

MINNESOTA GEOLOGICAL SURVEY

Harvey Thorleifson, Director

**TILL GEOCHEMICAL AND INDICATOR MINERAL RECONNAISSANCE OF
MINNESOTA**

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ABSTRACT

As a cooperative project of the Minnesota Geological Survey and industry, the entire State of Minnesota and adjacent regions was sampled for till geochemistry and indicator minerals at a 30-km spacing during summer 2004. Within target cells, each a quarter-degree latitude by a half-degree longitude, till from between about 1 and 2 m depth was sampled by filling a 15 liter plastic pail. At a few sites, vertical profiles were collected. In addition, three transects to the north were sampled, to help identify sediments derived by long-distance glacial transport, to obtain reference samples from the Thompson nickel belt, and also to extend sampling to the limit of Hudson Bay-derived carbonate-bearing sediments, to permit comparison to Minnesota carbonate-bearing sediments. Three control samples anomalous in kimberlite indicator minerals from Kirkland Lake, Ontario, were also obtained. The resulting batch consisted of 250 samples covering Minnesota and adjacent areas, 20 samples from Canada, and the three standards. Upon completion of the sampling, the samples were randomized, given numeric laboratory identifications, and shipped to a processing lab, where four quarter-liter splits, two for fine fraction geochemistry, one for texture, and one for an archive were removed. The remaining 14 liters were disaggregated, screened at 2 mm, and the gravel was retained for lithological analysis. The <2 mm fraction was then processed for gold grains, a ferromagnetic heavy mineral concentrate, and a nonferromagnetic heavy mineral concentrate that supported subsequent analysis for precious metal, base metal, and gemstone indicator mineral counts, indicator mineral chemistry, bulk mineralogy counts, and heavy mineral geochemistry. The resulting data are now a significant new information resource with respect to environmental geochemistry topics such as understanding the distribution of deleterious elements in food and water, while providing insights into transport history and composition of the sediments that make up our soil parent materials. Many variables provide insights into regional geology, and reflect known mineral deposits. Some of the data seem to provide faint insights into what may be mineralization that was not previously recognized, such as various base-metal and precious-metal-related elements that show patterns of varying clarity over portions of the state. None of these patterns, however, are obvious discoveries of something that was previously unknown, at the current stage of interpretation. With respect to kimberlite indicator minerals, however, there are two noteworthy patterns, including a few Cr-pyrope garnets in an area from the Twin Cities to southwestern Minnesota, as well as Mg-ilmenites and high-chrome Cr-diopsides in the far north-central part of the State. Sample spacing in the thin sediments of northeastern Minnesota was not adequate to fully test for the presence of sources such as potential single kimberlite pipes, although samples at a closer spacing are presently being processed by Natural Resources Research Institute to address this point. The current results are, however, faint but clear indications of kimberlite indicator minerals sources that are not unlike several of the patterns that have been found, for example, in Canada, where some of such patterns have eventually resulted in kimberlite discoveries. In the case of the Minnesota results, the data may indicate sources within the state, or quite possibly could be manifestations of long distance glacial sediment transport, possibly from known or unknown sources in neighboring states or in Canada. In summary, the results are a highly significant step forward in mapping our geochemical landscape, in clarifying mineral potential, in provision of reference data useful to environmental protection, public health, and exploration, and in supporting follow-up with respect to potential mineralization.

INTRODUCTION

Minnesota is a region with high potential for discoveries of economic base metal, precious metal, and gemstone deposits. The Minnesota Geological Survey (MGS) therefore maintains public knowledge that supports mineral exploration and mineral development, in cooperation with Minnesota Department of Natural Resources (DNR) and Natural Resources Research Institute (NRRI).

Indicator mineral methods are a field of mineral exploration methods that is advancing rapidly (Thorleifson and McClenaghan, 2003; McClenaghan et al., 1997). Indicator mineral methods rely on sampling of clastic sediments such as glacial and stream sediments, and detection of mineral deposit indicators dispersed by mechanical processes. These methods are part of a spectrum of clastic sediment-based approaches ranging from boulder tracing to detection of detrital debris or their weathering products by chemical analysis of soil parent materials and sediments. These methods are part of the array of mineral exploration tools that are now used in the search for base metal, precious metal, and gemstone deposits. Methods applied directly to prospective rocks at the preliminary stages of grassroots prospecting and the advanced stages of property evaluation include visual inspection, petrography, and litho-geochemistry. Intermediate between these phases of exploration are methods for remote detection of mineral deposits, achieved by geophysical or satellite observation, or by the detection of mineral deposit indicators transported from source. Whereas application of exploration geophysical methods is directed at the mineral deposit and/or associated alteration by detection of electrical, gravity, magnetic, seismic, or thermal properties, geochemical and indicator mineral methods involve tracing of material dispersed from source. While purely geochemical methods rely on indicators dispersed from source by aqueous and/or gaseous chemical processes, indicator mineral methods are based on clastic indicators that have been dispersed from source by mechanical means alone. Elemental analyses of sediments, as in till geochemistry, may be used to detect a combination of chemical and clastic signals, although a survey usually is directed at one signal or the other. For example, the B horizon might be sampled and appropriate analytical procedures applied to seek a dominantly chemical signal, while the C horizon might be sampled, as was the case in the survey presented here, and analyzed to seek primarily a clastic signal residing in mineral grains or their weathering products. In the case of visible indicator mineral grains, the signal is attributable to mechanical dispersal processes alone. The scope of these mineral-grain-based methods is expanding from well-established procedures, such as those for gold grains and kimberlite indicator minerals, to new approaches for targets such as base metals.

New information therefore is required to help adapt these methods to Minnesota geology, to demonstrate their application to Minnesota geology, to map regional background trends, and to map characteristics of the sediments that govern the manner in which the methods may be applied. Concurrently, efforts to obtain this regional information were recognized as an opportunity to obtain enhanced information on regional soil chemistry, a key factor in many topics, including considerations related to public health.

In mid-2004, plans to do so at MGS coincided with similar plans being developed by WMC Resources Ltd. (WMC). By entering into an agreement to cooperate on a survey, both parties were able to increase their effectiveness and likelihood of success. The agreement between MGS and WMC specified a survey design that satisfied the objectives of both parties, outlined a cost-sharing agreement in which about 5%

of the costs were borne by MGS, and specified that all resulting data would be made public by early 2007, allowing WMC a reasonable period to conduct their follow-up.

The State of Minnesota and immediately adjacent regions were sampled at a spacing of about 30 km. Target cells across Minnesota were designated at quarter-degree latitude and half-degree longitude spacing. Within each target cell, till from between 1 and 2 m depth was sampled at an arbitrarily chosen site by filling a 15 liter plastic pail. At a few sites, vertical profiles were collected.

In addition, three transects were sampled to the north in Canada, to assess the background inherited by long-distance transport of glacial sediment, to obtain reference samples from the Thompson nickel belt, and also to extend sampling to the limit of Hudson Bay-derived carbonate-bearing sediments in order to better constrain regional trends in sediment carbonate content. Three control samples from Kirkland Lake, Ontario, known to be anomalous with respect to kimberlite indicator minerals, also were added to the batch. The resulting sample set thus consisted of 250 samples covering Minnesota and immediately adjacent regions, 20 samples from Manitoba and northwestern Ontario, and three Kirkland Lake standards. Upon completion of the survey, the samples were randomized, given numeric laboratory identifications, and were then shipped to the sample processing contractor.

This report presents data resulting from the survey. Included are data for sample location, description of the sampled sediments, lithological analyses that include texture, matrix carbonate content, and pebble lithology based on the 8-16 mm fraction, mineralogy of the heavy mineral fraction, geochemistry of the <63-micron fraction, geochemistry of the heavy mineral fraction, visible gold grain morphology and count, mineral chemistry, and indicator mineral counts.

REGIONAL GEOLOGY

The Quaternary geology of Minnesota (Hobbs and Goebel, 1982) is dominated by till related to Late Wisconsinan glaciation. In the central and northeastern regions of the state, the till is sandier while sand and gravel deposits are more common. In addition, older tills occur, particularly in the subsurface, while sand and gravel are extensive in the central part of the State, and the silty clay deposits of Lake Agassiz dominate the northwest. The Late Wisconsinan tills are readily divisible into the carbonate and shale-bearing sediments of the Des Moines Lobe and associated St. Louis sublobe (Figure 5) that were derived from the Red River valley/Lake Winnipeg region, the red-volcanic-rock-bearing sediments derived from the Lake Superior basin and deposited by the Superior lobe, and intervening sediments of the Rainy Lobe that were derived from the northeast and that are dominated by debris such as granite clasts (Figure 5). The Rainy lobe split as it diverged around the bedrock high of the Mesabi Iron Range, resulting in the Wadena lobe to the north which deposited sediment in west central Minnesota that was moderately rich in carbonate, and the Brainerd lobe to the south which deposited carbonate-poor sediment in east central Minnesota. Beyond the limit of Late Wisconsinan glaciation in the southeastern and southwestern corners of the state, older tills occur that are dominantly derived from the northwest, and thus bear a moderate level of carbonate and a low level of shale.

Minnesota bedrock geology (Morey and Meints, 2000) ranges from thin and discontinuous Mesozoic sedimentary rocks in the southwest, to Paleozoic carbonates and sandstones in the southeast, to a diverse array of Precambrian rocks that intersect the bedrock surface from parts of southwestern Minnesota to the entire northern portion of the State. The youngest of these Precambrian rocks include Mesoproterozoic sandstones extending southwest from Lake Superior, as well as volcanic rocks and Duluth Complex gabbros and associated rocks along the north shore of Lake Superior. Paleoproterozoic rocks include the Sioux Quartzite of the southwest, and a broad array of rocks in central Minnesota, including the widely-mined iron formation of the Mesabi Range. The oldest rocks exposed at the bedrock surface, of Archean age, occupy roughly the northwestern third of the State, and consist of greenstone belts and intervening intrusions and metamorphic rocks ranging in grade up to gneiss and migmatite.

FIELD METHODS

Bearing in mind the need to conduct basic compositional mapping of sediments for multiple applications, till was chosen as the sampling medium for the regional survey due to the role that till plays as the source of other Quaternary sediments in the region, while also being the sampling medium likely having the clearest pattern of regional derivation. In addition, till is the principal control on geochemical trends in media such as soil. Till also permits accompanying lithological analysis of the gravel fraction and the silt and clay fine fraction, which may be used to assess the provenance of the sediments in relation to bedrock sources. In contrast, fluvial or glaciofluvial sand is irregular in distribution, highly variable in composition, and lacks consistently accompanying coarse and fine fractions. Till thus provided by far the most consistent and comprehensive sampling medium available. In addition to satisfying basic mapping objectives, the field procedures were equally designed to ensure collection and processing of a set of till samples that would, to the extent possible in a manageable and appropriate first campaign, detect indicator mineral and elemental plumes derived from potential economic mineralization, accompanied by an enhanced interpretation of glacial sediment provenance that would support interpretation and follow-up. A 30-km spacing statewide was considered adequate to consistently quantify known major features in the drift composition, to identify broad indicator mineral plumes in areas of thick sediments, and to map regional trends in background for geochemical and indicator mineral variables. Furthermore, this spacing was considered adequate for determination of what spacing would be required to carry out a follow-up survey to confidently detect individual mineral deposits such as isolated kimberlite pipes that would be missed, if present, by the low density survey in areas of thin and discontinuous sediments in the northeastern part of the State.

In addition, till was collected along three northern transects at a spacing of 75 to 100 km. These transects were designed to obtain data that would provide insight into the nature of sediments in Minnesota that were inherited by long distance glacial sediment transport from Canada. These results were regarded as needed for survey interpretation, given the likelihood that something would be found in Minnesota that could possibly be attributed either to derivation within the state, or to long distance transport from Canada. It was anticipated that something found within the State that was lacking in the Canadian samples would more readily be attributed to derivation within the State, while a compositional constituent in Minnesota sediments that could be shown to be abundant in the Canadian samples would be more likely to be attributed to long-distance glacial sediment transport. In addition, extension of the Manitoba

transect through the Thompson nickel belt resulted in collection of two samples that could be considered controls, as anomalous numbers of Cr-diopside indicator minerals were anticipated, based on previous surveys (Matile and Thorleifson, 1997). Furthermore, all three transects extended to within the contiguous limit of calcareous till derived from the Hudson Bay Lowland, allowing comparison of carbonate in Minnesota sediments to carbonate near Hudson Bay, given the possibility that some calcareous debris in Minnesota could possibly have been derived from the Hudson Bay Lowland.

Sampled sites were to be considered an example of till in the target cell, collected at a depth that would to the extent possible minimize the effects of carbonate leaching and pedogenic alteration. It was anticipated that a portion of each till unit resting on bedrock in any given region would have been reworked into overlying tills, resulting in a progressively fainter signal several tills up from initial dispersal from source. With each succeeding till, the signal was anticipated to be fainter, so in some cases it was accepted that the sampling would fail to detect clastic dispersion due to dilution of the signal to a level indistinguishable from background. Lower tills therefore were favored, such as sampling a stream cut rather than a nearby road cut, so long as this consideration did not significantly slow progress. Lower tills were also anticipated to possibly have a preserved sulfide component that would be of great interest to mineral exploration. It was, however, anticipated that an exception to this consideration would be cases where it was the judgment of the sampler that the lower till was entirely derived from an area smaller than the region between the site and the next sample up-ice. In this case, the lower till would have been considered too locally derived, and thus not able to provide the required information, so an upper till was to be favored. In most cases, however, whatever till was available at a readily accessible road cut, stream bank, or shovel hole was sampled, and rarely was there an easily accessed site where there was a choice between till stratigraphic units. Where an accessible exposure provided the opportunity to sample two or more till units, however, multiple samples were to be collected.

Plans were made for one till sample to be collected within each cell covering 0.25 degree of latitude and 0.5 degree of longitude, resulting in a spacing of approximately 30 km. Rows at 0.25 degree latitude spacing were labeled from A to Y, from A in Iowa to Y in Manitoba. The columns at 0.5 degree longitude spacing were numbered from 1 to 16, from 1 in the Dakotas to 16 in Lake Superior. Samples were given a field identification according to their row and column, such as F5 or M12. If two or more samples were collected at a site, the format used was e.g. F5-a and F5-b.

Where till was not readily accessible within a cell, no sample was collected. Effort was made to sample every cell located at least in part in Minnesota, as well as adjacent cells where the edge of a cell coincided or nearly coincided with the State boundary. In the case of cells located partially outside Minnesota, the Minnesota portion of the cell was not favored, and till was sampled wherever it was readily available within the cell.

Field equipment utilized by the sampling crews included a road atlas, 1:250,000 sample location maps, surficial geology maps, 15-liter plastic sample pails, shovel, GPS unit, Munsell color book, acid bottle, permanent markers, datasheets, labels for inside pail, spare batteries for GPS, cell phone, and a first aid kit. Vehicles utilized for the survey were two-wheel drive trucks and vans suitable for all-weather roads. A typical increment in sampling was for an MGS Quaternary geologist, with an assistant when possible,

to travel to the field on a Monday morning, spend four days sampling, and return to unload samples in St. Paul on a Friday afternoon.

All field activity followed guidelines mutually agreed upon by MGS and WMC relating to safety, environmental protection, and community relations. At the sites, a 15-liter till sample was collected from below the B-horizon, wherever possible clearly on public lands, along roadsides at an existing exposure such as a road cut or riverbank, or from a shovel hole (Figure 1). Sampling depth was commonly between 0.6 m and 2 m, but greater depths were considered fully acceptable. Where discontinuous stratified sediments cover till, an auger was in some cases used to test for the presence of till prior to digging with a shovel. Clasts larger than about 3 cm were rejected by hand. No attempt to homogenize the sediment was made, and the processing laboratory was advised that subsamples should be taken with this in mind. No contact with jewelry was permitted, and use of tools with coatings was minimized. Caution was exercised to avoid any disturbance of buried cables. Sample containers were 4 US gallon plastic pails. A permanent marker was used to label the upper & lower side of the lid and opposite sides of the pail. A water resistant tag was also labeled and placed in the pail on top of the sampled sediment. Tools were cleaned between sites, while bearing in mind that initial excavation at the subsequent site would reduce the chance of carryover. All fieldwork was completed between September 14, 2004 and October 29, 2004.

Locations were marked by hand on 1:250,000 topographic maps, and data sheets were completed in the field. The field data included site identification, WGS84 latitude, WGS84 longitude, date, collector, topographic map name, site name based on a nearby geographic feature, upper limit of the sampling depth range, lower depth limit, moist Munsell color as hue, value, and chroma, reaction to dilute hydrochloric acid (none, weak, moderate, strong), texture (clayey, silty, sandy, loam, gravelly), consistency (soft, firm, hard), gravel fraction lithology (Riding Mountain for shale-bearing sediments, Winnipeg for carbonate-bearing and shale-free sediments, Rainy for sediments lacking rock types derived from the Red River valley or Superior basin, and Superior for sediments bearing rocks of Lake Superior provenance), presence of carbonate pebbles, presence of secondary carbonate, and assessment of likely stratigraphic unit being sampled. Uncategorized notes were also taken on features such as texture, structure, mottling, pedogenesis, stratigraphy, and position relative to regional undissected landscape.

The resulting sample set consisted of 250 samples in the Minnesota survey (Figure 2), and 20 samples in the three northern transects, which extended to Gillam, Manitoba, Pickle Lake, Ontario, and Geraldton, Ontario (Figure 3). In order to obtain samples that were known to be anomalous and therefore would be a check on sample processing, three samples from the Kirkland Lake kimberlite field in Ontario were added to the batch. These sediments were collected by Beth McClenaghan of the Geological Survey of Canada (GSC), and processed under the supervision of Harvey Thorleifson, then of the GSC, in 1996, from two sites previously found to be anomalous with respect to kimberlite indicator minerals. One of the sites was more anomalous in oxide indicator minerals, while the other site was more anomalous in silicate indicator minerals. The three control samples used for the Minnesota survey were from the more silicate-indicator-mineral-rich reference material. To prepare these reference samples in 1996, several large pails of sediment were collected at each site, and the material was carefully homogenized. A representative test sample was analyzed to confirm indicator mineral abundance. Upon confirmation of the approximate indicator mineral abundance, the bulk samples were split in order to obtain an expected indicator mineral

frequency of about 10 kimberlite indicator minerals in the 0.25-2.0 mm fraction. The oxide reference is stored in Ottawa in vials, while the silicate reference is stored in bags. The control samples used in the Minnesota batch were further prepared in 1996 by mixing the silicate reference material with till from near the north end of Lake Winnipeg, as samples labeled with the prefix 96TCA-HT. The silicate reference material has previously been analyzed by GSC, and found to contain about twenty Cr-pyrope grains, and ten Mg-ilmenite grains in each subsample.

Following completion of all sampling, samples were relabeled with a laboratory identification number in random order relative to location. This was done to ensure that trends in the data due to gradual regional compositional change could be confidently distinguished from any possible analytical drift in the laboratory, including subjective personal criteria for visual selection of indicator minerals. With the addition of 3 Kirkland Lake control samples, the total number of samples was 273. Upon assignment of lab numbers, numbers 1 and 2 were set aside for use as additional control samples, and the batch was renumbered from 3 to 275.

Samples collected in Manitoba were shipped directly to the sample preparation laboratory in Ottawa, Ontario. Laboratory number labels were sent to Ottawa for these samples. Samples collected in Minnesota and adjacent states, as well as from Ontario, were accumulated at MGS, prior to reordering, re-labeling, and shipment by truck in November 2004 (Figure 4). Permission for export of material that could potentially be perceived as soil was obtained in advance from the Government of Canada. Samples collected in Ontario had been transported to St. Paul on the basis of acceptance by border crossing agents that the materials can be considered not to be soil, due to lack of admixed humus, so no formal arrangements had to be made for export to Minnesota in this case.

LABORATORY METHODS

Upon arrival of the Minnesota and Ontario samples in Ottawa in November 2004, this sample batch was merged with the shipment of samples from Manitoba, as well as the control samples that had been taken from storage in Ottawa after agreement was obtained from GSC for provision of these materials. Priority in initial indicator mineral recovery was placed on sites north of 47°, while second priority was placed on those south of 45°, due to WMC priorities. Highest priority samples were processed first, although some crossover between the areas was arranged for, to maintain as much geographic randomness as possible in the initial processing. In subsequent analyses, all batches were fully randomized.

At the sample-processing laboratory, Overburden Drilling Management Ltd. (ODM), four quarter-liter subsamples were removed from each 15-liter till sample (Figure 5). The splits were weighed before and after air drying, at less than 40° C to avoid loss of volatile Hg, in order to determine moisture content as a basis for correcting weight of the larger sample. One split was retained as a laboratory archive, for example as a reference should an investigation of possible laboratory contamination be required. A second was screened using a stainless steel 230 mesh sieve, in order to recover about 50 g of the <63 micron fraction for geochemical and mineralogical analyses, as well as a replicate for 5% of the samples. The oversize fraction in this preparatory step was discarded. The third split was shipped to MGS, to be processed for textural analysis of percent sand, silt, and clay by sieve and hydrometer analysis, as well as

recovery of the 1-2 mm fraction for future lithological analysis. The fourth set of splits was shipped to MGS for temporary storage prior to donation to USGS.

The remaining material, ~14 liters, was disaggregated with the aid of gentle mechanical agitation and suspension in a solution of water and sodium hexametaphosphate (Calgon®), and screened at 2 mm. The >2 mm fraction was washed, dried, screened at 4, 8, and 16 mm, weighed, and shipped to MGS for lithological analysis. The <2 mm fraction was pre-concentrated with respect to density using a shaker table, using a multiple-pass protocol designed to maximize recovery of coarse silicate heavy minerals. Table reject was discarded, except in the case of 5% of the samples, to permit an audit of table recovery. Visible gold grains were recovered at the table and by panning of the table concentrate under a stereoscopic binocular microscope, and subsequently counted and classified with respect to morphology. Final density concentrates were prepared using a heavy liquid, methylene iodide (MI) diluted with acetone to a specific gravity of 3.2. The ferromagnetic fraction that largely consists of magnetite was then removed, weighed and retained, while the MI light fraction was discarded. The nonferromagnetic concentrates were then screened at 0.25 mm, and the 0.25-2.0 mm fraction was visually scanned under a stereoscopic microscope for possible and probable mineral deposit indicator minerals. While the 0.5-2.0 mm fraction was examined without further treatment, the 0.25-0.5 mm fraction was processed into multiple magnetic susceptibility fractions, to reduce the amount of material examined and to add information to guide visual selection. A ~2000-grain split of the 0.063-0.25 mm nonferromagnetic heavy minerals was prepared for later visual mineralogical analysis of the nonferromagnetic concentrate as a whole at another lab.

In preparing for submission of the fine fraction, the randomized batch of 273 samples numbered 3 to 275 was supplemented by 14 duplicates numbered 276 to 289. A total of 16 reference materials also were added. These standards consisted of 7 splits of WMC reference WM5, 7 splits of WMC reference HL5, and 2 splits of GSC reference TCA8010, a gold standard originally prepared by Harvey Thorleifson (Thorleifson and Kristjansson, 1993). The TCA8010 splits were assigned lab number 22B and 262B, WM5 splits were labeled 1, 62B, 102B, 142B, 182B, 222B, and 282B, while HL5 splits were labeled 2, 42B, 82B, 122B, 162B, 202B, and 242B. In the case of the <0.25 mm nonferromagnetic heavy mineral concentrate, 14 samples were divided approximately in half to prepare duplicates, which were designated samples 276 to 289. No reference materials were added to this batch, due to the unavailability of appropriate materials.

The fine (<63 micron) fraction was analyzed geochemically at ALS Chemex in Vancouver, based on ~1 gram of sediment processed using their procedure ME-MS61. In procedure ME-MS61, a four-acid, near-total digestion was used, including an HF-HNO₃-HClO₄ acid digestion, and an HCl leach. This preparation dissolves nearly all elements in the majority of geological materials. Only the most resistant minerals, such as zircons, would be partially dissolved using this procedure. Analysis for 47 elements by a combination of Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma - Atomic Emission Spectrometry (ICP-AES) followed. The elements analyzed and ranges in ppm unless otherwise noted are as follows: Ag (0.02 - 100), Al (0.01% - 25%), As (0.2 - 10,000), Ba (0.5 - 10,000), Be (0.05 - 1000), Bi (0.01 - 10,000), Ca (0.01% - 25%), Cd (0.02 - 500), Ce (0.01 - 500), Co (0.1 - 10,000), Cr (1 - 10,000), Cs (0.05 - 500), Cu (0.2 - 10,000), Fe (0.01% - 25%), Ga (0.05 - 500), Ge (0.05

- 500), Hf (0.1 - 500), In (0.005 - 500), K (0.01% - 10%), La (0.5 - 500), Li (0.2 - 500), Mg (0.01% - 15%), Mn (5 - 10,000), Mo (0.05 - 10,000), Na (0.01% - 10%), Nb (0.1 - 500), Ni (0.2 - 10,000), P (10 - 10,000), Pb (0.5 - 10,000), Rb (0.1 - 500), Re (0.002 - 50), S (0.01% - 10%), Sb (0.05 - 1,000), Se (1 - 1,000), Sn (0.2 - 500), Sr (0.2 - 10,000), Ta (0.05 - 100), Te (0.05 - 500), Th (0.2 - 500), Ti (0.01% - 10%), Tl (0.02 - 500), U (0.1 - 500), V (1 - 10,000), W (0.1 - 10,000), Y (0.1 - 500), Zn (2 - 10,000), Zr (0.5 - 500)

The fine (<63 micron) fraction also was analyzed at ALS Chemex in Vancouver using ~30 grams by fire assay using procedure PGM-ICP23, in which a 30 g nominal sample weight is analyzed for Pt, Pd and Au by fire assay and ICP, at ppm ranges of Pt (0.005 - 10), Pd (0.001 - 10), Au (0.001 - 10).

The <0.25 mm nonferromagnetic heavy mineral concentrates were analysed by the non-destructive Instrumental neutron activation analysis (INAA) technique, using ALS Chemex procedure ME-NAA01, which is carried out by subcontractor Actlabs of Ancaster, Ontario, using their procedure 3A. Elements analyzed and lower detection limits, in ppm unless otherwise indicated are as follows: Au 5 ppb, Ag 5, Mo 20, Ni 200, Zn 200, Hg 5, As 2, Ba 200, Br 5, Ca 1%, Ce 3, Co 5, Cr 10, Cs 2, Eu 0.2, Fe 0.02%, Hf 1, Ir 50 ppb, La 1, Lu 0.05, Na 0.05%, Nd 10, Rb 50, Sb 0.2, Sc 0.1, Se 20, Sm 0.1, Sr 0.2%, Ta 1, Tb 2, Th 0.5, U 0.5, W 4, and Yb 0.2. The irradiated concentrates were then stored at ODM to permit follow-up mineralogical analysis following several months of cool-down. In addition, a 0.5 gram split of the concentrates was analyzed by Actlabs procedure code 3C, which is designed to test for base metals and associated elements in heavy mineral concentrates, such as those known to contain sulfide minerals, or to possibly contain at least remnant sulfide minerals and associated minerals that could be indicative of base metal mineralization. The Actlabs Code 3C procedure uses an aqua regia extraction Inductively Coupled Plasma Optical Emission Spectrometry (ICP/OES) package, providing results for the following elements, with an indication of the lower detection limit: Ag 0.2 ppm, Cu 1 ppm, Cd 0.5 ppm, Mn 2 ppm, Mo 2 ppm, Ni 1 ppm, Pb 2 ppm, Zn 1 ppm, and S 0.01%.

An estimate of calcite and dolomite content in the fine fraction was obtained using the Chittick gasometric method (Dreimanis, 1962) at the GSC in Ottawa.

Visually selected possible and probable indicator mineral grains were mounted in epoxy disks, polished, and analysed for Al₂O₃, CaO, Cr₂O₃, FeO, K₂O, MgO, MnO, Na₂O, SiO₂, TiO₂, and ZnO at the electron microprobe facilities of the Gemoc Labs in New South Wales, Australia, followed by additional trace element analyses where warranted. These data served as the basis for categorization of the indicator minerals in some cases.

At MGS, the 8-16 mm gravel fraction was visually classified with respect to lithology, and the classes were weighed in order to obtain weight percentages. In addition, textural analysis of percent sand, silt, and clay was completed by sieve and hydrometer analysis. At Consorminex in Gatineau, Québec, a portion of the 2000-grain split of the 63-250 micron nonferromagnetic heavy minerals was mounted in araldite on a glass slide, and 300 grains were visually identified by a highly experienced operator using a stereoscopic binocular microscope fitted for crossed polarized light.

RESULTS

Location and descriptive data are presented in the first appendix. Included are the field number, the lab number, WGS84 latitude and longitude, date of collection, name of collector, topographic map sheet name, site name based on nearby geographic feature, mean sampling depth, minimum sampling depth, maximum sampling depth, Munsell color, reaction to hydrochloric acid, field assessment of texture, degree of consolidation, provenance, presence of carbonate pebbles and secondary carbonate, and identification of the likely stratigraphic unit being sampled. From this table, maps follow in this appendix for reaction to HCl, texture, consistency, provenance, as well as presence of carbonate pebbles and secondary carbonate. In all appendices, the maps depict data for the Minnesota samples, including samples in adjacent jurisdictions along the border only. Data from the northern transects in Canada are only presented as tables.

Lithological analyses are presented in the next appendix. The first table presents data related to initial processing of the full-pail sample at Overburden Drilling Management in Ottawa, and presents total moist weight, weight after removal of splits, total gravel weight, weight of finer material processed for indicator minerals, moisture content determinations based on drying of the four subsamples, and weight of the gravel size fractions. Results of textural analyses completed on one of the subsamples at Minnesota Geological Survey are then presented, followed by matrix carbonate analyses completed at the Geological Survey of Canada in Ottawa. Data for visual categorization of the 8 – 16 mm pebbles completed by the authors at Minnesota Geological Survey are then presented, first as weight, and then as weight percent. These data are then presented in the form of maps for >2 mm gravel yield, percent sand, silt, and clay in the <2 mm fraction, calcite, dolomite, and total carbonate in the <63 micron matrix, followed by maps for the pebble lithology results.

As explained in Addendum 1, mineralogy of the nonferromagnetic 63-250 micron heavy mineral fraction data are presented in the next appendix, first at the highest level of subdivision, followed by comments from the person doing the visual identification, and then data combined in fewer groups. The following maps then present the heavy mineral count results, followed by the grouped data.

Geochemistry of the <63 micron fraction data are presented in the next appendix, including data for duplicates and standards. A similar appendix for the geochemistry of the nonferromagnetic, <250 micron heavy mineral fraction follows.

Indicator mineral data are then presented in the final data appendix, with the first several tables being derived from analyses at Overburden Drilling Management in Ottawa. The first table presents gold grain counts, as well as predicted assay for the heavy mineral concentrates, as a guide to interpreting the geochemical analysis of these fractions. This is followed by a table that presents detailed measurement of observed gold grains and remarks made at this stage of processing, in order of lab number following the prefix NA-01. The following table presents data related to preparation of the heavy mineral concentrates, followed by kimberlite indicator mineral counts based on visual identification supported by checks on a scanning electron microscope (SEM). Comments made at this stage of processing follow. The next table presents observations made during a scan of the 0.25 – 2 mm nonferromagnetic heavy mineral concentrates for the full range of mineral deposit indicators, having previously examined the concentrates for gold grains and kimberlite indicator minerals. Indicator mineral counts other than gold grains are then

summarized in the following table. Mineral chemistry analyses completed at GEMOC in Australia are then presented, beginning with clinopyroxene chemistry, which shows that the clinopyroxenes from the Thompson nickel belt in Manitoba differ from the grains scattered across Minnesota, for example in their Li concentration. Ilmenite data follow, and these data were used to refine the tentative identifications done in Ottawa, thereby confirming several Mg-ilmenite occurrences in Minnesota. Garnet chemistry follows, including major element chemistry, and both preliminary and final rare earth analyses. The Cr-pyrope grains are given categories based on the scheme of Thorleifson and Garrett (2000), with addition distinction of favorable mineral chemistry based on factors such as favourable Sc/Y data (Griffin and Ryan, 1995). Finally, chromite mineral chemistry is presented including an assignment to kimberlitic, lamproitic, ultramafic lamprophyre, or greenstone affinities, based on the classification scheme of Griffin et al. (1997). The following maps then show size of the heavy mineral concentrates, gold grain counts, kimberlite indicator mineral counts, and other indicator mineral occurrences.

SUMMARY

While the full results are presented as tables and maps in the appendices that accompany this open file report, several maps have been included as an addendum to this document, as examples of the results. These examples include carbonate pebbles, which show a clear pattern of sediment derivation from the northwest, granite and similar felsic intrusive and high-grade metamorphic pebbles, as an indication of sediment derivation from the shield terrane to the north and northeast, reddish volcanic pebbles as clear indicators of sediment derivation from the Superior basin, and shale pebbles, as an illustration of compositional zonation within the extent of calcareous sediments. Epidote is then presented as an example of results that are elevated in the central part of the state, in the zone between derivation from the Red River Valley/Lake Winnipeg region and derivation from the Superior basin, while goethite is elevated in the old tills of the southeast, ilmenite at least in the size fraction analyzed is elevated in a zone of the Superior sediments, while siderite is an example of a zone along the Minnesota River that perhaps is related to shale. With respect to geochemistry, cadmium in the silt and clay fraction is first presented as an element elevated in the southwest, perhaps shale-related and having a pattern similar to elements such as arsenic and molybdenum in this fraction. Barium in the silt and clay is then presented as an example of an element elevated along and beyond the upper Minnesota River in a manner similar to siderite, while bismuth in this fraction is elevated both in the southwest and the north-central region, presumably for varying reasons. Chromium in the silt and clay is then presented as an element that is clearly elevated in the northeast, while chromium in the heavy mineral fraction as analyzed by instrumental neutron activation analysis is then presented as an example of significant variation in relation to the sediment fraction that was analyzed, for various textural and mineralogical reasons. Zinc as indicated by partial acid extraction from the heavy mineral concentrate is then presented, including elevated results in southeastern Minnesota and northeastern Iowa in an area of known mineralization. Gold grain results are then presented, with a clear pattern of elevated regional background in the central part of the state, although it should be noted that these are microscopic gold grains that would not be seen by field panning except for rare exceptions. Other gold analyses presented in the appendices show anomalies in northern Minnesota near known mineralization. The Cr-pyrope map is then presented, to illustrate results for what is known throughout the world as the principal kimberlite indicator mineral, and as one of the most noteworthy kimberlite indicator mineral results in this survey, followed by the kimberlite indicator

minerals Mg-ilmenite, and Cr-diopside, which are progressively less specific to kimberlite than Cr-pyrope.

These results as a whole are now a significant new information resource with respect to environmental geochemistry topics such as understanding the distribution of deleterious elements in food and water, while providing insights into composition and transport history of the sediments that make up soil parent materials. Many variables provide insights into regional geology, and reflect known mineral deposits. Some of the data seem to provide faint insights into what may be mineralization that was not previously recognized, such as various base-metal and precious-metal-related elements that show patterns of varying clarity over the eastern portion of the state. None of these patterns are, however, obvious discoveries of something that was previously unknown, at the current stage of interpretation.

With respect to kimberlite indicator minerals, however, there are two noteworthy patterns, including a few Cr-pyrope garnets in an area from the Twin Cities to southwestern Minnesota, as well as Mg-ilmenites and Cr-diopsides in the far north-central part of the State. Sample spacing in the thin sediments of northeastern Minnesota was not adequate to fully test for the presence of sources such as potential single kimberlite pipes, although samples at a closer spacing are presently being processed by Natural Resources Research Institute to address this point. The current results, consisting of one grain per sample in a few samples, are similar to the results found in areas of thick multiple tills in, for example, southern Saskatchewan, where kimberlites are known to occur (Garrett and Thorleifson, 1995). It should be noted that only occasional kimberlites are diamond-bearing, and the present survey did not produce adequate data to assess diamond potential on the basis of mineral chemistry. These results are, however, faint but clear indications of kimberlite indicator mineral sources, which may be deeply weathered or otherwise at source, that are not unlike several of the patterns that have been found, for example, in Canada, where some of such patterns have eventually resulted in kimberlite discoveries. In the case of the Minnesota results, the data may indicate sources within the state, or quite possibly could be manifestations of long distance glacial sediment transport, possibly from known or unknown sources in neighboring states or in Canada. In the case of the Cr-pyrope occurrences, the samples tend to have been obtained from calcareous till derived from the northwest, but it is noteworthy that three of the grains are in Superior-basin-derived till, and the frequency of occurrences abruptly diminishes to the northwest. It therefore is suggested that the southern Minnesota Cr-pyrope occurrences may have been dispersed southwestward by an old Superior-basin ice lobe, and the mineral grains have subsequently been reworked into younger tills, an observation that is compatible with lithological data. In the case of Mg-ilmenites and Cr-diopsides in far-north-central Minnesota, a source close to the Canadian border, or in Canada, is implied.

In summary, the results are a highly significant step forward in mapping our geochemical landscape, in clarifying mineral potential, in provision of reference data useful to activities related to environmental protection, public health, and exploration, as well as in supporting follow-up with respect to potential mineralization.

ACKNOWLEDGMENTS

The highly productive partnership between Minnesota Geological Survey and WMC Resources Ltd. is acknowledged with much appreciation, as is excellent service provided by Overburden Drilling Management in Ottawa, ALS Chemex in Vancouver, Actlabs of Ancaster, Ontario, the Geological Survey of Canada in Ottawa, GEMOC Labs in New South Wales, Australia, Consorminex in Gatineau, Québec, and the Minnesota Geological Survey sediment lab. The assistance of Manitoba Geological Survey in obtaining samples in Manitoba also is acknowledged with sincere appreciation.

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Figure 1. Typical field sampling conditions

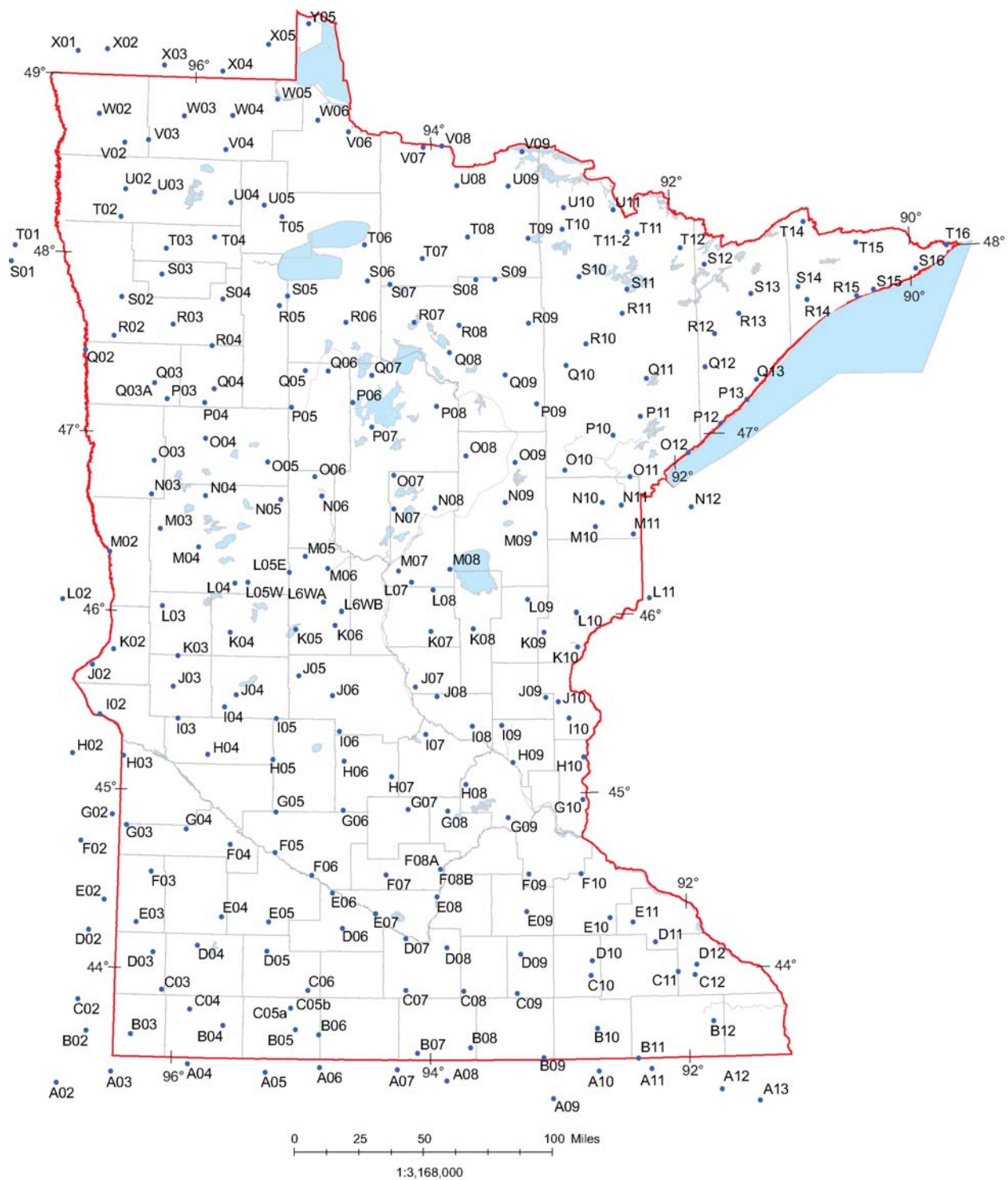


Figure 2. Location of Minnesota survey sample sites

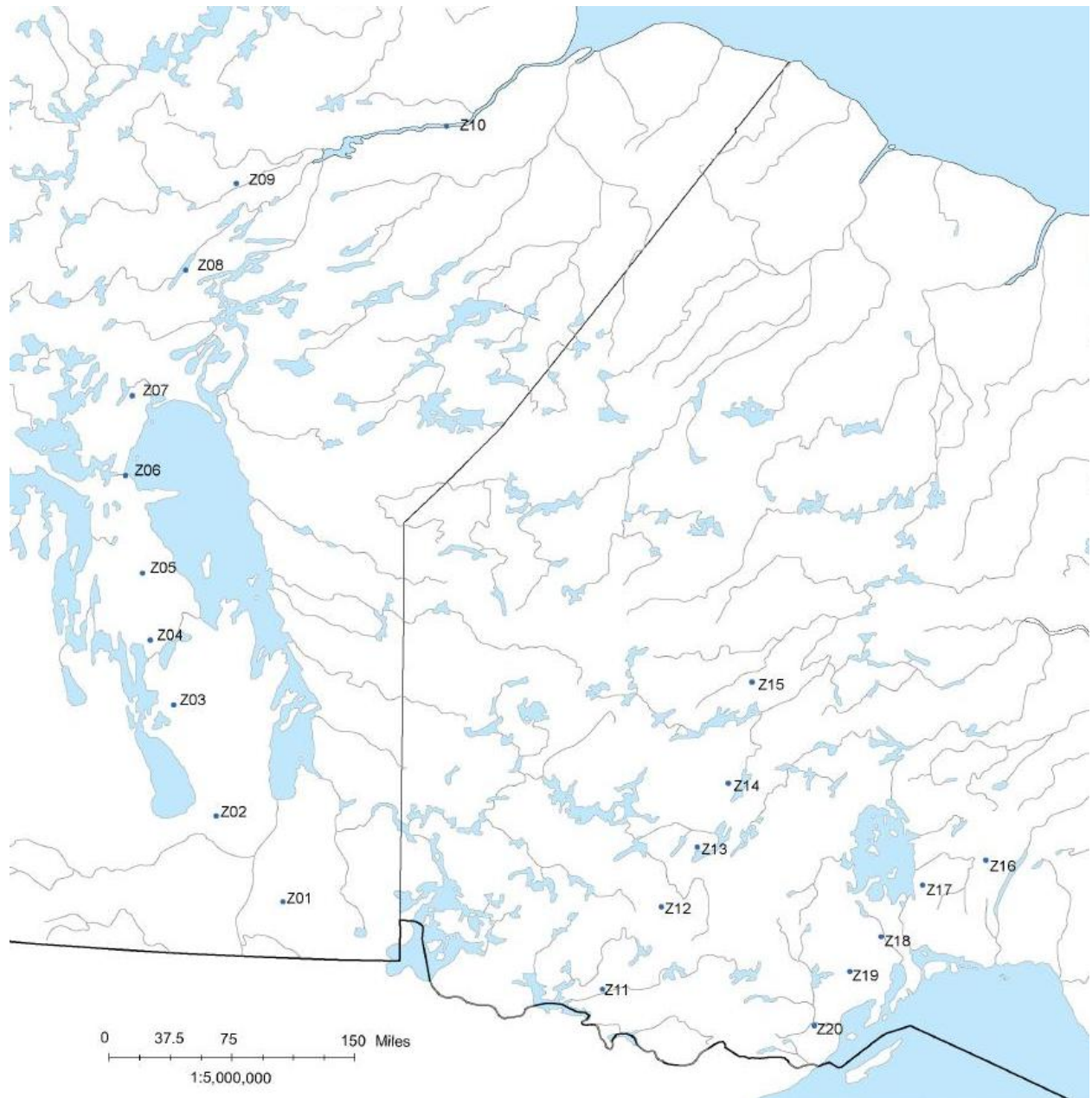


Figure 3. Location of northern transect sample sites



Figure 4. Sample shipment, Minnesota and Ontario samples

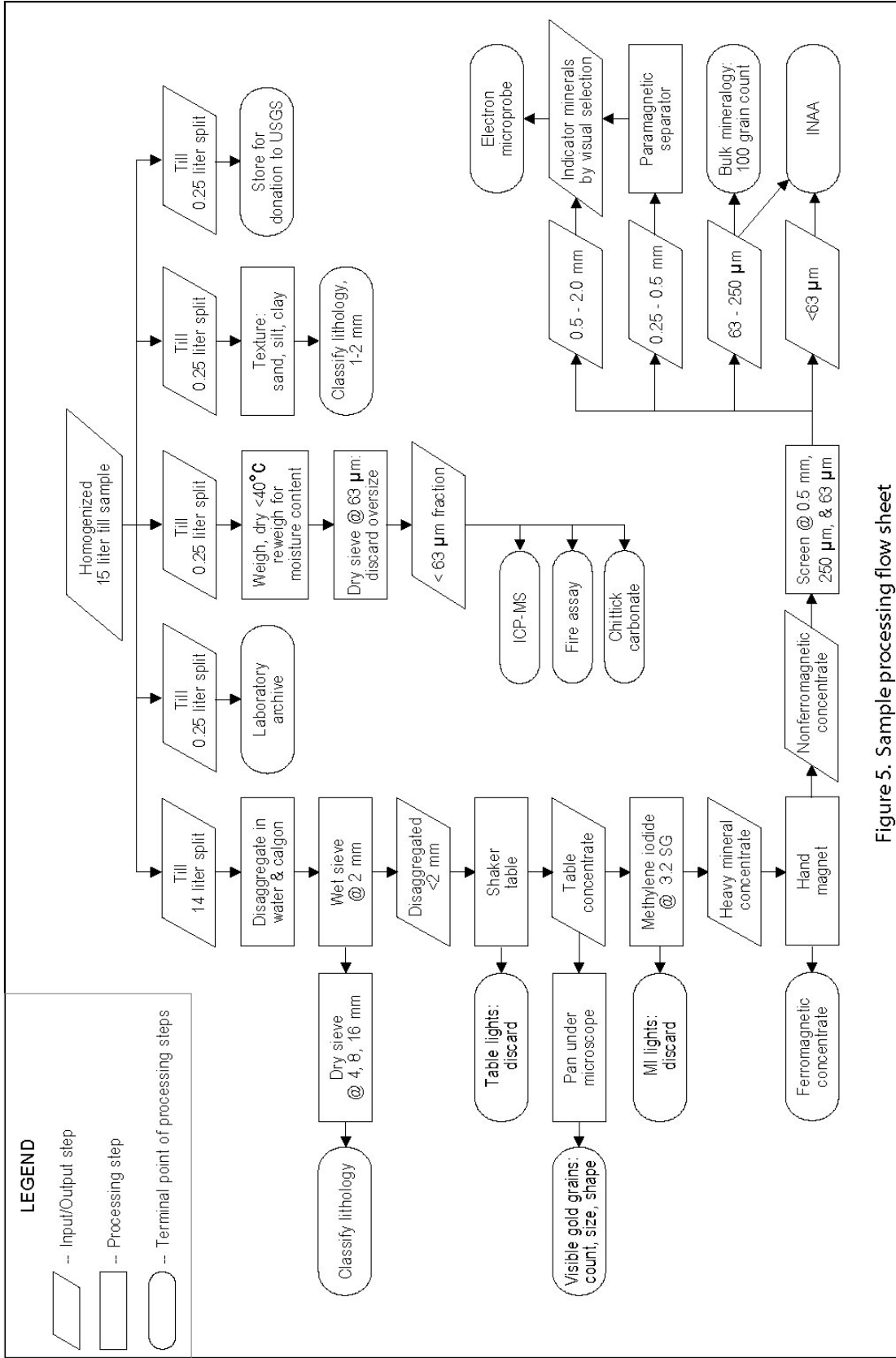


Figure 5. Sample processing flow sheet

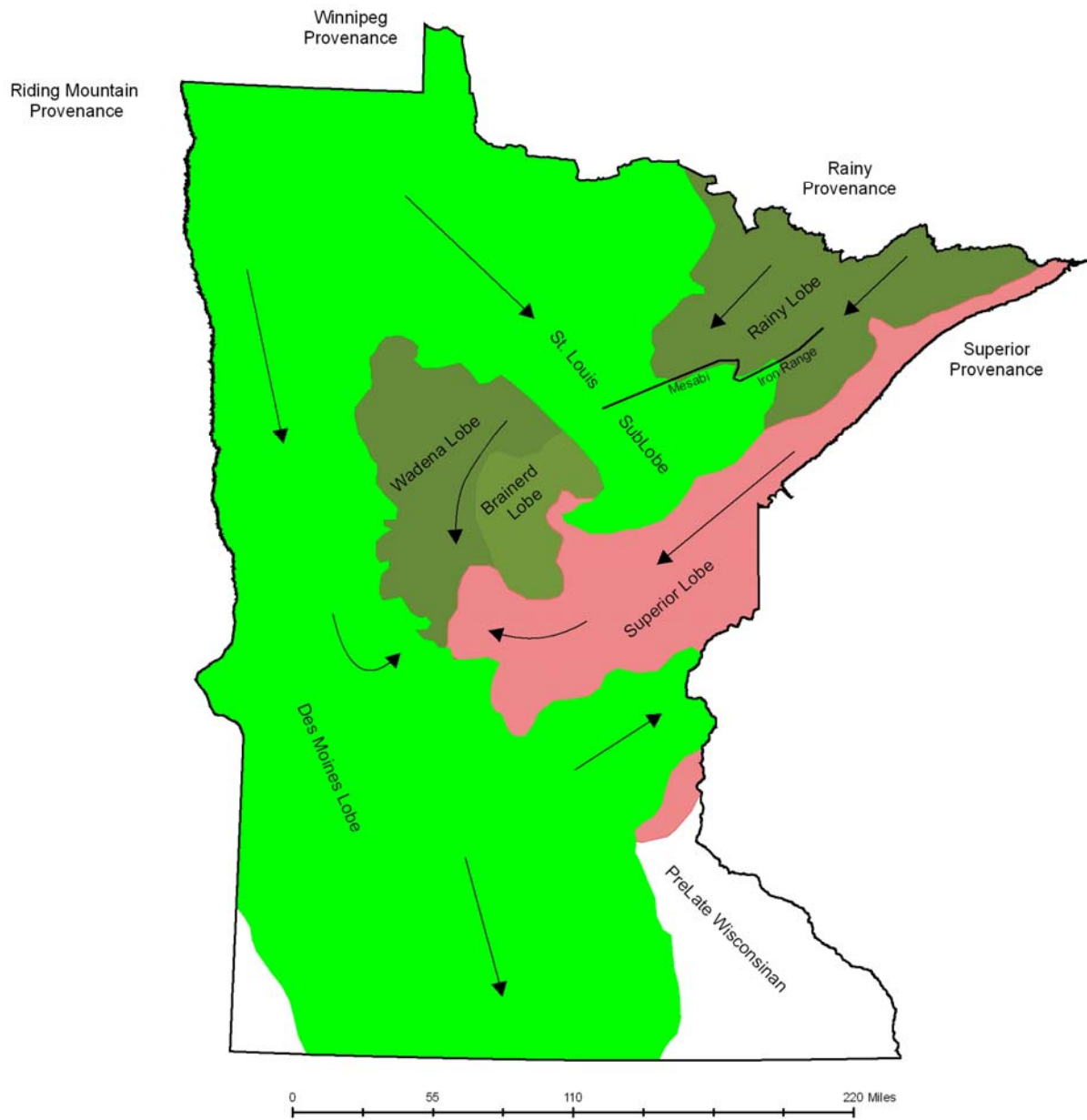


Figure 6. Overview of till provenance trends

Addendum 1: NOTES ON HEAVY MINERAL COUNTS

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May 1, 2005

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INTRODUCTION

DESCRIPTION OF HEAVY MINERALS

IMAGES – low resolution versions of images available from the MGS web site

INTRODUCTION

Heavy mineral analysis was done on the 63-250 μm , >3.2 s.g., non-magnetic mineral fraction of 273 till samples, (samples NA-01 3 to NA-01 275) mounted in epoxy cement on 1"x2" petrographic glass slides.

A Zeiss, Stemi SR, stereoscopic microscope with polar and Nicol, in conjunction with a Leitz petrographic microscope, was used to identify and count the heavy minerals fractions. The ribbon method was used to count 300 grains. A computer program was used to enter the data by keyboard in a similar manner as with a Swift blood cell counter.

The internet addresses in this report are hypertext links to images stored at www.consorminex.com

Most of these images as well as a description of the methodology used for making slides and counting can also be found in: Dallimore, S.R. and Matthews, J.V. Jr. 1997. The Mackenzie Delta Borehole Project. Environmental Studies Research Funds Report No. 135. Calgary, 1 CD-ROM

The digital images of the grain mounts (slides) were taken at 2400dpi with a scanner. Examples of grains representing the various mineral classes used in the study are indicated on the image. The image can be used as a map to find the same grain on the slide. Colourless minerals, such as kyanite, do not show up on the scan; the arrow on the image appearing to point to nothing.

A preliminary scan of all the slides was done before the mineral classes used for counting were established. The heavy mineral point count results are presented as an Excel spread sheet.

DESCRIPTION OF HEAVY MINERALS

No attempt is made here to interpret the data. However, the heavy minerals from the classification used for the point counts are described for the following reasons:

- 1) to describe the variation within a mineral group;
- 2) to allow comparisons with other heavy mineral studies;

- 3) to point out minerals that should be verified using SEM, microprobe, or XRD;
- 4) to describe the level of difficulty in identifying individual heavy minerals;
- 5) to point out minerals or mineral varieties, of possible interest and how they may be useful in interpreting the data.

Pyrite

Two classes were used to record the pyrite with most of the grains falling into the:

Pyrite, fresh consists of bright, unaltered, untarnished grains; fine to coarse multi-crystalline/complex twins grains; single crystals; broken crystals; and massive and irregular grains. Also included in this class are the pyrite fossils after vegetation other “biota” (rare, see sample NA-01 06, 131), framboidal pyrite grains (sample 200) and round pyrite grains.

Pyrite, goethite veneer consists of grains covered by a very thin coat of yellowish to orange or bright red goethite. The fresh pyrite can often be seen through the slightly translucent goethite or seen directly, where the goethite has flaked off and it is exposed. Some of these grains are so slightly altered that they can be considered only “tarnished” and it becomes difficult to decide if they should be classed as fresh pyrite or not (e.g.: sample NA-01 273, also see the image at <http://www.consorminex.com/apyr-var.htm> where a euhedral grain with goethite flaking away, can be seen in the left bottom corner).

These two classes could be combined, however, they may provide some indication of weathering.

The pyrite often occurs with siderite and in most samples, especially where it is plentiful, the pyrite is easily identified. The slide for sample NA-01 57, contains a polymineralic grain of pyrite and siderite.

Pyrite is absent in most of the samples. A handful of samples have one to ten grains, and ten samples contain over 10% pyrite. See Slide_NA-01 3.jpg

Hematite

Two classes of hematite were created:

Hematite, grey is medium grey, has a dull metallic lustre, and has an irregular shape. It varies little in appearance. There is almost always some red visible, on these hematite grains. Often it consists of the smallest of visible specks. Grains which were more than 50% red were counted as ***Hematite, red***. It is difficult to determine, at this point, if this distinction is of any importance.

The abundance of this mineral varies greatly from sample to sample. There are some nice anomalies. However the samples with 0% hematite are rare, those with more than 20% are also rare. Care should be taken not to count this mineral as ilmenite.

Many of the irregular shaped grains, grey and red, in the following image are typical of those observed in the NA-O1 samples: <http://www.consorminex.com/ahem.htm> See Slide_NA-01 3.jpg; Slide_NA-01 36.jpg

Ilmenite

The ***Ilmenite, grey*** class includes the common, dull grey variety of ilmenite as well as black, high lustre ilmenite. The grey ilmenite composition is usually FeTiO₃ whereas the black ilmenite may contain Mn

or Mg, as well as other elements, in small amounts. The black, high lustre ilmenite can be very difficult to differentiate from chromite, black rutile, magnetite (if insufficient care has been taken to remove all magnetite grains) and a host of other black minerals. This is especially true if it is anhedral. Adding to the problem, was the continuous nature of the transition from grey to black. Furthermore, weathering and orientation of the grains would have made attempts to accurately classify them into two groups difficult.

Ilmenite, euhedral grains, present in many of the samples, are quite distinctive when their hexagonal, slightly tabular, form is evident. The grains tend to be small, very black, and have a high, sub metallic lustre. Broken crystals are also easily identified. When small, irregular, and occurring in samples with no euhedral grains, identification is much less certain. These small black grains can be easily confused with black rutile, other black ilmenites (from a different population), various anhedral black spinels etc. When not certain enough to call a black, high lustre, rutile or “ilmenite, euhedral”, based on morphology or intuition, the grain was classed as a ilmenite. This is not very satisfying, however, SEM/EDS or microprobe work would have to be done to better define the appearance of these minerals in the suite. Several small hexagonal leucoxene are almost certainly after ilmenite, euhedral (NA-01 90, 152). Both ilmenite varieties show important variations in abundance and as they are resistant minerals and have not formed in situ , in contrast with pyrite for example, they can be important indicators of provenance and sediment maturity.

The names of the ilmenite classes are working names probably not suitable for a final report. Ilmenite undifferentiated and “Mg or Mn ilmenite (it would have to be checked) might be more appropriate names. Maybe this hexagonal ilmenite is a well known accessory mineral to the hard rock geologists familiar with the study area? <http://www.consorminex.com/aim.htm> See Slide_NA-01 3.jpg; Slide_NA-01 173.jpg

Rutile

Most of the ***rutile*** grains are orange to red, including amber, euhedral and represent the classic one or two background rutile grains found in many samples from north eastern North America. A few samples, e.g.: NA-01 50, 90, 118, 125, 169, 173 with 1.7 to 2.3%, were relatively rich in rutile. These may be interesting anomalies for provenance studies; note that 2.3% represents 7 grains.

Rutile, black represents black, high vitreous lustre rutile. These are hi Fe rutiles with chemistry very similar to ilmenite. EDS results can be ambiguous; XRD is preferable for identification. However, their distinctive crystal habit, abrasion features or twinning characteristics make it possible to identify them when they are euhedral. It is certain that some black rutile grains have been counted as ilmenite. The rutile grains in the image at: <http://www.consorminex.com/arut.htm> represent well both classes of rutiles used to count the NA-01 samples. See Slide_NA-01 3.jpg; Slide_NA-01 36.jpg

Goethite

The goethite is orange-brown and red, and has an earthy to varnished lustre. Some samples contain grains that are pseudomorphs after euhedral pyrite or fossiliferous pyrite. In some samples, such as NA-01 137, 93.7% goethite, the goethite is fairly distinctive and could be classed separately in a more detailed study.

<http://www.consorminex.com/agoe.htm> The goethite in the NA-01 samples is similar to those in the image. Note pseudomorph after euhedral pyrite in bottom right corner. See Slide_NA-01 3.jpg; Slide_NA-01 173.jpg

Siderite

The siderite in the NA-01 suite is light brown/tan to orange. Some grains are off-white. Most are earthy and delicate; some are framboidal or after biota. In most samples where they are plentiful, they accompany pyrite. A few massive grains were noted.

Siderite's habit is quite variable and it is often difficult to differentiate some siderite grains from goethite. Although not as variable as the siderite in the following image, a few of the varieties found in the NA-01 samples are represented. <http://www.consorminex.com/asid.htm> See Slide_NA-01 3.jpg

Monazite

The few grains of monazite observed resemble classic, yellow to light orange, lentil shaped, greasy, translucent seen as a weak background mineral in many samples in north east and central North America. With the exception of sample NA-01-13, where 4 grains were observed, only 1-2 grains were noted. <http://www.consorminex.com/amnz.htm> See Slide_NA-01 36.jpg

Garnet

Garnets were classified using three groups:

Garnet, pink consists of garnet that vary from very nearly colourless to medium pink. The majority of the grains are angular however there are some euhedral grains.(the pink garnets are the purple of Gwynn and Dreimanis, 1979). They are probably almandine/pyrope (solid solution series). Its abundance varies from 0.3 to 35.3% and, as it is a resistant mineral, if the sporadic dilution effect of large fluctuations of other minerals such as pyrite is considered, it could be a useful provenance indicator.

The ***garnet, orange*** class consists of grains that are light to medium orange. Some can have a salmon colour. Some orange grains were difficult to distinguish from the pink garnet. The pink and orange colours seem to be somewhat continuous. It is not normally difficult to distinguish pink from orange garnets. None of orange garnets is very likely to be eclogitic. They are garnets that have a few % Ca resulting in an orange colour.

Garnet, rounded and etched consists of garnets which are well rounded and etched resulting in a pattern with curves and no particular order. Grains etched with a geometrical pattern resembling an echelon gridirons were not observed. These grains are however very similar, if not identical to some of the round and etched garnet grains (pink and orange) found in tills of Manitoba and Ontario which are thought to come from the Hudson and James bay lowlands Paleozoic sediments. The Hudson Bay Lowland grains display both etching patterns. These garnets are believed to be formed by multiple cycles of sedimentation and their textures are thought to be due to etching by intrastratal solutions. Rounded garnets could be a very powerful provenance tool. Some of the rounded garnets in the NA-01 suite lack the etching and are somewhat different from the typical "Paleozoic" garnets. There is possibly more than one population of rounded garnets. A study which carefully compares rounded, etched garnets from tills of Ontario with

those from Minnesota could help establish exactly which rounded garnets should be included in this class. Then, possibly, a more accurate means of determining the abundance and distribution of Paleozoic garnets in the tills of Minnesota could be set up.

A rounded etched Paleozoic garnet can be found at about 750400 on slide NA-01 108. Finally, one euhedral melanite grain was noted, but not counted, in slide NA-01 179.

<http://www.consorminex.com/agar-var.htm> See Slide_NA-01 3.jpg; Slide_NA-01 36.jpg; garnet-rnd-NA-01 36.jpg

Zircon

The principal class, *zircon, euhedral* (table abbrev. = ZR) is the most easily recognized variety. The grains display the classic background habit: moderately elongated, occasionally unbroken terminations, mostly colourless grains. Some abrasion of edges was allowed.

The *zircon, round and rounded* class includes detrital grains rounded by abrasion and grains that may have been formed round (genetically round). Grains are all very round and, other than a slight ovoid shape in some grains, show no aspects of euhedral zircons. NA-01 173, 7% rounded zircon, is a strong anomaly which could prove useful for provenance as well as weathering of sediments studies. The distinctive zircon, purple round grains are small, very round, and light purple.

Finally, angular zircons, with no evidence of crystal habit, were also counted separately. All angular zircons counted are colourless.

<http://www.consorminex.com/azirrd.htm> <http://www.consorminex.com/azireuh.htm>

See Slide_NA-01 3.jpg; Slide_NA-01 173.jpg

Kyanite

The kyanite grains observed in the NA-01 tills are all colourless, undeformed crystals consistent with the one to two grains found as background in many samples taken from the Canadian shield and adjacent areas. A few grains exhibited rounding. Other than two samples, NA-01 143 (1.3%, 4 grains) and 147 (1%, 3 grains), samples contained no more than one to two grains. See Slide_NA-01 39.jpg; Slide_NA-01 173.jpg

Staurolite

These anhedral, translucent, vitreous, orange grains easily recognized under reflected light. They can be confused with other minerals such as garnet and titanite therefore all the staurolite grains were confirmed using a petrographic microscope to ensure they possess low order birefringence colours under X-polars.

The grains in the following image are very similar to the staurolite in the NA-01 samples:

<http://www.consorminex.com/astd.htm> See Slide_NA-01 39.jpg

Titanite

Anhedral, light orange to amber, translucent, slightly greasy lustre, some with leucoxene alteration, titanite in the NA-01 samples, although easily recognized, were confirmed under X-polars (anisotropy, high order birefringence, anomalous blue extinction). Sample NA-01 244 is particularly anomalous with 4.3% titanite. <http://www.consorminex.com/asph.htm> See Slide_NA-01 39.jpg

Epidote

Most of the *epidote* grains tend to be on the light and murky side of the easily recognised, classic, pistachio/epidote yellow-green. A few samples, e.g. NA-01 84, 91 have epidote grains with a rather unusual habit; as if there were small bubbles in the grains,

Clinzoisite, a member of the epidote, was counted separately. The clinzoisite is very pale “epidote yellow” to white. Although in most samples these grains were counted with confidence, in some samples where the average size of grains was small, mistakes may have been made. Barite is one mineral that could have been mistaken for clinzoisite if a few grains are present. Any appreciable abundance of barite should be detectable as a Ba anomaly in the geochemistry of the heavy mineral or the various size fractions of the whole sediment.

Furthermore, since, the colour at least, of these two species appears to be in a continuous series, there is somewhat of a problem to count them accurately. A boundary based on a colour which varies fairly uniformly from almost white to bright yellow makes for qualitative results. This does not mean that the ratio of epidote to clinzoisite is not useful.

<http://www.consorminex.com/aepidote.htm> shows grains typical of many of the epidote seen in the NA-01 samples. The very pale grains are clinzoisite. See Slide_NA-01 36.jpg

Orthopyroxene

The orthopyroxene is elongated, very light brown to medium brown, and translucent to troubled.

Very few grains could be identified as hypersthene (using pronounced green-brown pleochroism as a criteria). This class could be considered as orthopyroxene undifferentiated.

Since a great number of clinopyroxene grains, in many of the samples, also had this range of brown colours, often associated with orthopyroxene and hypersthene in particular, the extinction angle of a great many pyroxenes, throughout the suite, had to be verified under X-polars in order to determine clino vs. orthopyroxene.

Orthopyroxene, colourless grains were counted separately. The grains tended to be more elongated than the brown and green orthopyroxene. There was a clear cut boundary between the two species.

As with clinopyroxene (below), the extinction angle of the grains was verified.

Slide_NA-01 10.jpg; Slide_NA-01 36.jpg

Bronzite

The grains identified as bronzites in this study are pyroxenes that have Schiller structure; a series of fine, bronze coloured, well ordered, parallel, ribbon-like inclusions and varying in density of distribution. On occasion, the effect is to give the grain a bronze sheen which, more or less, obscures the inclusions. No attempt was made to ensure that all the grains classified as bronzite were enstatite. This may seem at odds with the criteria for classification of the other minerals in this suite, however, it does provide practical, easily tabulated information. It also appears to be the method used to classify grains with Schiller structure in many of the pre-1960's studies of detrital minerals.

A good representation of bronzite, very similar to those found in the NA-01 suit, can be seen at:

<http://www.consorminex.com/abrz.htm> See Slide_NA-01 36.jpg

Clinopyroxene

The grains in ***clinopyroxene, undifferentiated*** are for the most part light brown or tan. Some green grains were also observed. Grains are fresh to weathered. The brown clinopyroxene grains resemble the orthopyroxene grains found on the shield. Consequently the extinction angle of great number of grains, for all samples, had to be verified. For badly weathered pyroxene, this verification was not always conclusive. Diopside were classified separately and can be recognized by their distinctive (7Up) bottle green. The grains tend to be somewhat stubbier than other clinopyroxenes.

www.consorminex.com/adps.htm See Slide_NA-01 10.jpg; Slide_NA-01 36.jpg

Clinoamphibole

The three classes of clinoamphibole used in the point count include:

Clinoamphibole, undifferentiated used for a fairly abundant pale green amphibole which is probably hornblende. The transition between this pale hornblende and the darker green hornblende is fairly clean.

Hornblende, green consists of the classic dark green prismatic, angular hornblende so common in the tills throughout the shield. In general, the grains were easy to identify and no stubby variety of hornblende grains, some of which can be surprisingly difficult to differentiate from ilmenite, was noted.

Hornblende, brown grains were very similar, in all other respect aside from colour, to the hornblende, green grains. Sample NA-01 258 with 9% brown hornblende is particularly rich.

<http://www.consorminex.com/ahbl.htm> (Very similar)

<http://www.consorminex.com/ahblp.htm> (Very similar, with the exception of the blue variety)

See Slide_NA-01 36.jpg

Leucoxene

Most of the leucoxene is white to buff, irregular in shape, and varnished to earthy in texture. A few tan to brown grains were noted. A few leucoxene after euhedral, hexagonal ilmenite were also noted.

See Slide_NA-01 3.jpg

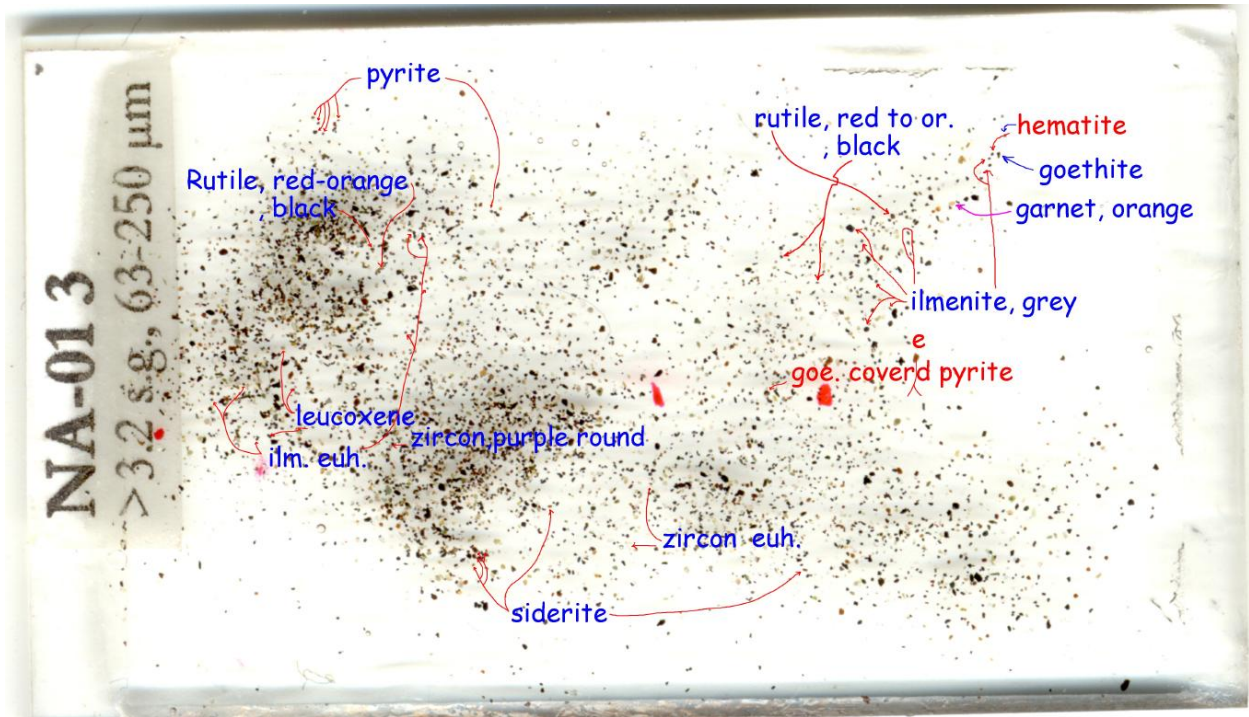
XI – colourless. r.i. > 1.56

Grains are colourless to cloudy, fairly low relief (however greater than the epoxy at 1.56 n), anisotropic, and display low birefringence colours. Some grains are rounded. These grains may be barite.

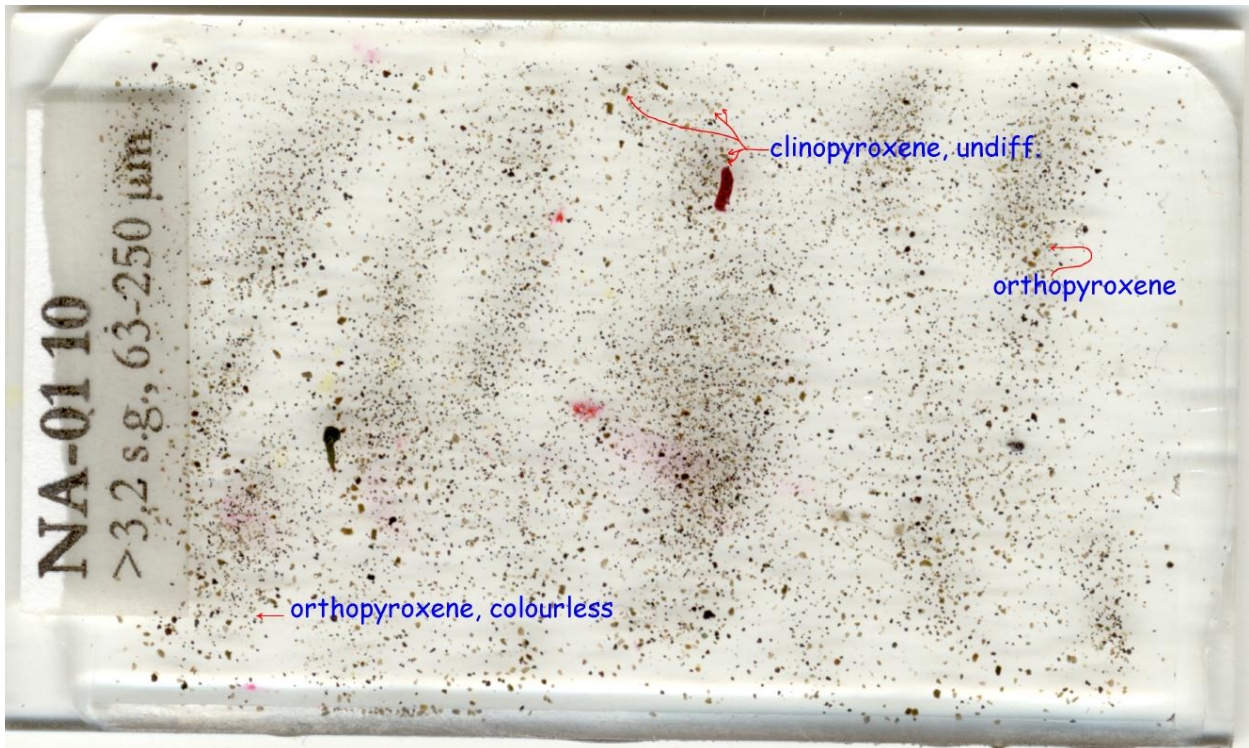
Contamination

Not a single grain of contamination was observed in the samples. This is quite exceptional. <http://www.consorminex.com/actm.htm> contains examples of the contamination found in heavy mineral concentrates.

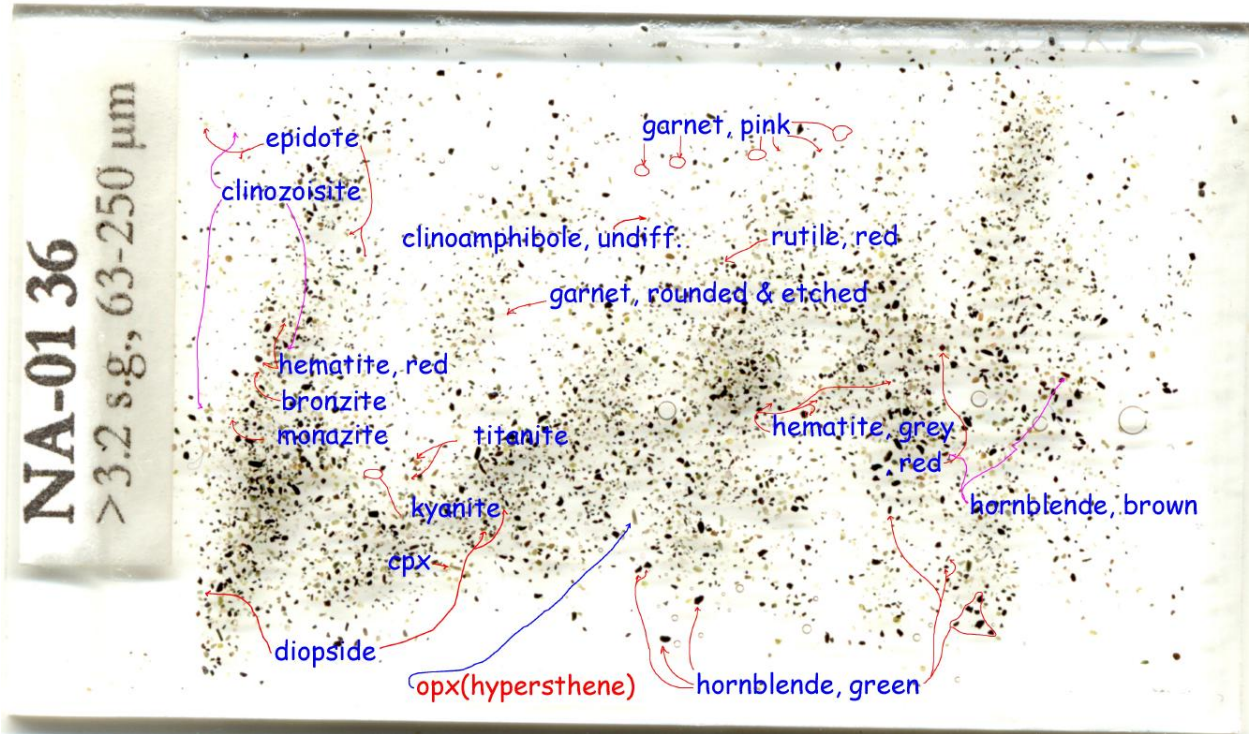
Slide_NA-01 3.jpg



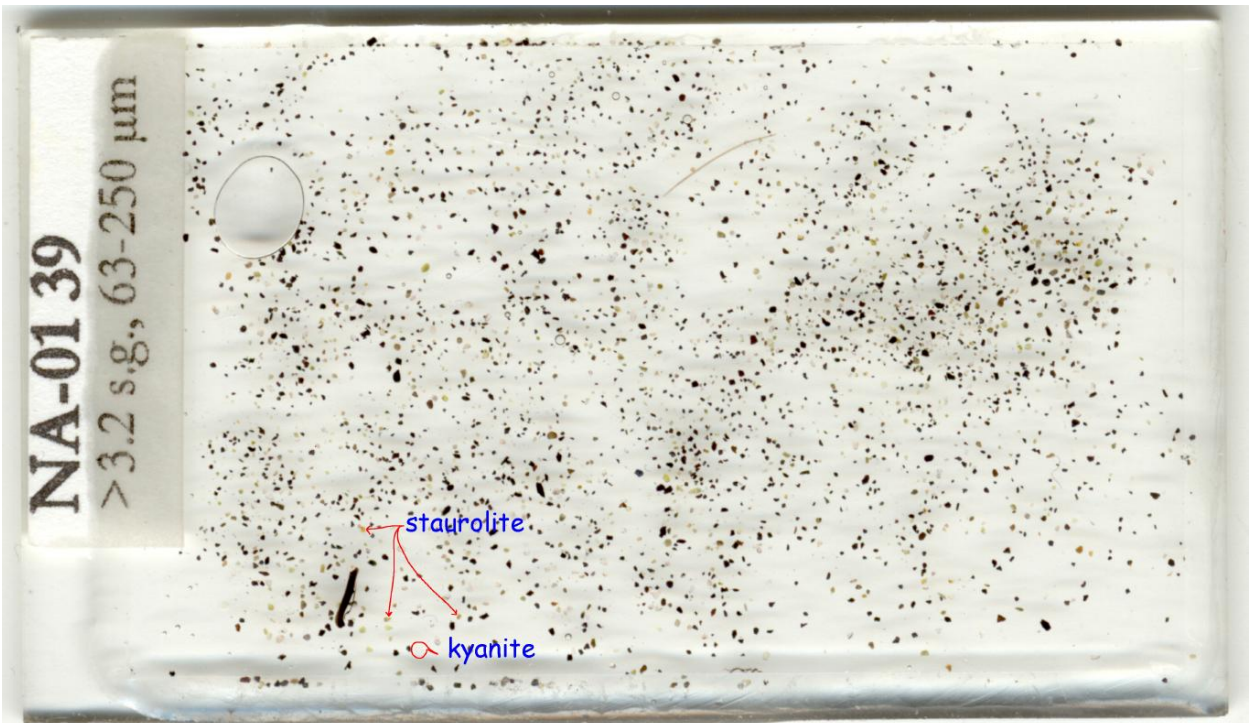
Slide_NA-01 10.jpg



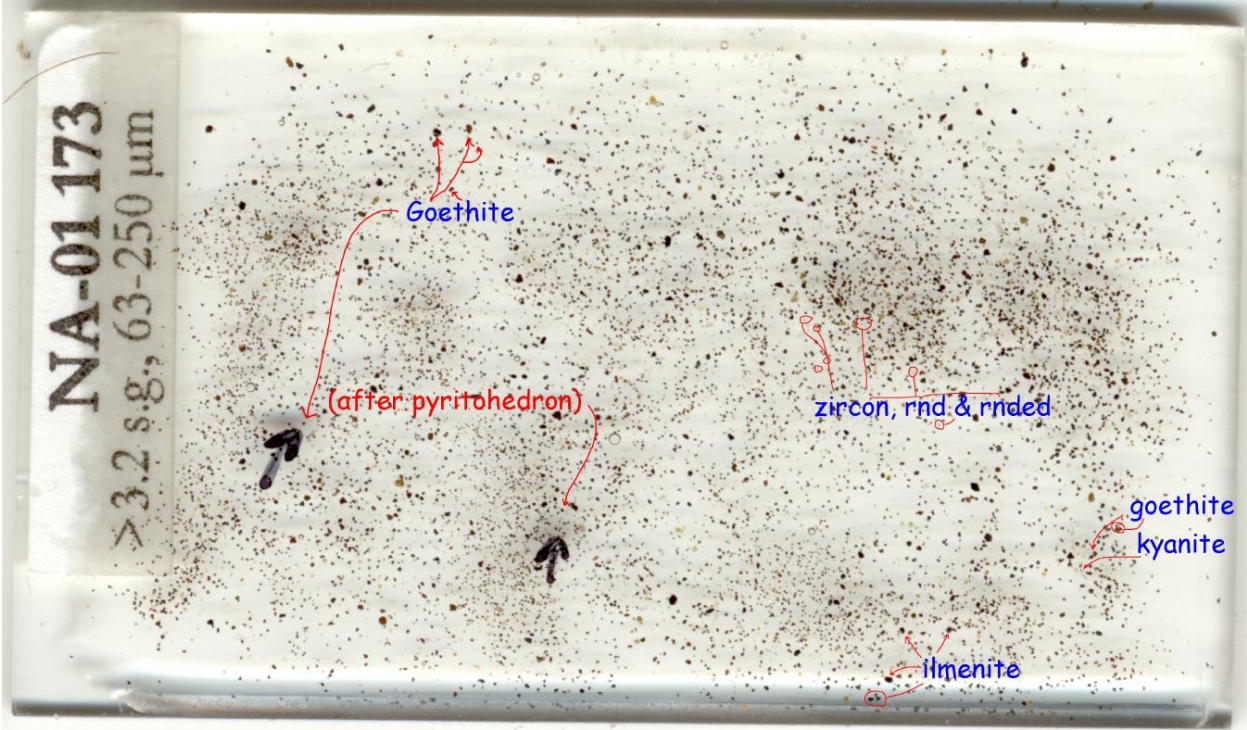
Slide_NA-01 36.jpg



Slide_NA-01 39.jpg



Slide_NA-01 173.jpg

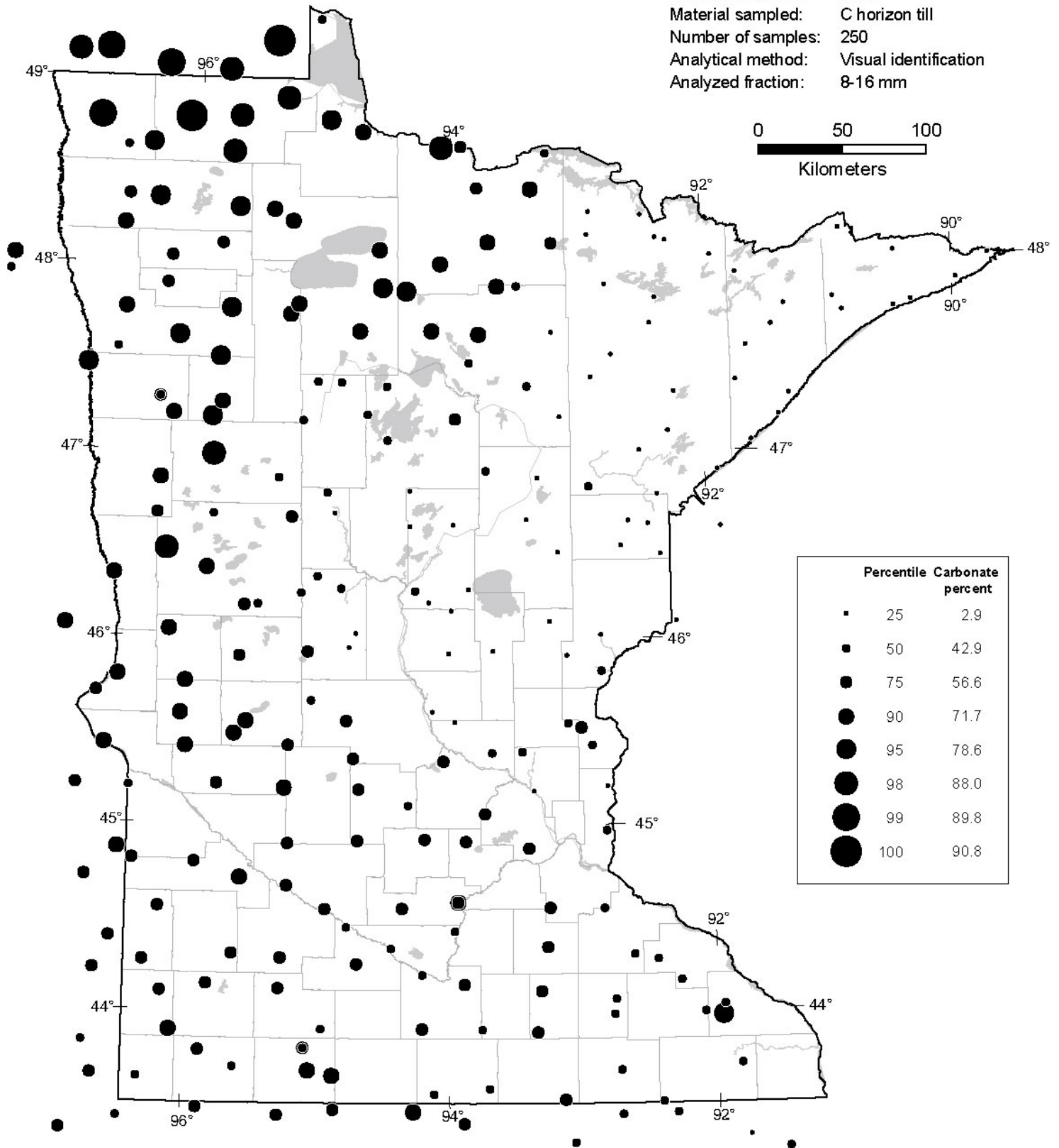


Addendum 2: EXAMPLES OF RESULTS

Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

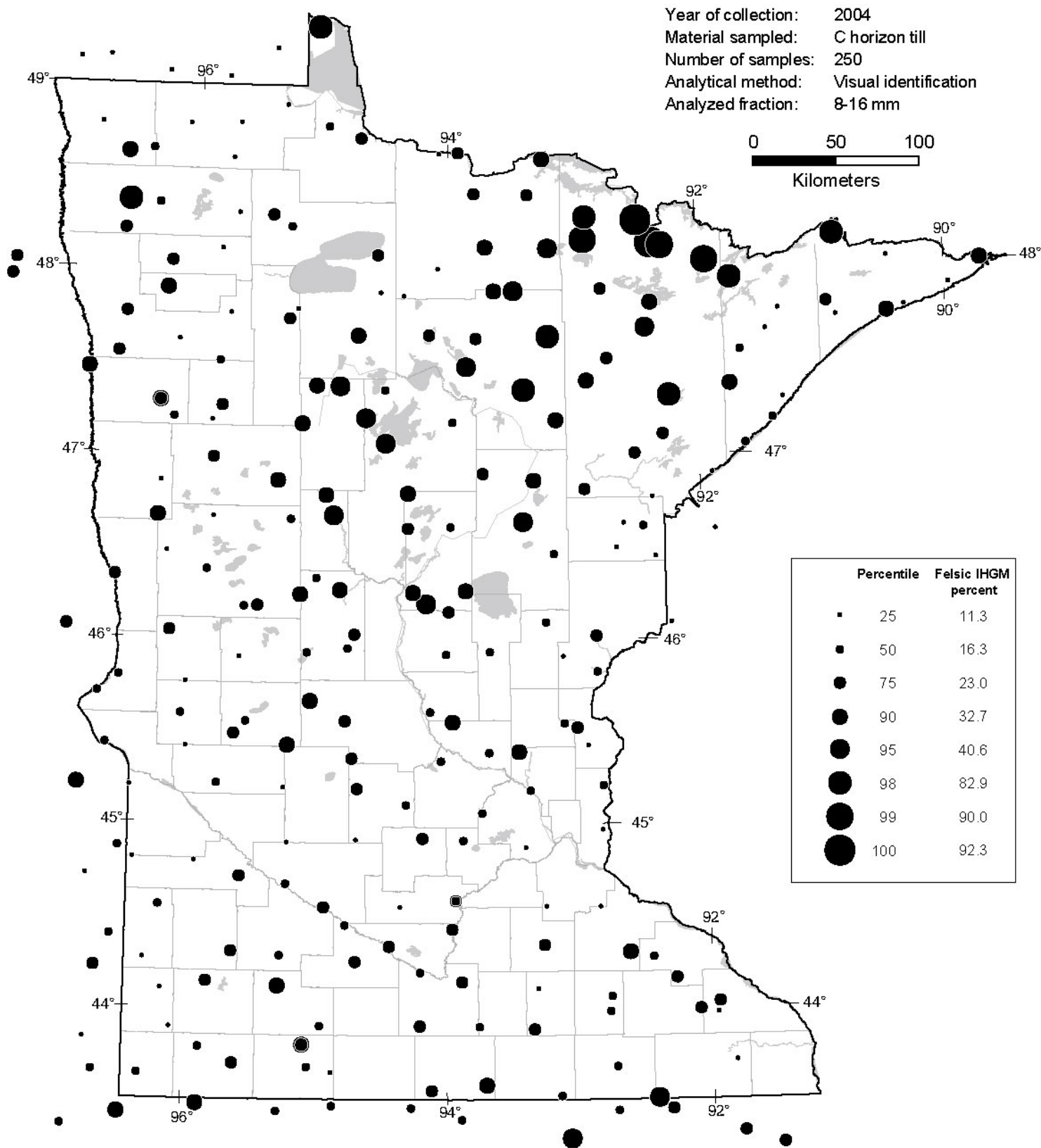
Carbonate

Year of collection: 2004
Material sampled: C horizon till
Number of samples: 250
Analytical method: Visual identification
Analyzed fraction: 8-16 mm



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

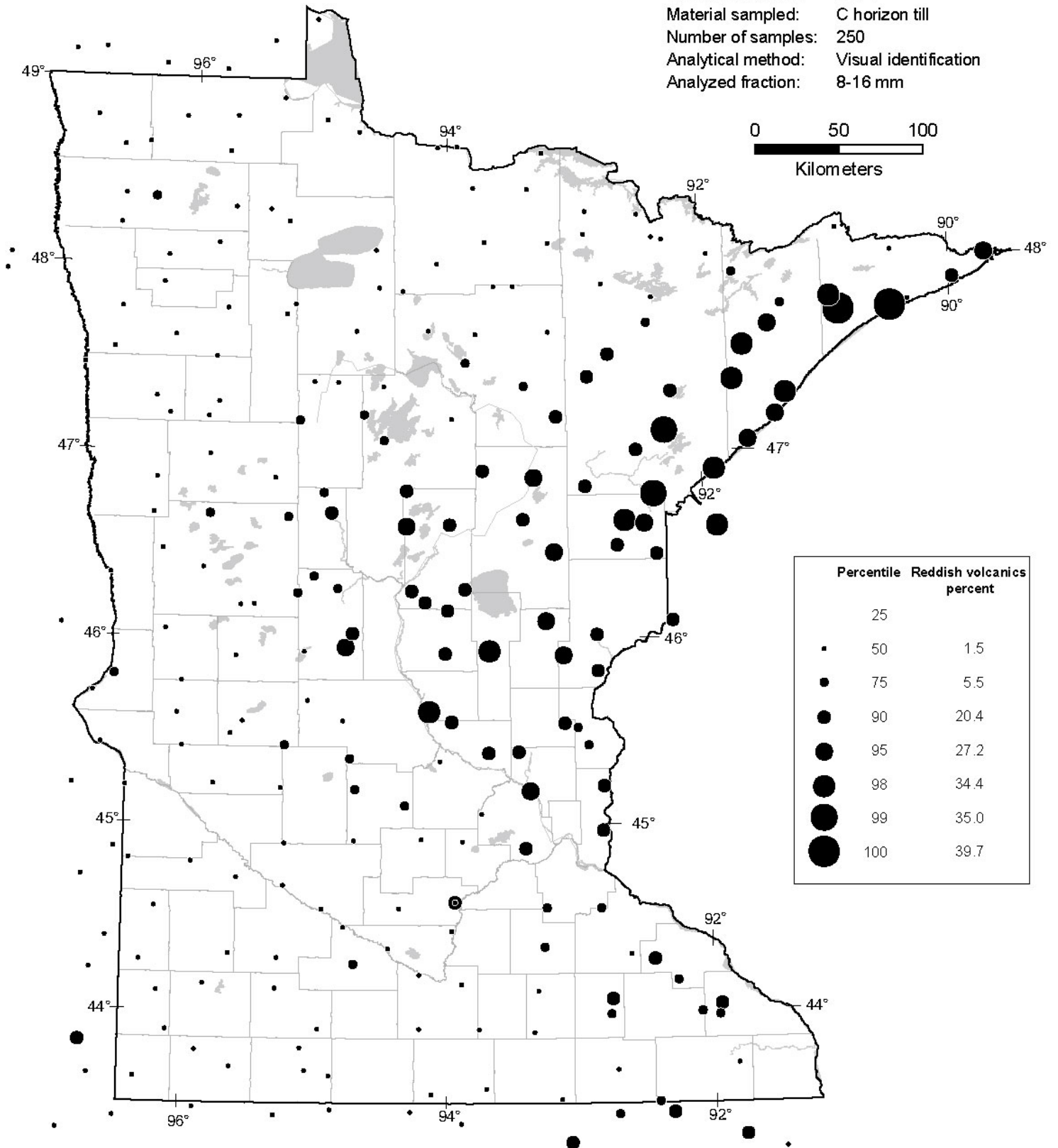
Felsic intrusive and high-grade metamorphic



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Reddish Volcanics

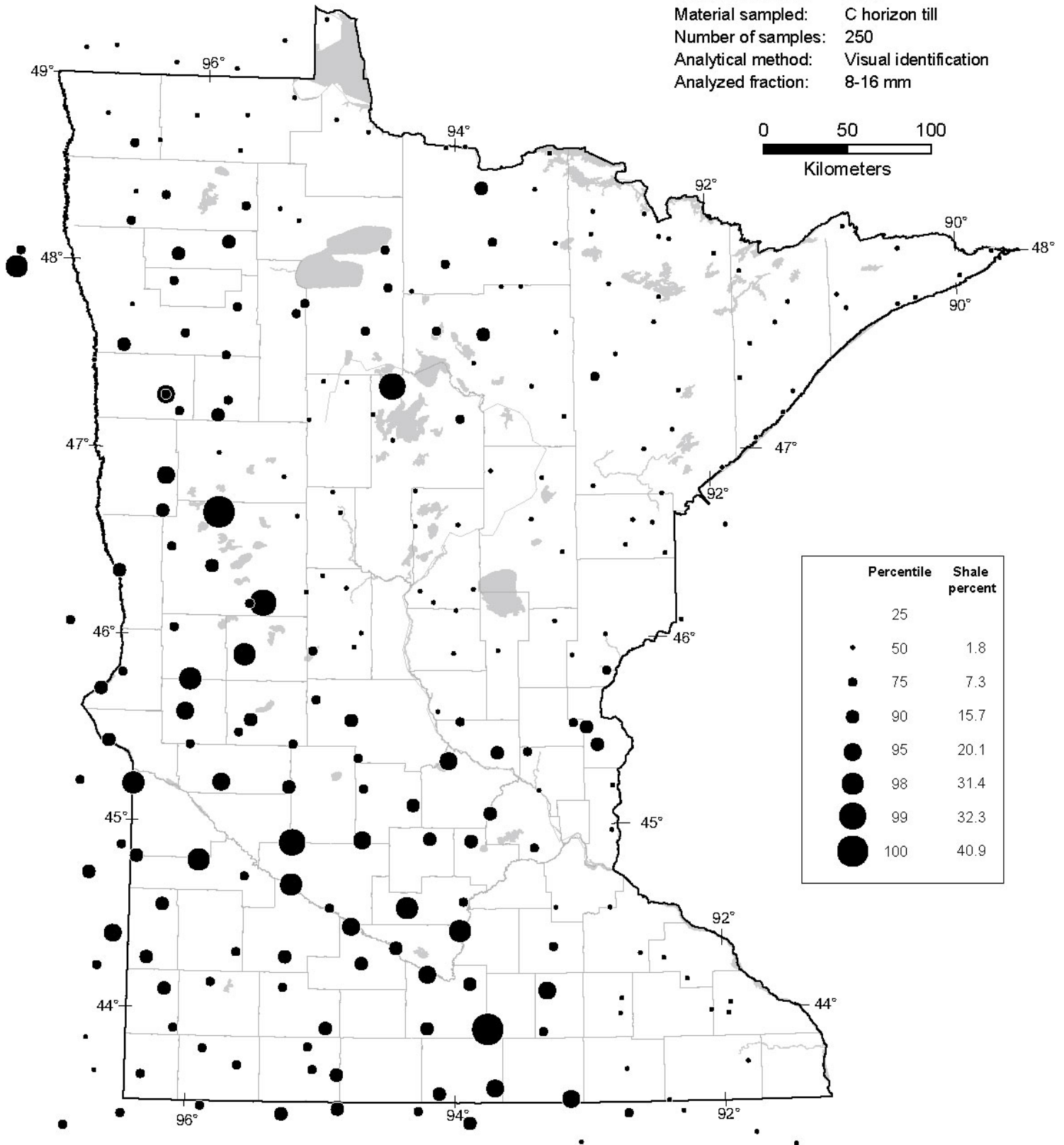
Year of collection: 2004
Material sampled: C horizon till
Number of samples: 250
Analytical method: Visual identification
Analyzed fraction: 8-16 mm



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Shale

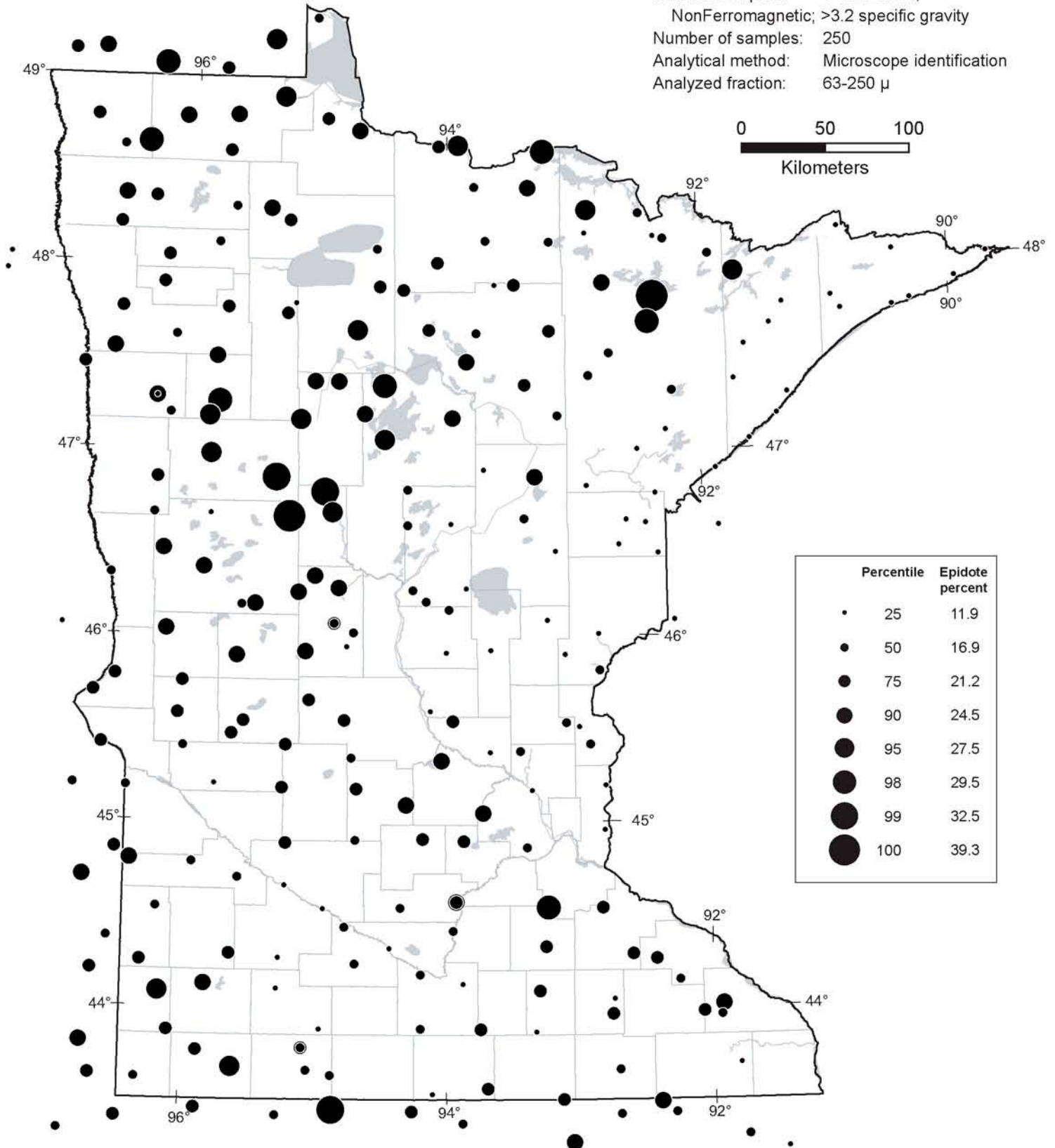
Year of collection: 2004
Material sampled: C horizon till
Number of samples: 250
Analytical method: Visual identification
Analyzed fraction: 8-16 mm



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Epidote

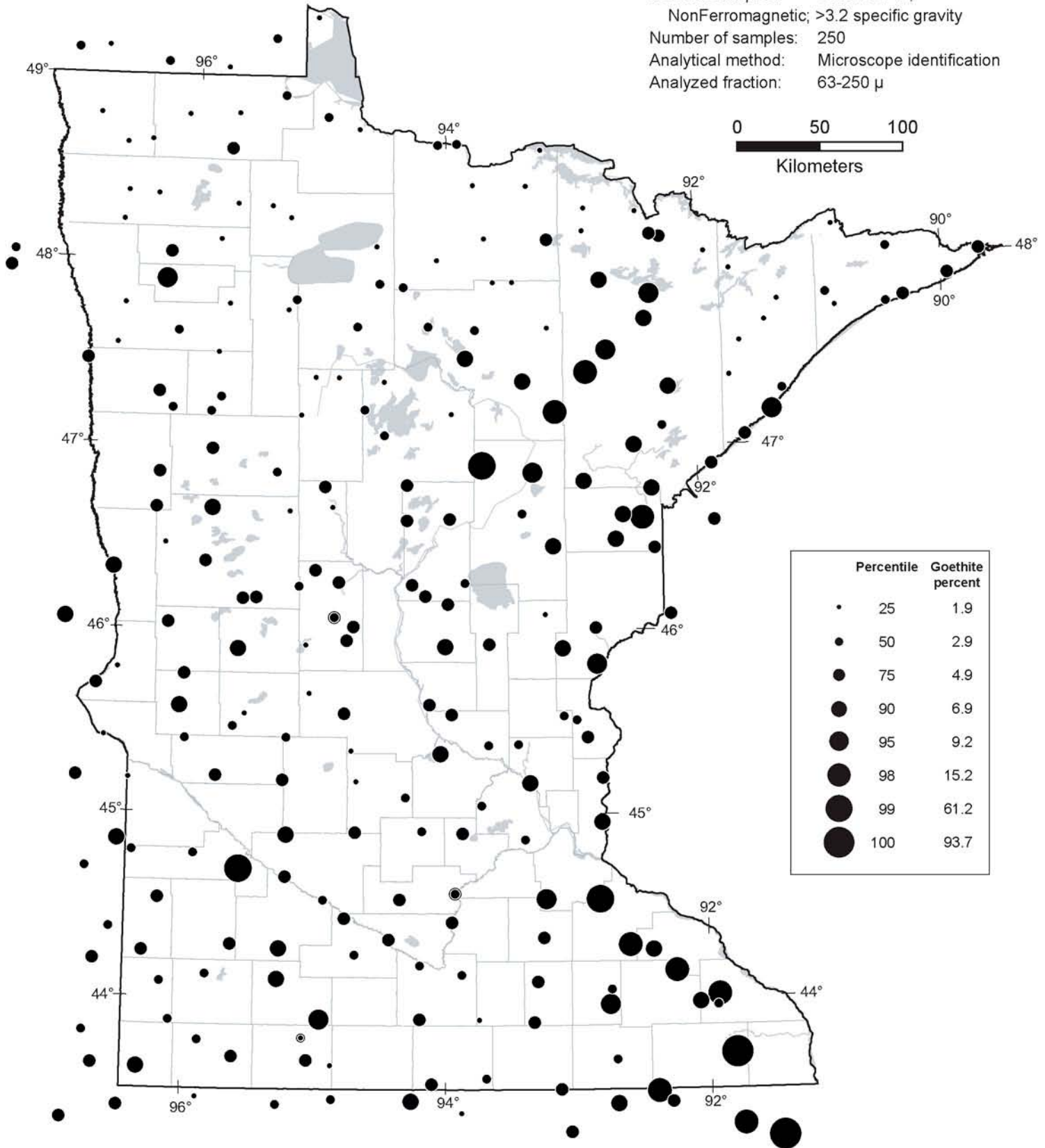
Year of collection: 2004
Material sampled: C horizon till;
NonFerromagnetic; >3.2 specific gravity
Number of samples: 250
Analytical method: Microscope identification
Analyzed fraction: 63-250 μ



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Goethite

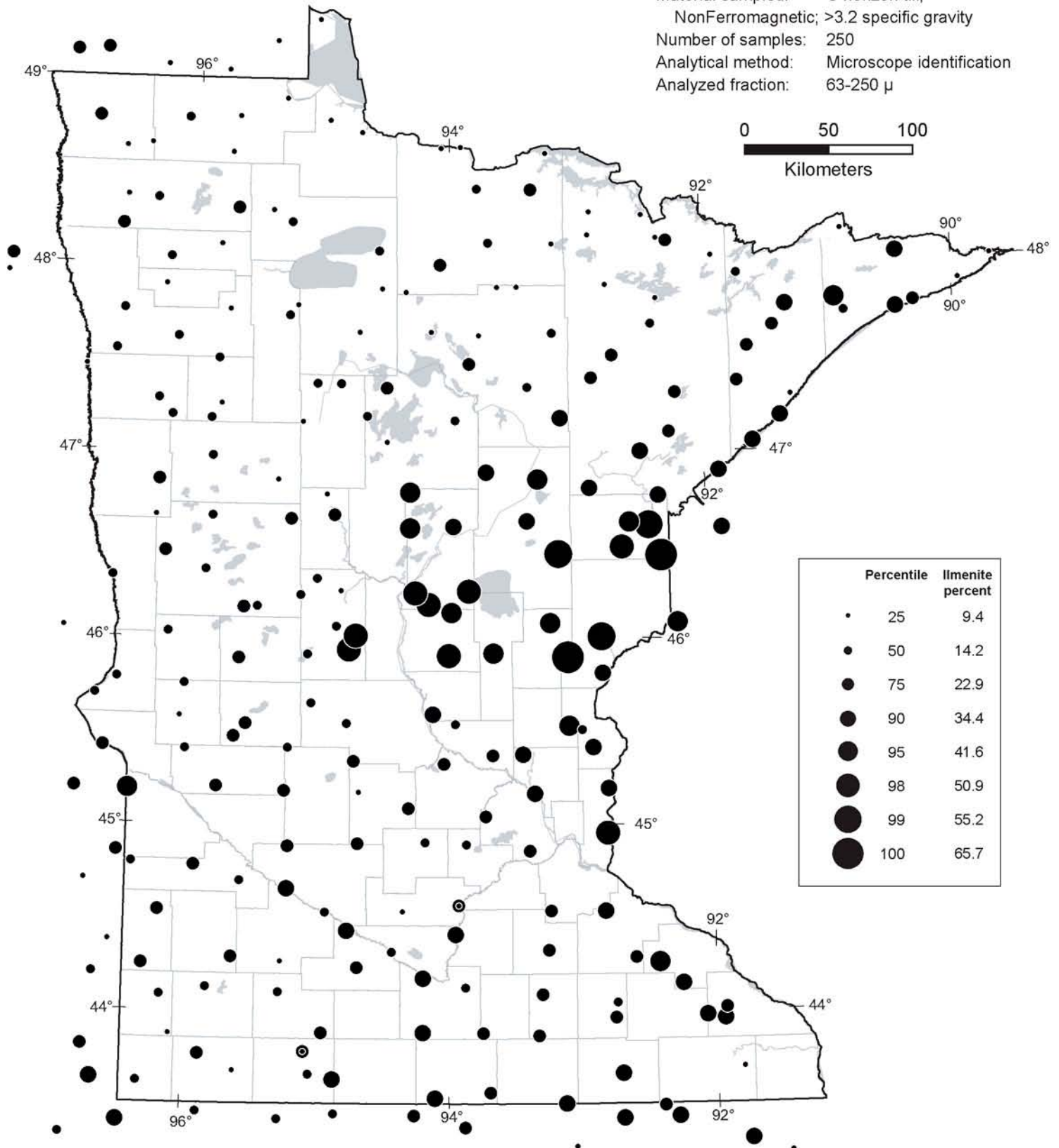
Year of collection: 2004
Material sampled: C horizon till;
NonFerromagnetic; >3.2 specific gravity
Number of samples: 250
Analytical method: Microscope identification
Analyzed fraction: 63-250 μ



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Ilmenite

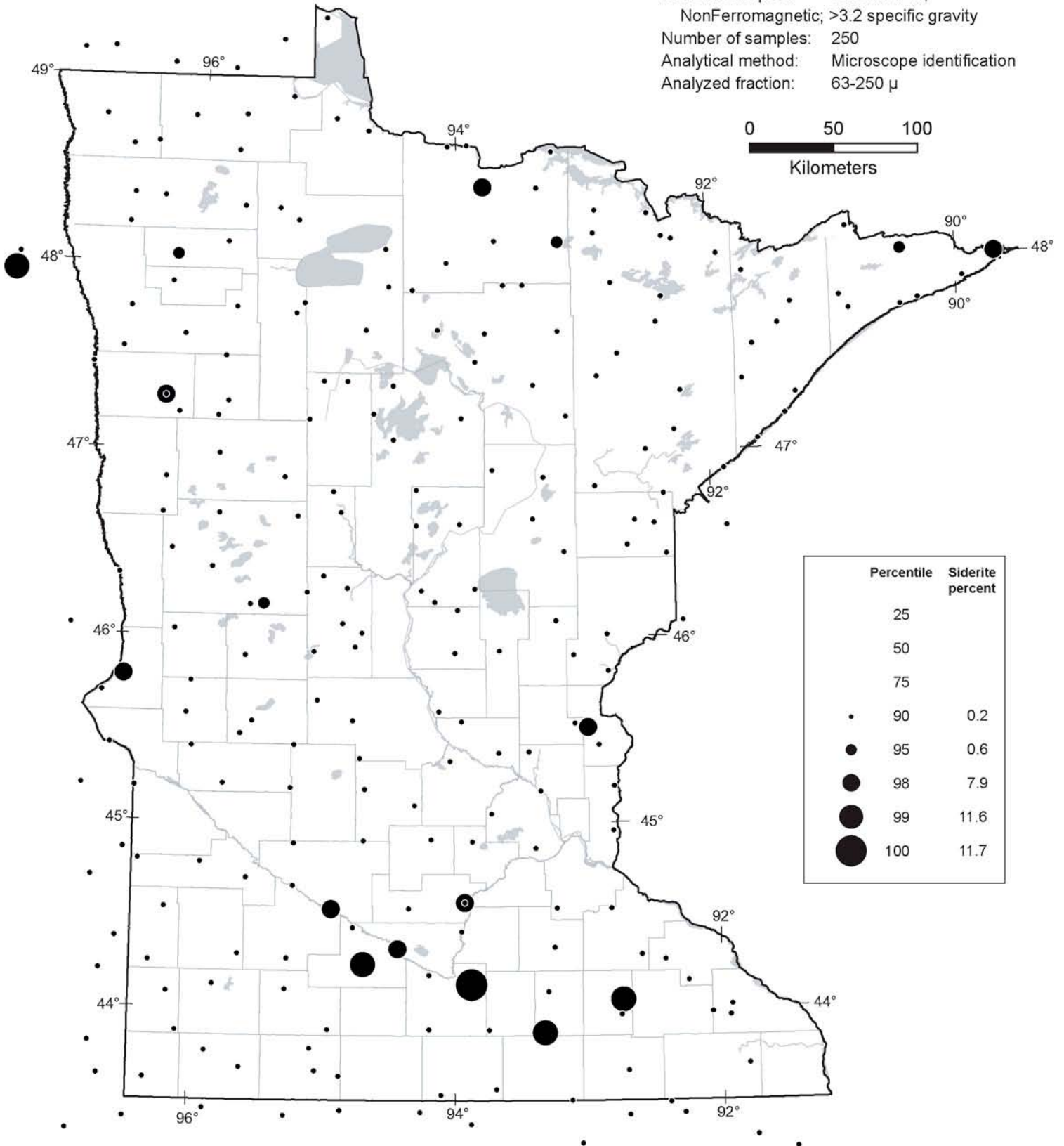
Year of collection: 2004
Material sampled: C horizon till;
NonFerromagnetic; >3.2 specific gravity
Number of samples: 250
Analytical method: Microscope identification
Analyzed fraction: 63-250 μ



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Siderite

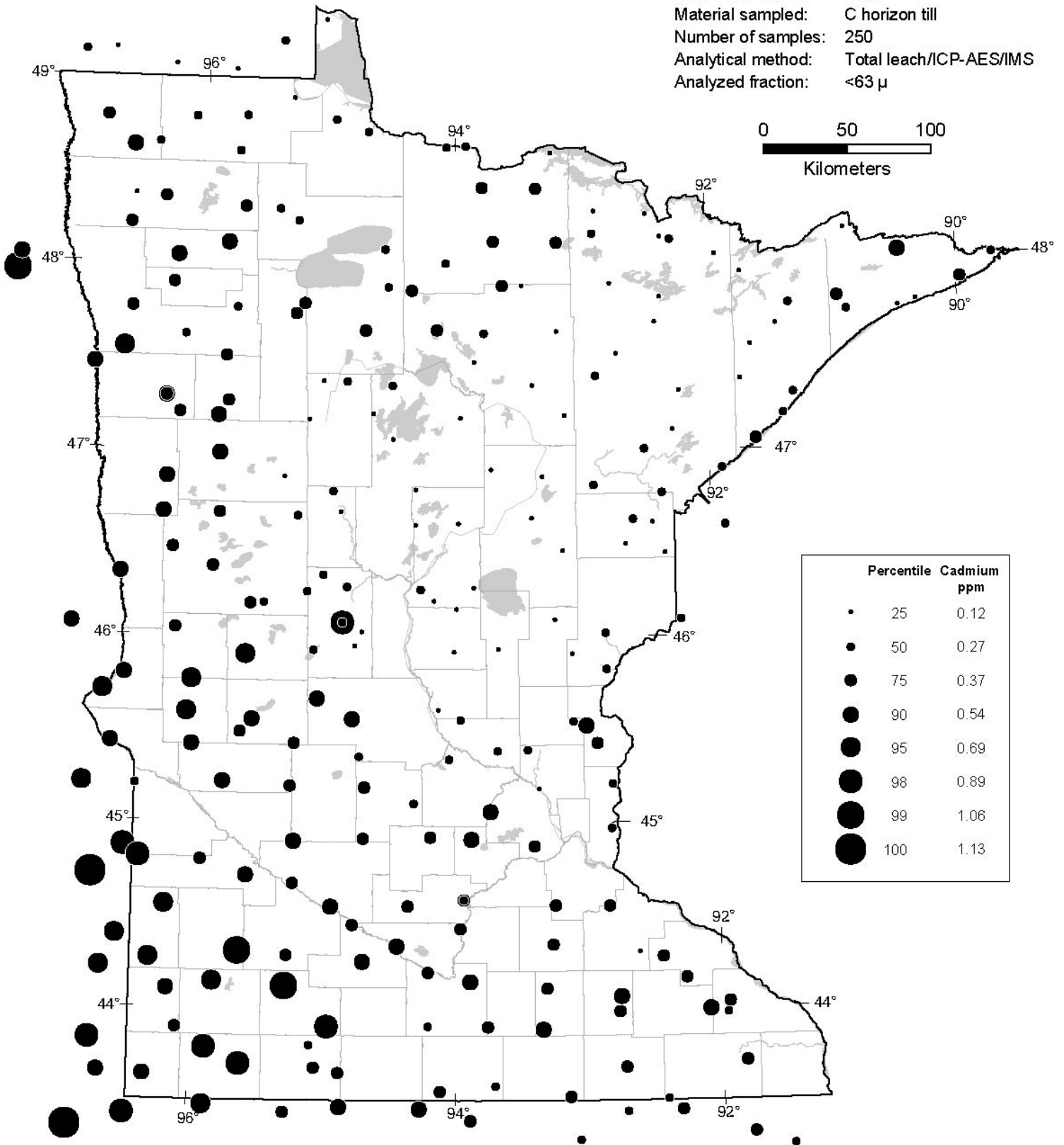
Year of collection: 2004
Material sampled: C horizon till;
NonFerromagnetic; >3.2 specific gravity
Number of samples: 250
Analytical method: Microscope identification
Analyzed fraction: 63-250 μ



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Cadmium

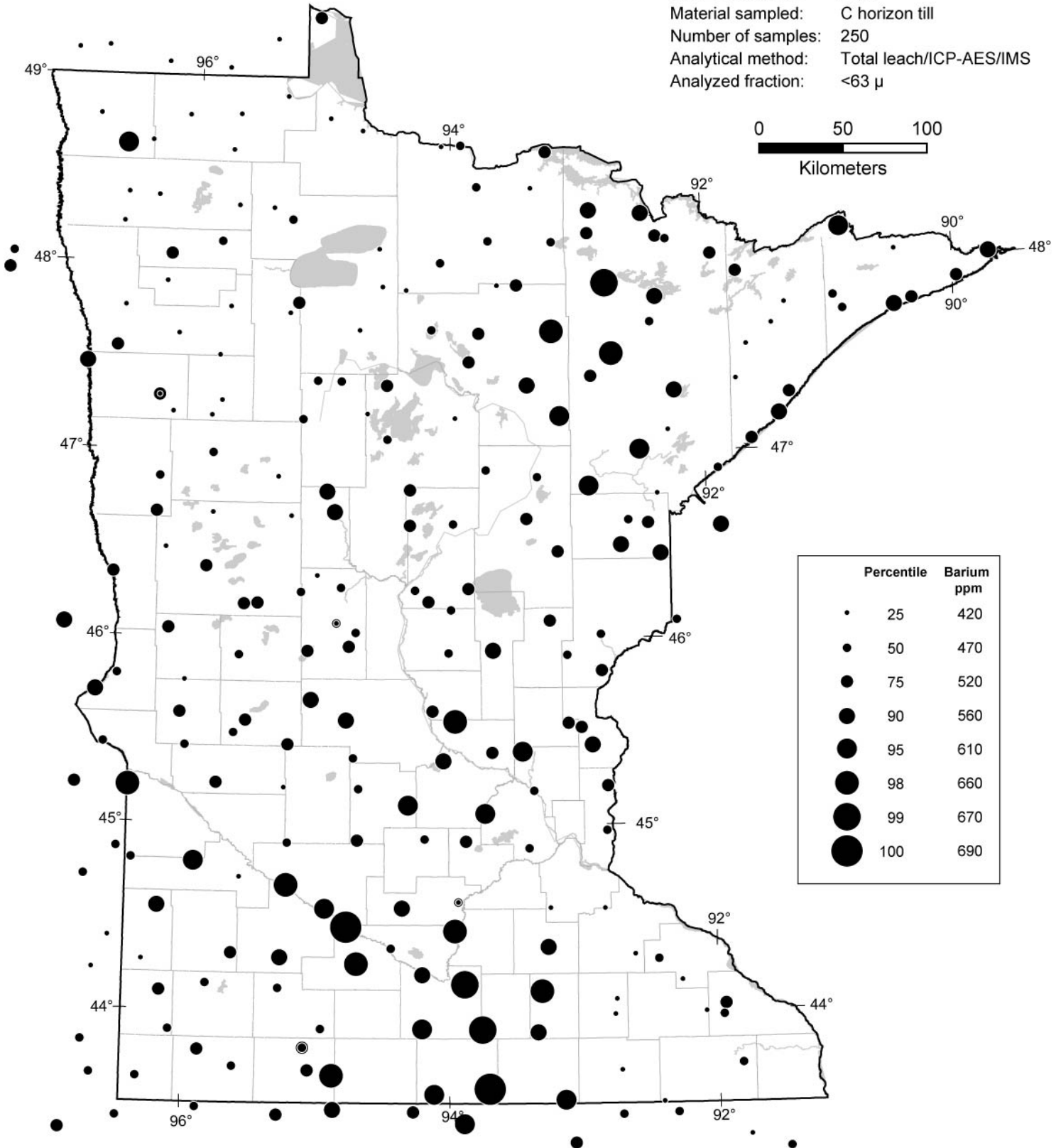
Year of collection: 2004
Material sampled: C horizon till
Number of samples: 250
Analytical method: Total leach/ICP-AES/IMS
Analyzed fraction: <math><63 \mu</math>



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Barium

Year of collection: 2004
Material sampled: C horizon till
Number of samples: 250
Analytical method: Total leach/ICP-AES/IMS
Analyzed fraction: <math><63 \mu</math>



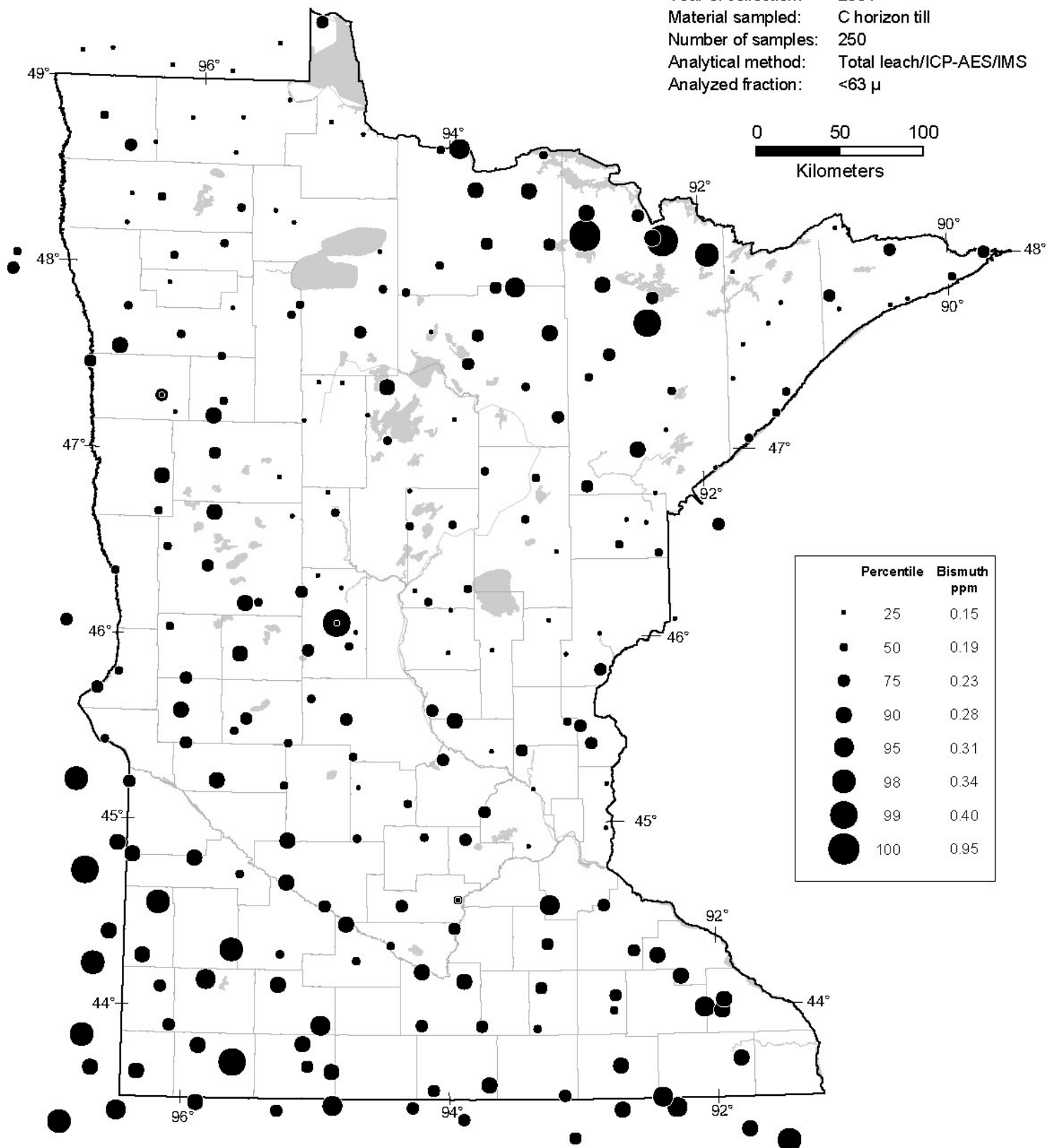
Percentile	Barium ppm	
•	25	420
•	50	470
•	75	520
•	90	560
•	95	610
•	98	660
•	99	670
•	100	690



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Bismuth

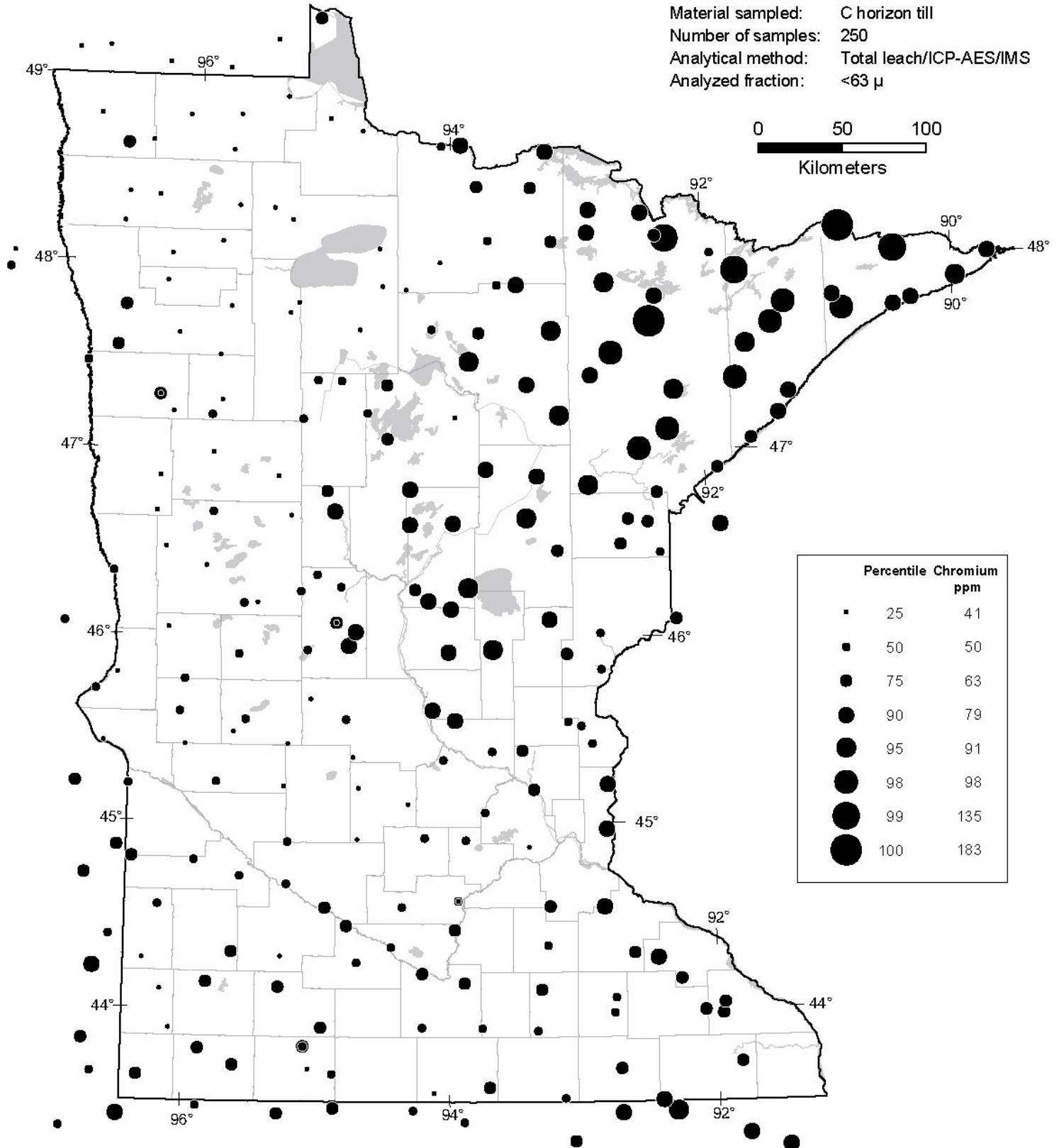
Year of collection: 2004
Material sampled: C horizon till
Number of samples: 250
Analytical method: Total leach/ICP-AES/IMS
Analyzed fraction: <63 μ



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Chromium

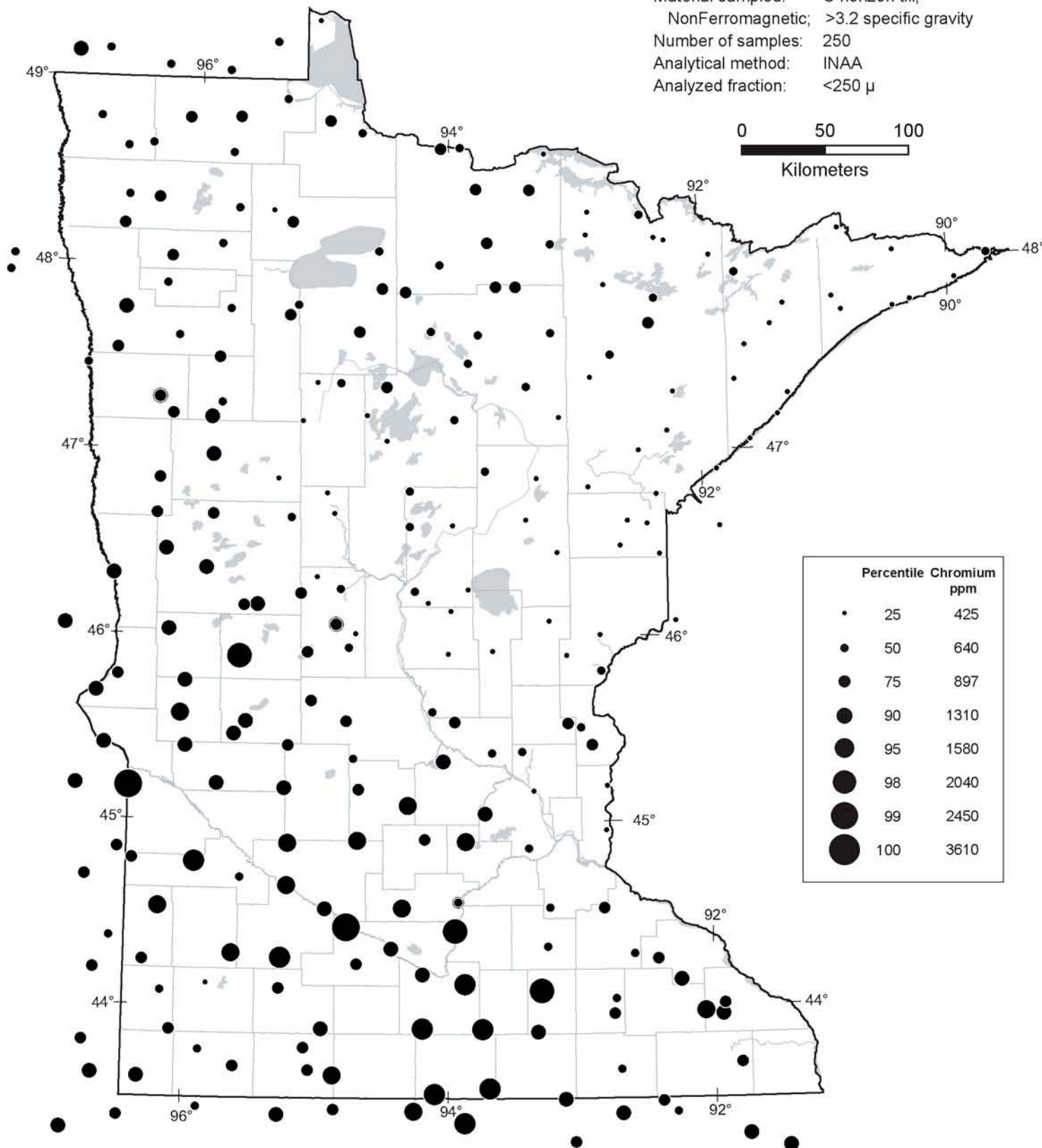
Year of collection: 2004
Material sampled: C horizon till
Number of samples: 250
Analytical method: Total leach/ICP-AES/IMS
Analyzed fraction: <63 μ



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Chromium

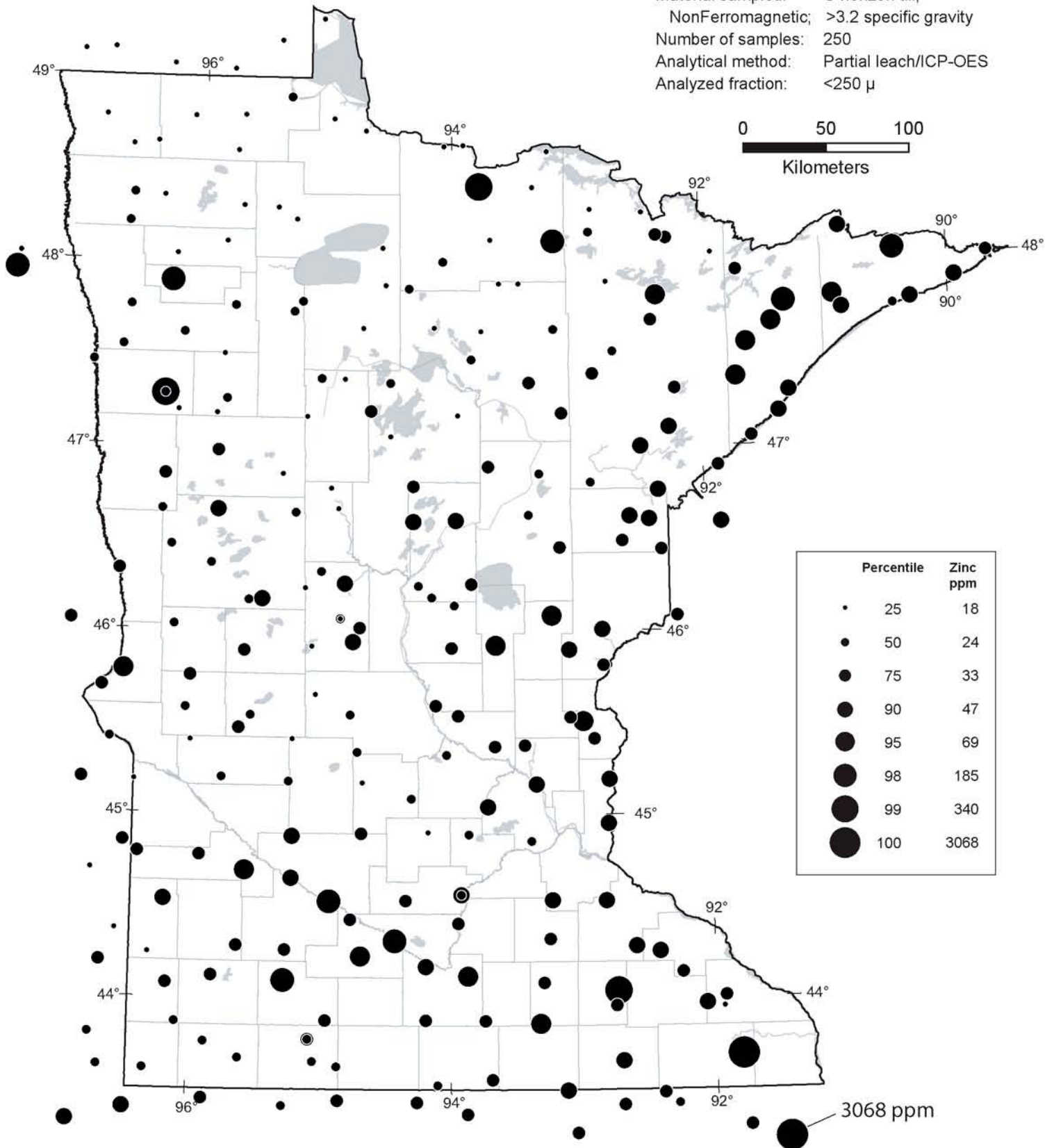
Year of collection: 2004
Material sampled: C horizon till;
NonFerromagnetic; >3.2 specific gravity
Number of samples: 250
Analytical method: INAA
Analyzed fraction: <250 μ



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Zinc

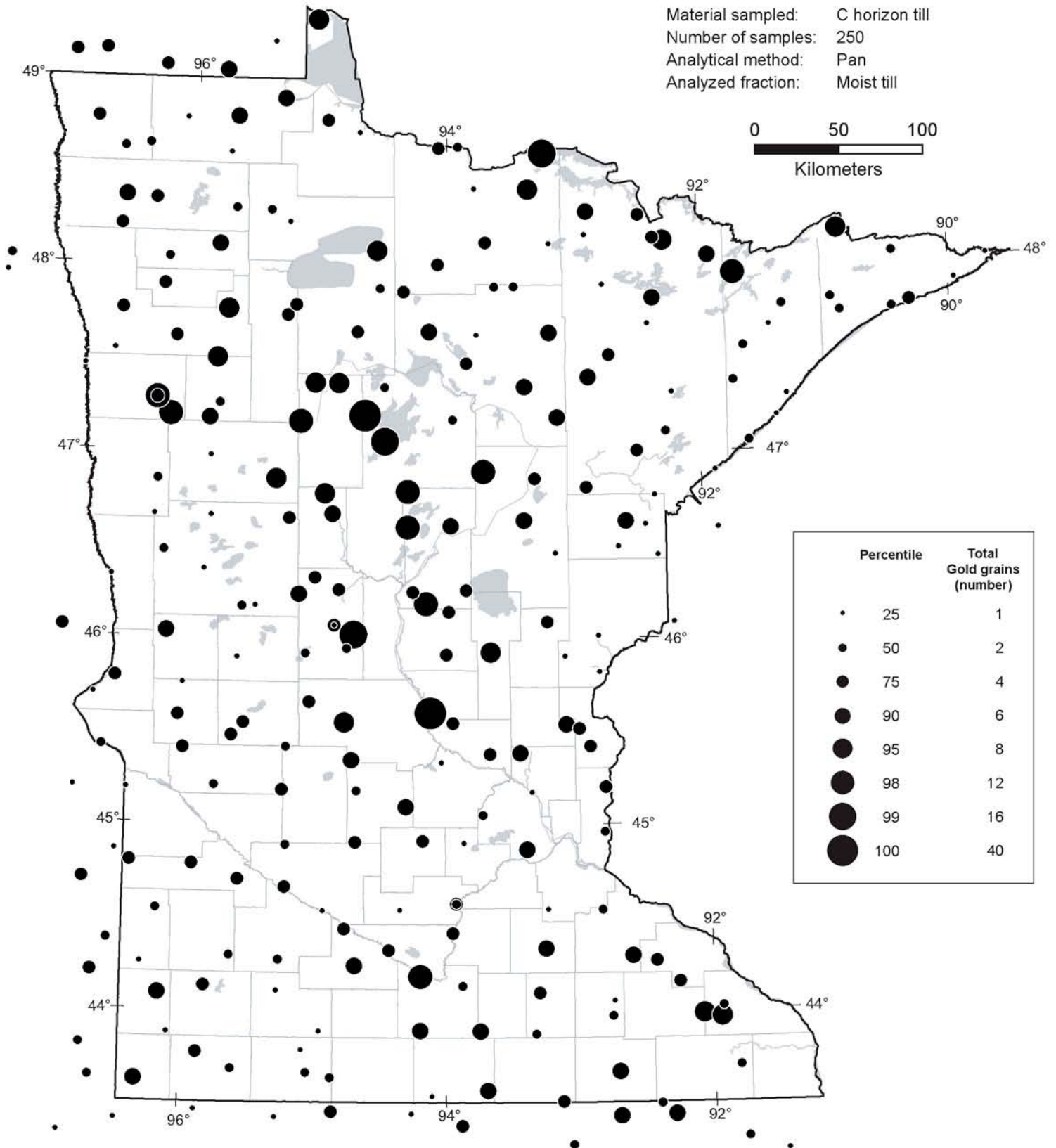
Year of collection: 2004
Material sampled: C horizon till;
NonFerromagnetic; >3.2 specific gravity
Number of samples: 250
Analytical method: Partial leach/ICP-OES
Analyzed fraction: <250 μ



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Total Gold Grains

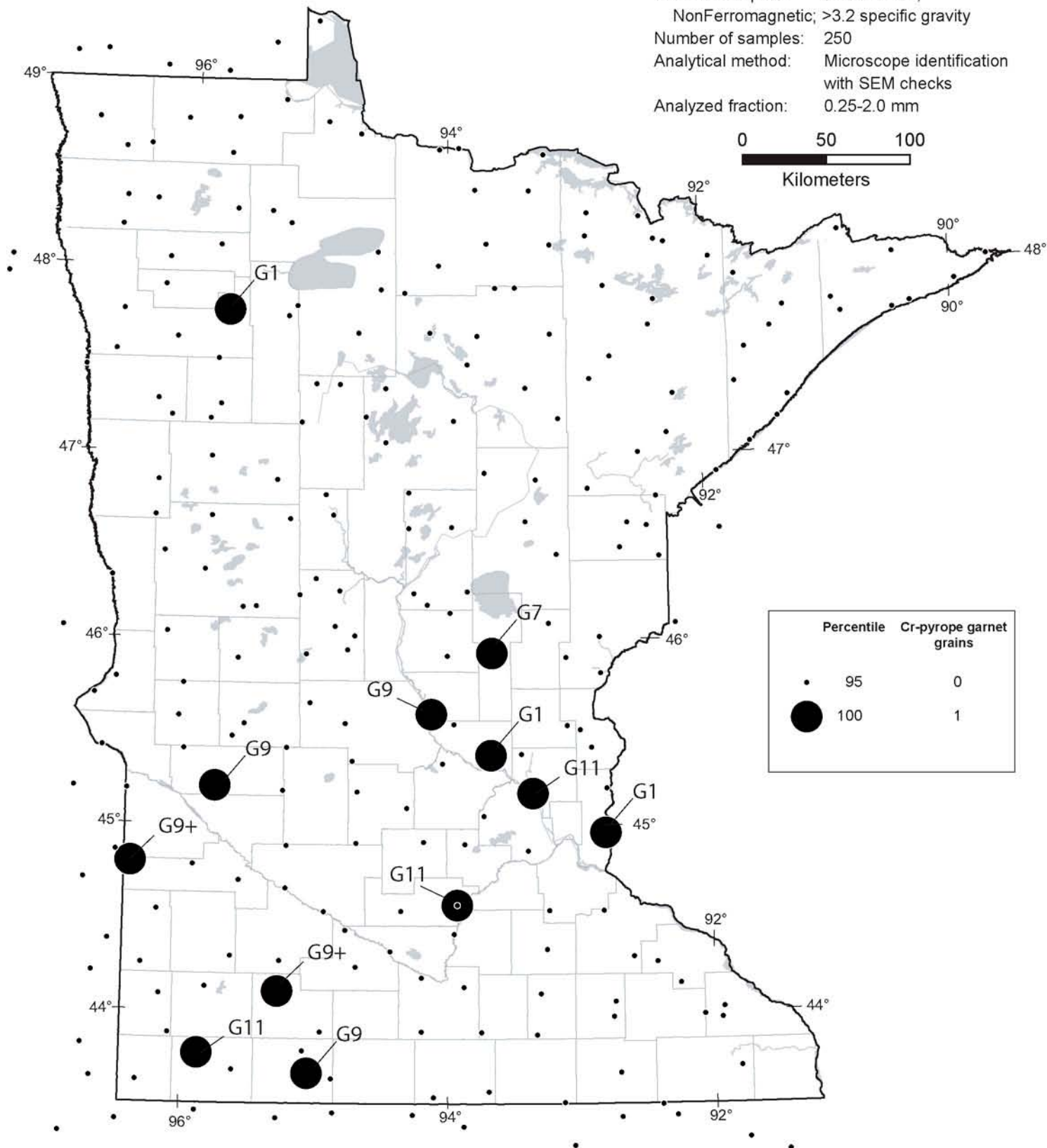
Year of collection: 2004
Material sampled: C horizon till
Number of samples: 250
Analytical method: Pan
Analyzed fraction: Moist till



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Cr-pyrope garnet

Year of collection: 2004
 Material sampled: C horizon till;
 NonFerromagnetic; >3.2 specific gravity
 Number of samples: 250
 Analytical method: Microscope identification
 with SEM checks
 Analyzed fraction: 0.25-2.0 mm



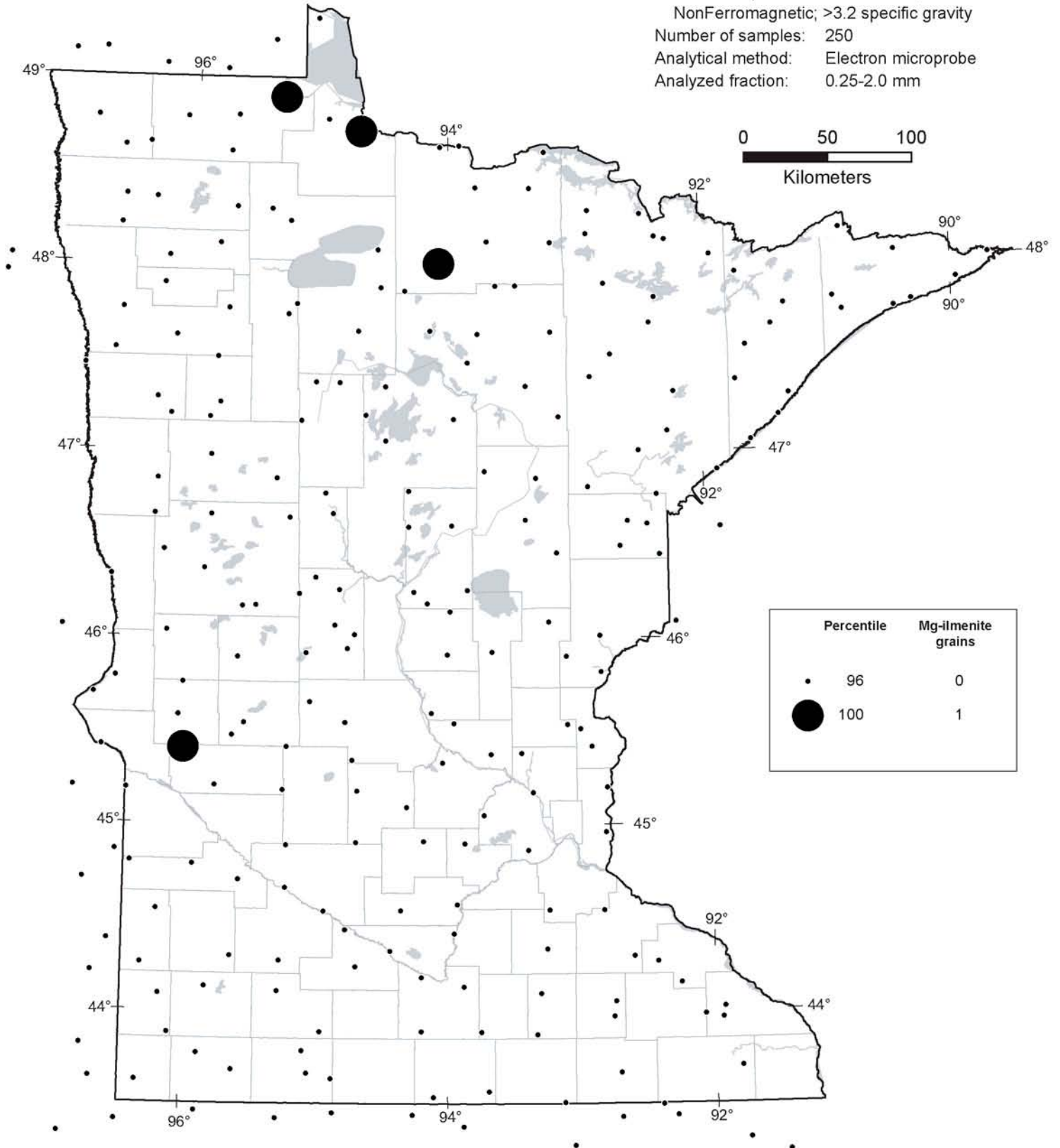
Percentile	Cr-pyrope garnet grains
•	95
●	100



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

Mg-ilmenite

Year of collection: 2004
Material sampled: C horizon till;
NonFerromagnetic; >3.2 specific gravity
Number of samples: 250
Analytical method: Electron microprobe
Analyzed fraction: 0.25-2.0 mm



Soil Geochemical and Indicator Mineral Reconnaissance Survey of Till in Minnesota

High-Cr-diopside

Year of collection: 2004
Material sampled: C horizon till;
NonFerromagnetic; >3.2 specific gravity
Number of samples: 250
Analytical method: Microscope identification
with SEM checks
Analyzed fraction: 0.25-2.0 mm

