting

There are two components of the geologic setting in this discussion that are pertinent to diamond prospecting. One pertains to interpreting the most prospective areas in the state and the other pertains to the geologic dispersal processes that affect the exploration methods applied here.

According to Helmstaedt and Gurney (1995), area selection for diamond exploration should be based upon the prediction of areas where diamonds may have formed, where they may have survived to become entrained and transported by kimberlites and where mantle-root-friendly-structures may have served as pathways for diamondiferous kimberlites. This review will briefly list applicable Minnesota geologic events pertinent to these criteria. It also describes the relevance of glacial dispersal to the survey.

Precambrian bedrock underlies the entire state of Minnesota. The following features in Minnesota are permissible for diamondiferous kimberlites: (a) the presence in the northern half of the state of a stable craton of Late Archean crust (or Archon), part of the Superior Province; (b) the presence in the southern half of the state of a stable craton of Middle Archean crust (or Archon); and (c) the presence in the east-central part of the state at the boundary zone of the Archean cratons, of the Early and Middle Proterozoic terranes (or Proton).

Numerous younger geologic events have affected the prospective Precambrian basement rocks, including large scale crustal transpression and dike emplacement, weathering and erosion, rifting, deposition of platform sedimentary rocks, and glaciation. Some of these events should be permissible of emplacement of diamondiferous kimberlites, including the Hollandale embayment-Transcontinental arch of 550 to 350 Ma, the crustal weakness evident from the 2125 Ma. Kenora- Kabetogema dike swarm or major faults such as the Vermilion, the Leech Lake Structural Disconformity, or the Great Lakes Tectonic Zone. Other events, such as the 1100 Ma Midcontinent rift, an Early Proterozoic rift, and the periods of deep weathering and erosion, are detrimental to the preservation of the diamondiferous mantle roots or to the kimberlite pipes. Extensive weathering occurred during or prior to the late Cambrian and also during the Late Cretaceous.

The geologic history pertinent to KIM dispersal and sampling is summarized here as a synopsis of Cretaceous weathering and Quaternary glacial processes. During the Late Cretaceous, thick weathering zones formed (up to 60 meters) on the bedrock under tropical conditions (Parham, 1970) and are best exposed along the Minnesota River Valley. The most commonly preserved zones of the Cretaceous laterite profile are usually the saprolite or grus zones. It is likely that garnet, ilmenite, and chromite, KIMs would have survived the weathering. It is likely that the kimberlite primary source would have been weathered deeply, forming a depression. In the eastern part of the state, the repeated glacial advances eroded the saprolite so that by the late-Wisconsinan Rainy lobe advance, mostly fresh unweathered bedrock was exposed, eroded, and entrained within the glacial deposits. In the western, central, and southwestern portions of the state, the saprolite was not completely eroded by the many advancing glaciers. Thus, the upper layers of weathered kimberlite may be the only component expected to be entrained within the glacial deposits in some locations.

The geologic column in many areas of Minnesota can be generalized by describing glacial drift deposits overlying Precambrian bedrock, but there are large-scale exceptions as cited in the previous paragraph. Southeastern Minnesota is completely covered with Paleozoic sedimentary rocks with a thin veneer of glacial drift. Significant portions of southwestern Minnesota have glacial drift and Cretaceous marine sediments covering the weathered Precambrian bedrock.

Glacial erosion, transport, and deposition play a key role in this survey as it had the greatest effect upon the sample media, and also was the last mechanism of dispersal for the KIMs. A pertinent overview of glacial events over a large portion of Minnesota is presented in Nelson, et al. (in press). Glacial dispersal may be either the only cycle of dispersal or it may be simply the last cycle of dispersal for any KIM.

During the Pleistocene in Minnesota, there have been many glacial advances and retreats, resulting in a complex glacial stratigraphy in some parts of the state. The glacial erosion incorporated the older (Tertiary, Cretaceous, and older) overburden materials first, then weathered bedrock to progressively fresher bedrock. Further, the glaciofluvial materials should work very well for identification of kimberlites emplaced in the Paleozoic platform sediments in southeastern Minnesota by helping with the erosion plus dispersion process. That glacial dispersal combined with the persistent, extensive stream drainage system, should help to create large targets. The benefit to improved sample representation in this survey is that glacial transport tends to disperse the KIMs from many tiny primary bedrock sources into thin layers of glaciofluvial sediments covering relatively large areas. The net result is increasing the size of the target several orders of magnitude. Backtracking to the primary source may be a complex task, depending on the specific site. On a continental scale, there is a contrast between the greater erosion that occurred to the north of Minnesota, and the greater deposition that occurred in Minnesota and southward. This is evident in the greater thickness of glacial drift, especially southwestward of the current continental divide in Minnesota. That greater deposition should create greater dilution of kimberlite indicator minerals in the glacial drift in our region in contrast to farther north. Greater dilution means that a larger sample size is necessary, and the background may be expected to be lower than other northerly regions.

Methodology

Fifty -seven samples from the Department of Natural Resources (DNR) sample storage facility were used. No new samples were collected from the field. Original sample collection was for previous projects for different purposes and by 5 different methods--channel samples from gravel pits, auger drilling of 5 foot deep postholes, Rotasonic drill core samples, air rotary cutting drill samples, and mud rotary drill cuttings. The breakdown of sample types includes: 41 samples selected from Rotasonic cores, 6 samples from gravel pits, 4 samples from air rotary drilling, 4 samples from mud rotary drilling, and 2 samples from augured postholes. See Appendix A for the reference citation to obtain more information on the previous history of the collection and handling for each sample used in this survey). Three additional samples were spiked with KIMs from Upper Michigan kimberlites for a blind quality control test.

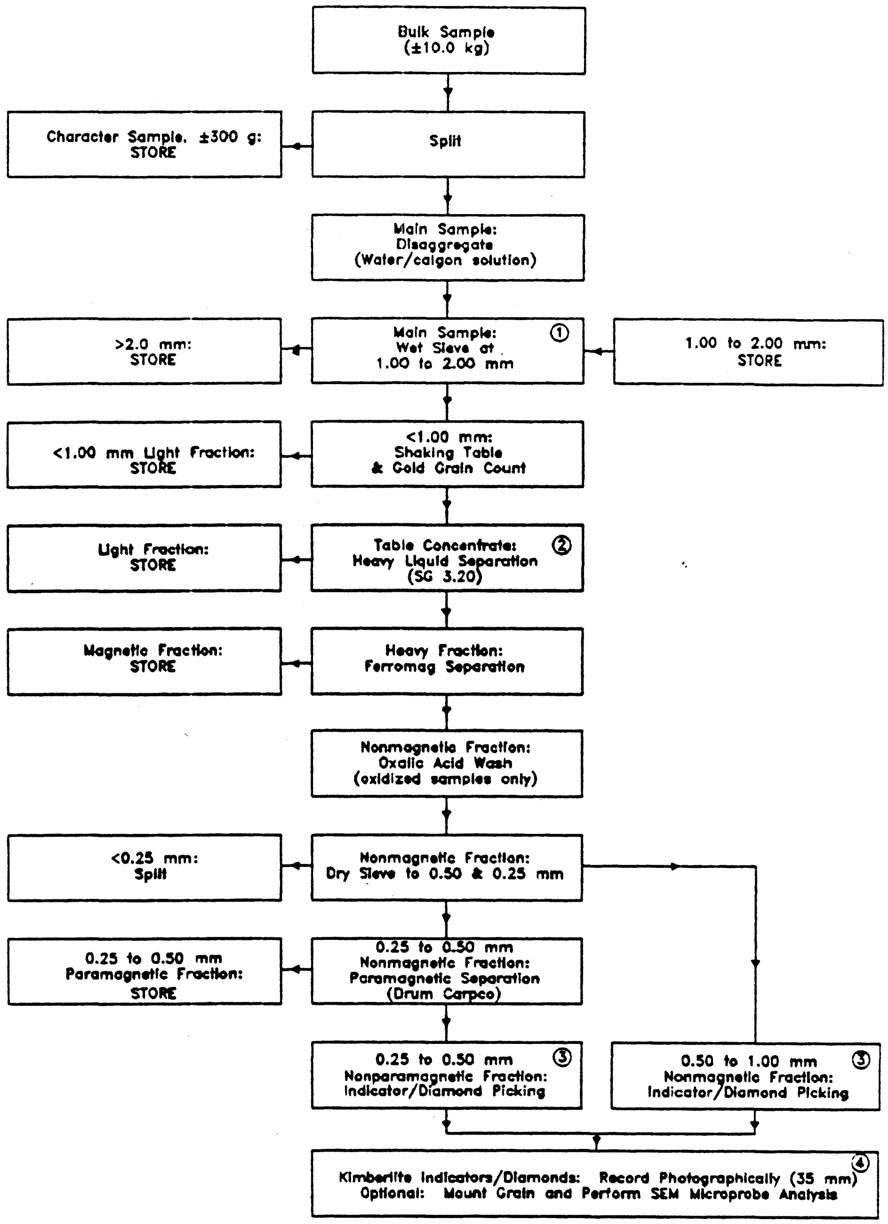
All samples were selected from glaciofluvial sediments. Labradorean (northeast) provenance glaciofluvial sediments were preferred during sample selection over those of Keewatin provenance because previous work (Martin, et al., 1988) showed that in the majority of cases the Labradorean provenance materials contained significantly more clasts indicative of the regional bedrock and less exotic, continental-scale transported clasts. Approximately 10 kilograms per sample was used for processing, but in some cases less material was available. In most cases, there is not enough sample remaining in storage to obtain another sample split.

Overburden Drilling Management (ODM) Lab, Ottawa, Ontario, was contracted to perform the heavy mineral concentration, the picking of the KIMs, and subcontracted the microprobe analysis of the selected grains to Carleton University. ODM Lab has extensive experience with the separation of KIMs from glacial drift materials. Five kimberlite indicator minerals were sought during the processing stages -- purple chrome pyrope garnet, chrome diopside, certain orange garnets, chromite, and picroilmenite.

The sample processing flowsheet (Figure 1) utilizes procedures commonly applied to glacial drift materials. Approximately 10 kg of bulk sample was submitted (see Averill and McClenaghan, 1994). The sample is wetted and stirred, then screened at 10 mesh to prepare a feed to a shaking table. The wet minus 10 mesh material is passed over the shaking table. The table concentrate is cleaned with a heavy liquid separation at 3.2 specific gravity. The >3.2 S.G. heavy mineral concentrate is passed across a hand magnet, and the magnetic fraction is separated. The >3.2 S.G., nonmagnetic heavy mineral fraction is screened, and the KIMs are picked from this 0.25mm to 1.00mm fraction. The concentration factor, defined here as the feed weight divided by the weight of the concentrate that is examined, is in the range of 100 to 10,000.

The three samples used for quality control tests were #13, #18, and #51. The samples were spiked as follows. Sample #13 is a replicate of sample #3; similarly #18 is a replicate of #12; and #51 is a replicate of #49. A total of 18 kimberlitic garnets and 9 kimberlitic ilmenites -- distributed as 7 garnets + 3 ilmenite into #13, 5 + 3 into #18, and 6 + 3 into #51--were put into the interior of the samples within the sample buckets. The selected KIMs were in the size range of 0.5 mm to 1.0 mm. ODM was notified that quality control samples would be included in the set.

Figure 1. Flowsheet for the heavy mineral concentration process and the picking of KIMs.



Footnotes: Optional Procedures

Footnote 1 May also wet sieve at 0.50 mm followed by direct heavy liquid separation on 0.50 to 1.00 mm fraction. The <0.50 mm is tabled.

Footnote 2 Methylene iodide may be diluted to customer specification to obtain any specific gravity <3.32.

Footnote 3 Indicator minerals to be picked out: Cr-diopside, purple peridotitic pyrope garnet, orange peridotitic and eclogitic garnet, picroilmenite, chromite } >0.50 mm fraction only

Footnote 4 SEM and probe work performed at extra cost.

Results

A list and brief description of the observed kimberlite indicator minerals, KIM compositions from microprobe analysis, and a discussion of the results from the point of view of the mineralogy has been previously released (Averill, 1995). The emphasis here is upon the heavy mineral processing quality control, and the spatial distribution of KIMs, including stratigraphy and regional bedrock geology.

The three samples spiked with KIMS for a blind quality control test were successfully identified by the lab. ODM found 9 out of 10 of KIM grains spiked in sample #13, 6 out of 8 in sample #18, and 5 out of 9 in sample #51. The main point is that each of the three spiked samples was identified as anomalous, and thus the lab is rated as performing their processing and picking very effectively. A detailed discussion of these results was provided by the lab following disclosure of which samples were spiked (Huneault, in DNR open file release, 1995).

A total of 57 regular samples from 39 different sites were processed and analyzed (Map 1). Significant findings include the identification of four pyrope garnets, three Cr-diopsides with Cr > 1.1%, and two high-Cr chromites within eight of the samples (Table 1 & Map 2). The microprobe analysis of each grain is presented and discussed by Averill (1995). The pyrope garnets all fit the Group 9 composition category of Dawson and Stephens (1975). All nine of these grains are proposed to be of possible kimberlite affinity, although the Cr-diopsides are close to the lower Cr_2O_3 limit for kimberlitic Cr-diopsides(see discussion in Averill, 1995).

The sum of all 57 sample weights of 582 kg yielded a total of 9 KIMs, or a simple average of 1 KIM per 65 kg (Table 1; see DNR open file for ODM data sheets).

Four of the KIM-bearing samples, #3, #9, #20, #49, occur in the Archean Superior Province bedrock terrane, or Archon. At least three of these, #3, #20, #49, occur in association with one Rainy lobe recessional moraine feature, here informally referred to as the Holstrum Trail moraine (Map 3). The concentration of KIMs of these three samples, expressed cumulatively, is 4 KIMs per 33.9 kg of sample, or, expressed as a simple average, 1 KIM per 8.5 kg of sample. The concentration of the remaining 54 samples, expressed cumulatively, is 5 KIMs per 548.1 kg of sample, or, expressed as a simple average, roughly 1 KIM per 110 kg of sample.

The two sites with KIMs in central Minnesota, samples #19 & 28, occur within the Early Proterozoic bedrock terrane, or Proton. The sample #28, containing a G-9 pyrope, is an ultramafic drill core sample reported as having a composition similar to kimberlite (Southwick & Chandler,1987). The site in southwestern Minnesota, sample #32, containing a G-9 pyrope, occurs in the Middle Archean terrane or Archon. It is in the same county as a drill core reported to contain a possible lamproite association, because of the alteration observed in the core (Southwick et al., 1993).

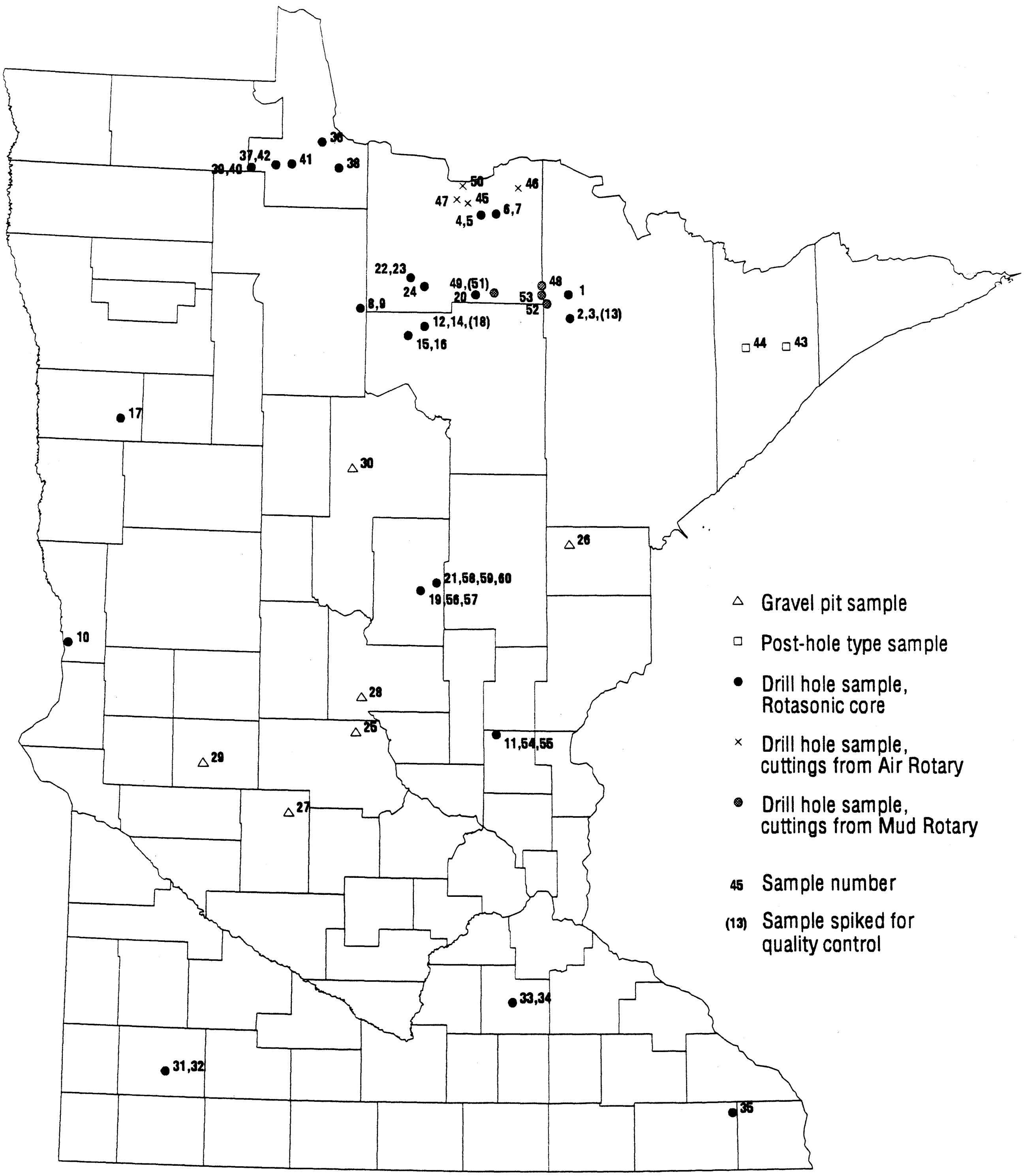
The ODM lab initially labeled many ilmenites as possible KIMs. The ilmenites have a luster and appearance that were described as very similar to that of ilmenites from kimberlites (R. Huneault, pers. communication). Taking a conservative approach,

Table 1

The locations and compositions of the KIM candidates.
Some of the chrome diopsides were interpreted by Averill (1995) as being probably of crustal provenance.

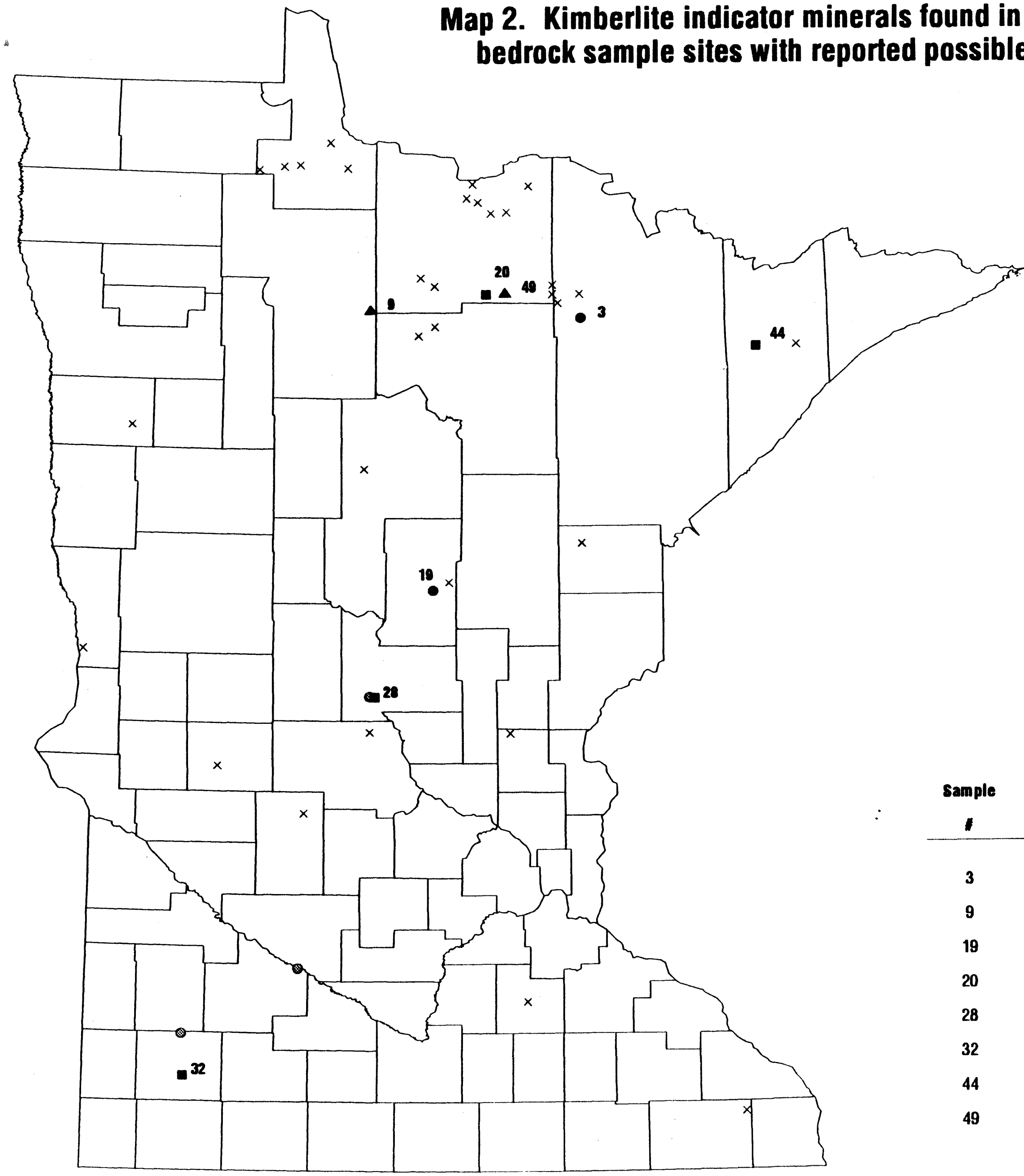
		KIM Composition (%)											Sample Location		
Sample #	Kimberlite Indicator Mineral	Na2O	K2O	CaO	FeO	MgO	Al2O3	MnO	TiO2	Cr2O3	SiO2	Total	Sec-Twp-Rng(W)	DDH	Depth Interval (ft.)
3	Chromite	Not Available. Composition "confirmed by SEM" at ODM lab.											27-62-20	OB-208	47-62
9	Cr-diopside	.74	NA	22.95	2.36	16.80	3.63	.00	.14	1.12	52.51	100.25	27-151-30	KR-73	114-128
19	Chromite	NA	NA	.00	17.20	11.71	18.61	.00	.31	47.70	NA	99.65	27-46-29	OB-401	20-34
20	Pyrope, G-9	NA	NA	6.25	6.74	20.56	18.33	0.40	0.18	6.93	41.10	100.49	19-63-25	OB-303	126-138
28	Pyrope, G-9	NA	NA	5.39	6.51	21.16	19.62	0.32	0.43	5.06	42.08	100.57	13-128-30	Gravel Pit Sample 23954	3-7
32	Pyrope, G-9	NA	NA	5.32	9.49	20.66	21.65	0.39	0.56	1.85	41.05	100.97	23-106-41	SWRA-2	215-228
44	Pyrope, G-9	NA	NA	4.80	7.80	20.55	20.55	0.39	0.24	2.92	42.56	99.81	23-60-10	Post Hole Sample 21713	0-5
49	Cr-diopside	.66	NA	20.13	4.04	19.04	2.06	.22	.17	1.17	52.70	100.19	18-63-24	OB-20104	131-146
49	Cr-diopside	.00	NA	22.69	3.53	17.08	3.10	.00	.15	1.21	51.77	99.53	18-63-24	OB-20104	131-146

Map 1. Sample locations, sample numbers, and sample types



Fifty-seven glaciofluvial samples, representing 39 different sites across Minnesota, were submitted to Overburden Drilling Management Lab for processing to identify kimberlite heavy mineral indicators. Sample types include 41 Rotasonic cores, 4 mud rotary drill cuttings, 4 air rotary drill cuttings, 6 gravel pit, and 2 post-hole samples. Three duplicate samples were spiked with indicator minerals.

Map 2. Kimberlite indicator minerals found in this survey, with several additional bedrock sample sites with reported possible kimberlite or lamproite affinity.



- Sample with Chromite
- Sample with Cr-diopside
- Sample with Pyrope
- Bedrock sample reported possible kimberlite or lamproite affinity
- Other sample

Sample #	Kimberlite Indicator Mineral (# grains)	Provenance of Stratigraphic Unit	Depth (ft)
3	Chromite (1)	Northeast (Rainy)	47-62
9	Cr-diopside (1)	Northwest (Winnipeg)	114-128
19	Chromite (1)	Northeast (Rainy)	20-34
20	Pyrope (1)	Northeast (Rainy)	126-138
28	Pyrope (1)	North (Wadena)	7
32	Pyrope (1)	unclassified	215-228
44	Pyrope (1)	Northeast (Superior)	0-5
49	Cr-diopside (2)	Northeast (Rainy)	131-146

Map 3. Kimberlite indicator mineral bearing samples in the Holstrum Trail moraine area (modified from Hobbs and Goebel, 1982, scale 1:500,000)

- ● Sample with kimberlite indicator mineral (sample number indicated)
- × Other sample
- Rainy lobe, Vermilion Moraine Association, end moraine
- Rainy lobe outwash
- Rainy lobe, Vermilion Moraine Association, ground moraine
- Rainy lobe sediments buried under Koochiching lobe or peat

a few hundred ilmenites from widely scattered samples across the state were analyzed by microprobe. The results show they do not have a kimberlitic composition. The point is that visual examination for kimberlitic ilmenite in some parts of the state will be very difficult. Geographically, the ilmenites are distributed widely in eastern, south eastern, and central Minnesota. For example, sample #29 is from Pope county, approximately 180 miles down-ice from the probable source bedrock of the Duluth Complex, and contained 51 ilmenites picked for evaluation. ODM lab was notified, soon after the first sample set of results of high ilmenite counts were received, to examine the ilmenites from sample #44 from a known Duluth Complex source. It was apparently not possible to discriminate visually between the different types of ilmenite.

Discussion

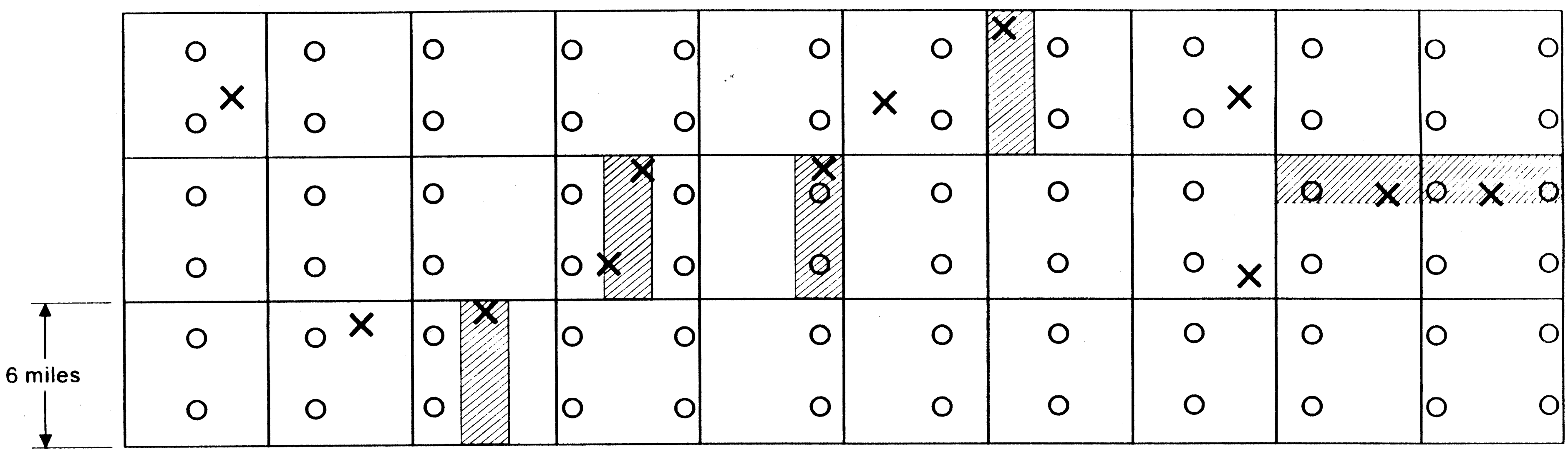
The concentration of 1 KIM per 110 kg of sample, from a subpopulation of 54 samples per above, is proposed to be a gross representation of the background concentration of KIMs in the sand and gravel in Minnesota. It primarily represents late-Wisconsinan deposits of Labradorean provenance. The sample distribution, differing sample types, sample density, and sample size are not adequate at this time to support a completely quantitative approach to the data evaluation. For comparison, the author suggests a minimal sample representation for the search for a kimberlite field in Minnesota to consist of a sample set from one stratigraphic unit such as Rainy lobe deposits, with sample density of one 30 kg sample per 15 square miles for each hypothetical cell of 1080 square miles. That means a sample density of 72 samples per 1080 square miles to successfully identify an anomalous pattern of KIMs associated with scattered kimberlite intrusives of a field (Figure 2), using a conservative approach to the geological processes working against successful discovery.

Within the realm of qualitative interpretation of the significance of the 9 KIMs found, there are a range of interpretations from pessimistic to optimistic. An example pessimistic view is that all 9 observed KIMs are from bedrock sources outside Minnesota, or are otherwise unrelated to diamondiferous kimberlite bedrock sources. In contrast the focus here is on an optimistic interpretation of a plausible Minnesota source, and the discussion is an attempt to understand where it might be, based on this new data.

The 5 most northerly samples that have KIMs occur, in a very general manner, along a major boundary within the Superior Province between terranes of the Quetico Subprovince and the Wawa Subprovince. Alternatively, these 5 samples occur, in a very general manner, near the Vermilion fault system, which may be a major break in the Archean crust.

There are three lines of logic that suggest a pattern of dispersal exists for three of these 5 samples. The author participated in the original sample collection phase of 3 of these samples that contain KIMs, samples # 3, 20, & 49. These 3 samples are spatially associated with one recessional moraine complex, including outwash and lacustrine sediment, of the Rainy lobe(Map 3). Because the associated deposits are buried under younger glacial drift, the argument to correlate them is empirical, based upon the spatial location, type of sediments, and sediment clast compositions. Secondly, the KIM

Figure 2. Hypothetical kimberlite field, glacial dispersal, and sample density in a Minnesota setting. Note that this applies to one glacial stratigraphic unit, such as the Rainy lobe sediments. Success is defined conservatively here as 3 samples with 2 or more KIMs.



X Kimberlite pipe in bedrock (12)

O sample of glaciofluvial sediments @ density of 1/15 sq. mile (72 samples in 1080 sq. miles)

[hatched box] KIMs in glaciofluvial sediments; (6 areas x 12 sq. miles = 72 sq. miles) concentration, expressed cumulatively, for these samples is 4 KIMs per 33.9 kgs or, expressed as a simple average, 1 KIM per 8.5 kg. This is 8 times greater than the overall simple average. Such an order of magnitude increase in the concentration of KIMs fits the typical pattern for glacial drift anomalies. Thirdly, there are many other samples surrounding or to the north of #3, #20, & #49, but those do not contain any KIMs. Hence, a higher background for this immediate area is ruled out. These types of evidence suggest the possibility that the KIMs are from a kimberlite field located to the northeast, the up-ice direction, at an unknown distance. There are published examples where KIMs from known kimberlite sources show up in such recessional moraines, as in Michigan's Upper Peninsula (Carlson and Floodstrand, 1994) and in the northern part of the Russian Platform (Golubev,1995).

The lack of G-10 garnets at this time is to be expected, and is not discouraging. Within a given diamondiferous kimberlite pipe, G-10 garnets make up, in a general approximation, 5% or less of the pyrope population (Govett, 1992). Therefore, 50 or more pyrope grains need to be recovered and analyzed to obtain a statistically meaningful result in the search for G-10 garnets (op.cit.).

On a more general note, there are at least two important components to consider in evaluating any area of the state where a KIM is found - the ratio of fresh bedrock to saprolite exposed as subcroppings to glacial erosion, and the glacial stratigraphy. Where the ratio of fresh bedrock to saprolite is high, then more KIMs should be present in the bedrock source and available for entrainment in glacial drift and subsequently, for sampling. When the glacial stratigraphy is simply late-Wisconsinan over bedrock, then KIMs should be available in a higher concentration. As either one of these changes, then the probability of the presence of KIMs in the samples is lowered, or put another way, the concentration of KIMs should be lowered. As these two components vary across the state, the background concentration of KIMs in glacial drift may change. Unfortunately, we have an imperfect knowledge of the map of these two factors at the state scale.

The case for use of a larger sample size is strong. Some kimberlite source rocks have very few KIMs to contribute to glaciofluvial sediments, such as the field in Quebec (S. Averill, pers. communication). An example from a field of diamondiferous kimberlites in northern Russia (64 degrees N) cites 1 to 3 KIMs per 40 to 60 kg of glacaiofluvial sediments (Golubev, 1995). The apparent background in Minnesota is very low, which is good in regard to the contrast between anomaly and background, but the anomaly in Minnesota may also be low. Furthermore, each time a KIM is recycled upward into a younger glacial drift package, then theoretically significant dilution occurs. There are many possible recycling events in the Quaternary in Minnesota. The statewide preglacial weathering episodes may have destroyed some of the KIMs, such as garnets and diopsides, rendering them unavailable to the subsequent glacial erosion and deposition. This would have the effect of lowering the anomaly contrast. All of these problems would be improved by a larger sample size, such as 30 kg.

Recommendations

The results have led to recommendations regarding sample size, follow-up of an anomalous pattern, follow-up of the pyropes found, and other sample opportunities. Specific recommendations include the following ideas.

1) Sample the gravel pits in the three sequential Rainy lobe recessional moraines, including the Effie moraine, the Holstrum Spur moraine, and the Vermillion moraine, to accumulate 30 samples from approximately Cook to Big Falls to evaluate and define the proposed anomaly in sample #3, #20, and #49.

2) Sample gravel pits in the areas surrounding the other three pyrope garnet-bearing samples (#28, 32, 44) to accumulate up to 30 samples across a 1000 square miles around each sample to try to search for supporting evidence for the presence of a field of kimberlites.

3) Increase the sample size, if possible, to 30 kg or more, in order to obtain two or more KIMs per anomalous sample,.

4) Sample the well developed drainages overlying the Paleozoic sediments in southeast Minnesota. The pre-late Wisconsinan glaciation would have helped to disperse KIMs in this region, which may have subsequently been concentrated in the extensive stream network.

5) Sample the numerous end moraines of Labradorean provenance that are accessible across a wide part of Minnesota.

6) Develop a sample strategy for every area in the state where geological information and/ or appropriate aeromagnetic features suggest a fit for models of buried kimberlite or lamproite bodies.

Conclusions

This work has resulted in the first public dataset on kimberlite indicators in Minnesota. The primary conclusion is that the background content in glaciofluvial materials widely distributed across Minnesota, both in space and stratigraphic unit, is very low, based upon the total of 9 KIMs for all 582 kg of all samples in this survey. Obtaining large sample sizes is prudent, due to many uncertainties in the geologic processes. The presence of the four pyrope garnet KIMs in Minnesota's glaciofluvial materials are somewhat encouraging, and should be followed-up with further sampling. However, due to low sample density, the extensive pre-glacial weathering, and the uncertainties in the chain of necessary geologic processes, the lack of KIMs in any given set of glaciofluvial samples should not be used to eliminate any area as being nonprospective at this stage of sample density.

The secondary conclusion is the possible weak pattern of four KIMs in three samples. Those three samples are spatially associated with one recessional moraine feature, the Holstrum Trail moraine near the southern Koochiching County border. That pattern is viewed as an anomaly that should be followed up with further sampling. Sample sizes of 30 kg or more should be evaluated.

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APPENDIX A

Sample Information

Appendix A. Sample information. Part 1 - Locations.

Sample No.	Dup. Sample	Prev. Sample No.	DDH	Drill Hole DNR Unique No.	County	Twp	Rng	Sec	Forty	UTMN	UTME	Interval True Dpt. Top (ft)	Interval True Dpt. Bot. (ft)	Sa. Int. L.-Box (in.)	Sample Weight (lbs)	Approx. Sample Remain	Sampled by:	Date Sampled
3140000001			OB-209	14159	St. Louis	63	20	16	NE\SE	507950	5309540	55	65	85	21	.25	RR-ME-PG	1/12/94
3140000002			OB-208	14063	St. Louis	62	20	27	SE\SW	508840	5296060	32	47	171	23	.25	RR-ME	1/13/94
3140000003			OB-208	14063	St. Louis	62	20	27	SE\SW	508840	5296060	47	62	220	24	.50	ME	1/13/94
3140000004			OB-105	12167	Koochiching	68	25	28	SE\SW	458510	5354640	18	33	213	25	.25	RR-ML	1/19/94
3140000005			OB-105	12167	Koochiching	68	25	28	SE\SW	458510	5354640	33	48	220	21	.25	RR-ML	1/19/94
3140000006			OB-107	12166	Koochiching	68	24	29	NE\SE	467110	5355290	81	95	160	22	.25	RR-ML	1/19/94
3140000007			OB-107	12166	Koochiching	68	24	29	NE\SE	467110	5355290	101	115	236	23	.25	RR-ML	1/19/94
3140000008			KR-73	16235	Beltrami	151	30	27	SE\SE	390610	5301760	99	113	265	22	.66	RR	1/30/94
3140000009			KR-73	16235	Beltrami	151	30	27	SE\SE	390610	5301760	114	128	206	23	.66	RR	1/30/94
3140000010			RVR-3	16270	Wilkin	131	47	35	NE\NE\NE	690540	5110500	125	136	135	23	.25	RR	2/01/94
3140000011			AR-2	16251	Isanti	37	25	11	SE\NW	467190	5061780	40	54	117	23	.66	RR	2/01/94
3140000012			OB-320	12008	Itasca	150	26	28	SW\SE	426790	5291640	40	54	127	23	.25	RR	2/02/94
3140000013	yes		OB-208	14063	St. Louis	62	20	27	SE\SW	508840	5296060	47	62	220	28	.25	ME	1/13/94
3140000014			OB-320	12008	Itasca	150	26	28	SW\SE	426790	5291640	80	94	109	23	.25	RR	2/02/94
3140000015			OB-325	11999	Itasca	149	27	16	NE\NE	417430	5286420	218	232	140	23	.50	RR	2/04/94
3140000016			OB-325	11999	Itasca	149	27	16	NE\NE	417430	5286420	113	127	157	23	.66	RR	2/04/94
3140000017			RVR-1	16268	Norman	144	44	23	SE\SE\SW	709810	5238400	117	131	159	23	.50	RR	2/24/94
3140000018	yes		OB-320	12008	Itasca	150	26	28	SW\SE	426790	5291640	40	54	127	22	.25	RR	2/25/94
3140000019			OB-401	11184	Crow Wing	46	29	27	NE\SE	424500	5142970	20	34	100	23	.66	RR-ML	2/28/94
3140000020			OB-303	12158	Koochiching	63	25	19	NW\NW	455600	5309430	126	138	184	24	.66	RR-ML	2/28/94
3140000021			OB-402	10782	Crow Wing	46	28	10	SE\SW	433580	5147270	48	62	80	22	.66	RR-ML	3/01/94
3140000022			OB-329	12186	Koochiching	153	27	34	SW\SE	418870	5319060	97	111	150	23	.66	RR-ML	3/01/94
3140000023			OB-329	12186	Koochiching	153	27	34	SW\SE	418870	5319060	81	95	134	24	.66	RR-ML	3/01/94
3140000024			OB-322	12182	Koochiching	152	26	16	SW\SE	426680	5324180	124	138	140	24	.66	RR-ML	3/02/94
3140000025		23963			Stearns	126	30	22	NW\NW\NW\NE	388020	5063320				25	0.00	RR	3/03/94
3140000026		23912			Carlton	48	20	4	SE\NW\NE\NW	508610	5169190				23	0.00	RR	3/03/94
3140000027		23970			Kandiyohi	121	34	11	NE\NW\NE\SE	350250	5018150				26	0.00	RR	3/03/94
3140000028		23954			Morrison	128	30	13	SE\SW\NE\SW	391170	5083200				26	0.00	RR	3/03/94
3140000029		23968			Pope	124	39	14	SW\SE\SE\SW	302270	5046130				26	0.00	RR	3/03/94
3140000030		22637			Cass	141	30	5	SE\SW\SE	386220	5211960				25	0.00	RR	3/03/94

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Sample No.	Dup. Sample	Prev. Sample No.	DDH	Drill Hole DNR Unique No.	County	Twp	Rng	Sec	Forty	UTMN	UTME	Interval True Dpt. Top (ft)	Interval True Dpt. Bot. (ft)	Sa. Int. L.-Box (in.)	Sample Weight (lbs)	Approx. Sample Remain	Sampled by:	Date Sampled
3140000031			SWRA-2	18418	Murray	106	41	23	NE\NW	280500	4872870	180	207	153	24	.66	RR	3/10/94
3140000032			SWRA-2	18418	Murray	106	41	23	NE\NW	280500	4872870	215	228	131	23	.66	RR	3/10/94
3140000033			RICE-2	18421	Rice	110	21	12	NW\NW	476010	4911150	110	122	244	24	.66	RR	3/10/94
3140000034			RICE-2	18421	Rice	110	21	12	NW\NW	476010	4911150	43	64	98	23	.66	RR	3/10/94
3140000035			FIL-2		Fillmore	104	8	23	NE\SW	599420	4849470	72	85	176	24	.66	RR	3/10/94
3140000036			OB-507	14324	Lake of the Woods	160	32	5	SE\SE	368920	5395550	215	227	178	24	.25	RR	4/20/94
3140000037			OB-518	14335	Lake of the Woods	159	35	22	SW\NE	342810	5382690	186	200	220	25	.66	RR	4/25/94
3140000038			OB-502	14320	Lake of the Woods	159	31	20	SE\SE	378360	5381120	153	167	143	23	.66	RR	4/26/94
3140000039			OB-520	14337	Lake of the Woods	159	36	29	SW\NW	329010	5381190	53	67	184	24	.66	RR	4/26/94
3140000040			OB-520	14337	Lake of the Woods	159	36	29	SW\NW	329010	5381190	79	93	295	24	.66	RR	4/26/94
3140000041			OB-514	14331	Lake of the Woods	159	34	15	SE\SW	351720	5383260	188	202	165	23	.66	RR	4/27/94
3140000042			OB-518	14335	Lake of the Woods	159	35	22	SW\NE	342810	5382690	91	105	135	23	.66	RR	4/27/94
3140000043		21011	DU-C-SO		Lake	60	7	19	SW\NE	630450	5280600	0	5		22	.50	RR	4/27/94
3140000044		21713	DA-C-SO		Lake	60	10	23	NE\SW	607650	5279880	0	5		31	.50	RR	5/03/94
3140000045		18778	OB-10401		Koochiching	68	26	3	SE\SE	451260	5361180	157	167		27	0.00	RR	5/18/94
3140000046		18884	OB-10901		Koochiching	69	23	10	SW\NE	479590	5369780	123	128		20	0.00	RR	5/18/94
3140000047		18812	OB-10303		Koochiching	69	26	31	SW\SW	444900	5363330	115	118		24	0.00	RR	5/23/94
3140000048		18669	OB-20502		Koochiching	64	22	36	NW\SE	492960	5314510	152	168			0.00	RR	5/23/94
3140000049		18698	OB-20104		Koochiching	63	24	18	NW\NE	466100	5310570	131	146		31	.50	RR	5/24/94
3140000050		18814	OB-10304		Koochiching	69	26	4	SW\SW	448300	5371050	133	137		15	0.00	RR	5/24/94
3140000051	yes	18698	OB-20104		Koochiching	63	24	18	NW\NE	466100	5310570	131	146		23	.12	RR	5/31/94
3140000052		18642	OB-20603		St. Louis	63	21	32	SE\SW	495880	5304400	165	176		33	0.00	RR	6/02/94
3140000053		18650	OB-20401		Koochiching	63	22	13	SE\SW	492840	5309270	99	109		21	0.00	RR	5/31/94
3140000054	Yes		AR-2	16251	Isanti	37	25	11	SE\NW	467190	5061780	40	54	123	20	.50	ME	11/08/84
3140000055			AR-2									25	40	149	22	.50	ME	11/08/94
3140000056	Yes		OB-401	11184	Crow Wing	46	29	27	NE\SE	424500	5142970	20	34	87	21	.50	ME	11/08/94
3140000057			OB-401									6	20	61	21	.25	ME	11/08/94
3140000058	Yes		OB-402	10782	Crow Wing	46	28	10	SE\SW	433580	5147270	48	62	81	22	.25	ME	11/07/94
3140000059			OB-402									62	79	174	29	.25	ME	11/07/94
3140000060			OB-402									79	85	63	22	.25	ME	11/07/94

Sample No.	Sample Type	Sample Description	Reference	Comments
3140000001	Rainy lobe sand/gravel	(55.0-60.0) Dirty fine and medium sand. (60.0-65.0) Coarse sand, layer of large pebbles at 64', coarse to very coarse sand below pebbles.	DNR Report #252 1988	* see page of notes for Project
3140000002	Rainy lobe sand/gravel	(32.0-36.0) Fine to medium sand. (36.0-38.5) Fine sand. (38.5-47.0) Fine to medium sand.	DNR Report #252 1988	#314 for sampling procedure.
3140000003	Rainy lobe sand/gravel	(47.0-50.0) Mostly fine sand. (50.0-52.0) Fine sand, laminated silt and clay. (52.0-62.0) Fine sand, medium sand, small clay clasts at 54', 58'.	DNR Report #252 1988	Footage between 55 ft. was wet.
3140000004	Rainy lobe sand/gravel		DNR Report #252 1988	
3140000005	Rainy lobe sand/gravel	(33.0-48.0) Coarse to vcgr sand; unoxidized; 29-38.5 w/some granules, sl calc; 38.5-41 fair amt mgr sand; 41-43.5 mgr to cgr sand; 43.5-45 some iron staining; 45-46.5 mgr to cgr sand; 47.5-48 w/gravel, fining up, sharp contact at base.	DNR Report #252 1988	Footage 35 ft. sluff was not included.
3140000006	Rainy lobe sand/gravel	(81.0-89.0) Coarse sand; unoxidized; 80-83 mgr to cgr; 83-86 cgr; 86-89 vcgr; v sl calc. (89.0-95.0) medium sand; unoxidized; some cgr, gray, v sl calc.	DNR Report #252 1988	
3140000007	Rainy lobe sand/gravel	(101.0-102.0) Coarse sand; unoxidized; gray. (102.0-115.0) Medium sand; unoxidized; noncalc, gray, v uniform.	DNR Report #252 1988	
3140000008	Unclassified at this time	not available at present time.	in press	
3140000009	Unclassified at this time	not available at present time.	in press	
3140000010	Unclassified at this time	not available at present time.	in press	
3140000011	Unclassified at this time	not available at present time.	in press	
3140000012	Rainy lobe sand/gravel	(40.0-52.0) Coarse sand; cob at 40 ft; few sm pebs below; 42-43 mgr to cgr sand, v cgr sand w/occ pebs below; some large pebs 46-48 1/2; gnl size or smaller below 50; carb fairly common, but Precambrian dominate. (52.0-54.0) medium sand; unoxidized; fgr sand bed at 56 ft, fgr to mgr and mgr sand beds below; mgr to cgr in last few feet, w/few pebs towards base.	DNR Report #263 1989	

Sample No.	Sample Type	Sample Description	Reference	Comments
3140000013	Rainy lobe sand/gravel	(47.0-50.0) Mostly fine sand. (50.0-52.0) Fine sand, laminated silt and clay. (52.0-62.0) Fine sand, medium sand, small clay clasts at 54', 58'.	DNR Report #252 1988	3 ilmenite and 7 garnet grains added to sample.
3140000014	Rainy lobe sand/gravel	(80.0-86.0) Fine-coarse sand; unoxidized; 80 ft fgr to mgr, 80-82 mgr to cgr, 82-83 cgr, 83-83 1/2 v cgr, 83 1/2-85 1/2 mgr to cgr, 85 1/2-86 v cgr bed then mgr. (86.0-91.0) No core. (91.0-94.0) Medium-coarse sand; 91-94 ft mgr w/increasing coarse grains to 94, then cgr w/few sm pebs.	DNR Report #263 1989	
3140000015	Old Rainy lobe sand/gravel	(218.0-224.0) Gravelly medium-coarse sand; 218 ft cgr sand w/peb layers; 218-218 1/2 gvl, fair amount of carb pebs; 220-222 cgr sand & fine gvl, lot of dark pebs, uncommon carb; mgr sand 222-223; pebbly cgr sand to base. (224.0-232.0) Gravel; cobbly in upper foot, rather poorly sorted; carb uncommon, lot of dark pebs.	DNR Report #263 1989	
3140000016	Old Rainy lobe sand/gravel	(113.0-116.0) Gravelly coarse-very coarse sand; unoxidized; fgr to cgr sand to 113 ft; large peb at 114 1/2, most pebs sm. (116.0-127.0) Coarse-very coarse sand; few gnl.	DNR Report #263 1989	
3140000017	Unclassified at this time	not available at present time.	in press	Footage between 55 ft. was wet.
3140000018	Rainy lobe sand/gravel	(40.0-52.0) Coarse sand; cob at 40 ft; few sm pebs below; 42-43 mgr to cgr sand, v cgr sand w/occ pebs below; some large pebs 46-48 1/2; gnl size or smaller below 50; carb fairly common, but Precambrian dominate. (52.0-54) Medium sand; unoxidized; fgr sand bed at 56 ft, fgr to mgr and mgr sand beds below; mgr to cgr in last few feet, w/few pebs towards base.	DNR Report #263 1989	3 ilmenite and 5 garnet grains added to sample.
3140000019	Rainy lobe sand/gravel	(20.0-34.0) Silty, gravelly medium-coarse sand; oxidized; non calc; 0-9 ft mgr, more pebbly below; v silty, couple sm cobs 15-20; cgr from 26; more	DNR Report #263 1989	

Sample No.	Sample Type	Sample Description	Reference	Comments
		pebs below 28, but are sm; some larger pebs by 30; no carb grains noted; last foot unox & sl calc w/few carb grains.		
3140000020	Rainy lobe sand/gravel	(126.0-130.0) Gravelly sand; oxidized; loamy cgr to v cgr sand w/sev cobs to 128 ft, then v cgr pebbly sand; little or no carb; unox by 129. (130.0-136.5) Sand & gravel; unoxidized; cobs to 134 ft, then fine gvl; carb peb at 131. (136.5-137.5) Sand; oxidized; cgr to v cgr; unox by 137 1/2 ft except at base.	DNR Report #263 1989	
3140000021	Superior lobe sand/gravel	(48.0-62.0) Gravelly coarse-very coarse sand; oxidized; pebbly cgr sand to 50 ft, pebbly v cgr sand to 52, sand & gvl to 54; few carb grains; 54-61 pebbly, v cgr sand, somewhat silty; few large pebs at 58; 61-62 fine gvl; 62-63 pebbly cgr sand, sm cobs.	DNR Report #263 1989	
3140000022	Rainy lobe sand/gravel	(97.0-102.0) Coarse sand & fine gravel; much dark pebs. (102.0-108.0) Coarse sand; few sm pebs; mgr to cgr from 105 ft. (108.0-111.0) Coarse-very coarse sand & granules; peb layers at 100 1/2, 111 ft.	DNR Report #263 1989	
3140000023	Rainy lobe sand/gravel	(81.0-87.0 Gravelly coarse sand; mgr to cgr sand in upper 1/2 ft; sm cob at 84 ft. then v cgr sand w/gnl; some carb, Precambrian dominates. (87.0-89.0) Medium-coarse sand. (89.0-95.0) Fine-medium sand; v fgr to fgr 92-92 1/2 ft; 93-95 1/2 silty; v fgr sand; fgr to 95.	DNR Report #263 1989	
3140000024	Rainy lobe sand/gravel	(124.0-128.5) Fine sand; 124-125 1/2 fgr to mgr sand w/silt beds; 125 1/2-126 pebbly cgr sand; fgr grading to silty v fgr by 127. (128.5-135.0) Fine-medium sand. (135.0-138.0) Fine sand.	DNR Report #263 1989	
3140000025	Superior lobe sand/gravel	Sandy, pebbly gravel, very poorly sorted.	DNR Report #284 1992	5.75L -10 mesh Arc. (gravel pit sample).

Appendix A. Sample information. Part 2 - Descriptions.

Sample No.	Sample Type	Sample Description	Reference	Comments
3140000026	Superior lobe sand/gravel	Fine to medium sand, with fine gravel, well sorted.	DNR Report #284 1992	6L -10 mesh Arc. (gravel pit sample).
3140000027	Wadena lobe sand/gravel	Pebbly sand.	DNR Report #284 1992	6L -10 mesh Arc. (gravel pit sample).
3140000028	Wadena lobe sand/gravel	Sandy, very-fine to medium pebble gravel and very-fine to medium pebbly sand, medium to very coarse, moderately to poorly sorted.	DNR Report #284 1992	6L -10 mesh Arc. (gravel pit sample).
3140000029	Wadena lobe sand/gravel	Medium to fine gravel, well sorted, massive.	DNR Report #284 1992	5.5L & 1.75L -10 mesh arc. (gravel pit sample)
3140000030	Wadena lobe sand/gravel	Pebbly sand?	DNR Report #284 1992	subsa. B,C,E -10m Arc.(g.p.s.) screen frac. comb
3140000031	Unclassified at this time	(180.0-207.0) Gray fine-medium sand. Well sorted and uniform with depth. Mud used at 155'. At 185' sand is coarser. Coarse and fine sand in alternating layers. Siltier sand at bottom. Drilled harder when siltier, drilled like till.	in press	Footage 180 to 207 ft. est. 15 ft. not recovered.
3140000032	Unclassified at this time	(215.0-228.0) Gray fine-medium sand. Well sorted and uniform with depth. Coarse sand and fine sand in alternating layers. Siltier sand at bottom. Drilled harder when siltier, drilled like till.	in press	1.5 lbs. of sample spilled in shipment. Saved spill material in bag.
3140000033	Unclassified at this time	(110.0-112.0) Gray fine and medium grained loamy sand. Wet. Easy drilling. Driving 20' of casing. (112.0-120.0) Medium to coarse grained gray sand. A lot of recovery. Sand heaving up into hole. Filled casing too. Mixing mud to flush casing out. Redrill from 115 = mush. Till or silty clayey layers about 6" thick near 120'. (120.0-122.0) Bright yellow sand (color affected by the presence of limestone bedrock). Broken limestone in bottom of bit.	in press	
3140000034	Unclassified at this time	(43.0-45.0) Gray loamy till. Firm, moist, matrix-rich. (45.0-50.0) Coarse sand, gravel, cobbles. (50.0-64.0) Sand. Poor recovery. Chattery bit but may have been plugged. Some sand was dry and compact. Cased afterwards and washed sand away,	in press	

Sample No.	Sample Type	Sample Description	Reference	Comments
		but can be pretty sure that it was all sand.		
3140000035	Unclassified at this time	not available at present time.	in press	ftg. 72 to 85ft. wet sa. (core currently at MGS)
3140000036	Old Rainy lobe sand/gravel	(215.0-218.0) Very fine sand; unoxidized; v silty; coarsens downwards. (218.0-226.0) Medium-very coarse sand; unoxidized; silty mgr sand coarsenng downwards to silty cgr sand below 220 1/2 ft; pebbly & silty layers; well sorted v cgr sand below 221 1/2 ft; cobs below 225 1/2 ft, w/large cob at base.	DNR Report #280 1991	
3140000037	Winnipeg lobe sand/gravel	(186.0-188.0) Gravelly fine-coarse sand; unoxidized; silty, v poorly sorted, many v large pebs; lower foot cobs. (188.0-198.0) Gravelly coarse-very coarse sand; unoxidized; mod sorted; silty; common carb; occ large pebs; poorly sorted below 196 ft; some v large pebs below 197 ft. (198.0-200.0) Silty fine-medium gravel; unoxidized; some large pebs; 199 1/2-200 ft v dark gray clay loam till; gvlly v cgr sand to 200 ft, silty gvl below.	DNR Report #280 1991	
3140000038	Rainy & Old Rainy lobe sand/gr	(153.5-156.0) Gravelly sand; unoxidized; silty, cgr, poorly sorted w/common large pebs, sm cob at 154 ft; carb pebs rare; silt clast at base, abrupt lower contract. (156.0-163.5) Coarse sand; unoxidized; v well sorted; cgr-vcgr w/few gnt by 158 ft; sm clast of gray, mod calc sandy till at 159 1/2 ft; last 2 ft not as well sorted, mostly mgr, w/some gnl at 162 ft; abrupt lower contact. (163.5-167.0) Silty very fine sand.	DNR Report #280 1991	
3140000039	Winnipeg lobe sand/gravel	(53.0-54.5) Fine sand; unoxidized; mod sorted; 45 1/2-47 ft silty mgr-cgr gvl, v poorly sorted, w/common carb pebs. (54.5-64.0) Medium-coarse gravel; unoxidized; silty, v poorly sorted; common	DNR Report #280 1991	

Sample No.	Sample Type	Sample Description	Reference	Comments
		carb. (64.0-67.0) Gravelly coarse sand; unoxidized; poorly sorted; gvl 67 ft.		
3140000040	Winnipeg lobe sand/gravel	(79.0-82.5) Gravelly coarse sand; unoxidized; poorly sorted; below 76 ft silty, v gvlly & poorly sorted w/large pebs; cob at 78 1/2 ft. (82.5-85.0) Medium sand; unoxidized; mod sorted; v fgr sand at top; mgr-cgr below 84 ft. (85.0-90.5) Gravelly coarse sand; silty, poorly sorted; most pebs fgr-mgr. (90.5-93.0) Coarse-very coarse sand; unoxidized; mod sorted.	DNR Report #280 1991	
3140000041	Rainy lobe sand/gravel	(188.0-191.0) Gravelly coarse sand; unoxidized; mod sorted; uncommon carb; cob at 190 ft, more gvlly & not as well sorted below. (191.0-193.5) Coarse gravel; unoxidized; v silty, v poorly sorted; couple cobs at base. (193.5-202.0) Gravelly very coarse sand; unoxidized; mod sorted at best; upper foot silty cgr sand; possible inclusion of sandy till at 195 ft; cob at 199 ft; poorly sorted below 200 ft, carb fairly common.	DNR Report #280 1991	
3140000042	Rainy lobe sand/gravel	(91.0-95.0) Medium-very coarse sand; unoxidized; mod sorted; occ sm peb; not much carb. (95.0-98.5) Fine sand; unoxidized; mod sorted, some coarser grains; couple silt beds or inclusions at 97 ft, over bed of fgr-cgr sand. (98.5-105.0) Medium-coarse sand; unoxidized; well sorted; fair amount of v cgr sand below 103 ft; last 1/2 foot pebbly fgr sand, poorly sorted.	DNR Report #280 1991	
3140000043	Superior lobe sand/gravel	Undivided Superior lobe outwash.	DNR Report #262 1989	Bucket sample split. 0 to 5 ft. int.
3140000044	Superior lobe sand/gravel	Undivided Superior lobe outwash.	DNR Report #262 1989	Bucket sample split. 0 to 5 ft. int.
3140000045	Rainy lobe sand/gravel	(157.0-162.0) Gravelly sand; unoxidized; mostly fgr to mgr sand; peb zone at 161; too much sample. (162.0-167.0) Gravelly sand; unoxidized; 162-164	DNR Report #252 1988	

Sample No.	Sample Type	Sample Description	Reference	Comments
		mgr sand w/some rounded pebs; heaved 13 ft up casing; 164.0-167.0 cgr sand w/subrnd-subang gnls to pebs; v water bearing.		
3140000046	Rainy lobe sand/gravel	(123.0-128.0) Medium sand; unoxidized; w/fgr sand and +-10% pebs.	DNR Report #252 1988	
3140000047	Rainy lobe sand/gravel	(115.0-117.0) Gravelly, sandy till; unoxidized, rainy, w/ang pebs up to one inch. (117.0-118.0) Bedrock; quartz biotite schist; no thin section; Roller Bit had to be used here.	DNR Report #252 1988	
3140000048	Rainy lobe sand/gravel	(152.0-168.0) Gravelly sand; unoxidized; sa 152-168 has +10M subang & subrnd; -10M has mgr to vfg sand; cob at 160.	DNR Report #252 1988	
3140000049	Rainy lobe sand/gravel	(131.0-133.0) Sandy silt; unoxidized; fgr w/incr peb content; top of Rainy Lobe? cob at 132. (133.0-146.0) Gravelly sand; unoxidized; Rainy Lobe; v cobbly; stopped due to artesian flow; sa 131-146 +10M mostly subang pebs and chips.	DNR Report #252 1988	-10 mesh
3140000050	Rainy lobe sand/gravel	(133.0-134.0) Gravelly sand; unoxidized; Rainy; at 133 ang to subrnd pebs up to 3/8 inch in the sand; 133.5 more clasts less sand, pebs ang to rnd; possibly till. (134.0-136.0) Medium sand; unoxidized; w/some fgr & cgr sand, few clasts; ang-subrnd; water bearing. (136.0-137.0) Bedrock; metasediment w/stringers on monzonite.	DNR Report #252 1988	
3140000051	Rainy lobe sand/gravel	(131.0-133.0) Sandy silt; unoxidized; fgr w/incr peb content; top of Rainy Lobe? cob at. (133.0-146.0) Gravelly sand; unoxidized; Rainy Lobe; v cobbly; stopped due to artesian flow; sa 131-146 +10M mostly subang pebs and chips.	DNR Report #252 1988	-10 mesh; 3 ilmenite and 6 garnet grains added to sample.
3140000052	Rainy lobe sand/gravel	(165.0-176.0) Gravelly sand; unoxidized; Rainy Lobe; boulder 165-167; sand is mgr-cgr; sa 165-176 has subang vf pebs in +10M; sa 176, +10M has subang	DNR Report #252 1988	

Sample No.	Sample Type	Sample Description	Reference	Comments
		vf-fine pebs; sa 165-176, approx 20 wt% +10M.		
3140000053	Rainy lobe sand/gravel	(99.0-109.0) Gravelly sand; unoxidized; Rainy Lobe; sa 99-109 has 25 wt% +10M of subang pebs and chips; sa 109 has 20 wt% +10M of subang pebs and chips.	DNR Report #252 1988	
3140000054		Not available at present time.		
3140000055		Not available at present time.		
3140000056	Rainy lobe sand/gravel	(20.0-34.0) Silty, gravelly medium-coarse sand; oxidized; non calc; 0-9 ft mgr, more pebbly below; v silty, couple sm cobs 15-20; cgr from 26; more pebs below 28, but are sm; some larger pebs by 30; no carb grains noted; last foot unox & sl calc w/few carb grains.		
3140000057				
3140000058	Superior lobe sand/gravel	(48.0-62.0) Gravelly coarse-very coarse sand; oxidized; pebbly cgr sand to 50 ft, pebbly v cgr sand to 52, sand & gvl to 54; few carb grains; 54-61 pebbly, v cgr sand, somewhat silty; few large pebs at 58; 61-62 fine gvl; 62-63 pebbly cgr sand, sm cobs.		
3140000059				
3140000060		(70.0-85.0) Granually coarse sand; unoxidized; some silt; some large pebbles; carb rare; some falsite; sandstone.		