

KIMBERLITE INDICATOR MINERAL AND GEOCHEMICAL RECONNAISSANCE OF SOUTHERN ALBERTA¹

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Abstract

An indicator mineral and geochemical survey designed to examine diamond and metallic mineral potential, glacial sediment transport history, and both exploration and environmental geochemistry, was carried out in southern Alberta in 1992. Sampling sites were randomly selected prior to field work, with two sites in 40 x 40 km cells designated for the sampling of till (unsorted glacial sediments) and soil, and additional sites designed to define local variability of soils. At 252 sites, a 25 l sample of till was collected from 1 to 2 m depth from surface exposures, mainly road cuts. Soil samples from the A and C horizons were obtained from 352 sites randomly distributed on all parent materials. Processing of the till samples, followed by mineralogical and chemical analysis, resulted in the confirmation of an average of one indicator mineral per two samples. Several areas where favourable kimberlite indicator mineral results are clustered were defined. Additional lithological, mineralogical, and geochemical analyses of till were used to provide evidence of the bedrock source of the sediment. Sediment consisting of material transported generally southwestward by Pleistocene glaciation radiating from the Canadian Shield can be distinguished from Pleistocene sediments north and south of Calgary which contain abundant material glacially transported from the Cordillera. The soil geochemical data are of less direct application to mineral exploration than the till data, owing to variable texture and greater modification by pedological processes, but these data provide useful information of relevance to environmental and agricultural issues.

Résumé

En 1992, un levé géochimique et un échantillonnage de minéraux indicateurs ont été réalisés dans le sud de l'Alberta. Ces travaux visaient à analyser le potentiel en diamants et en minéraux métalliques de cette région, à reconstituer l'histoire du transport des sédiments glaciaires et à recueillir des données utiles en géochimie de l'exploration et de l'environnement. Les sites d'échantillonnage ont été choisis au hasard avant les travaux sur le terrain. Il y avait d'abord des sites désignés pour échantillonner le till (sédiments glaciaires non triés) et le sol, au nombre de deux par cellule de 40 km de côté, mais aussi des sites additionnels définis pour déterminer la variabilité locale des sols. Ainsi, dans les matériaux de surface de 252 sites, surtout dans des tranchées routières, on a prélevé un échantillon de 25 litres de till à une profondeur de 1 à 2 m. On a aussi recueilli des échantillons de sol dans les horizons A et C de 352 sites répartis au hasard parmi tous les matériaux mères. Le traitement des échantillons de till, suivi de leur analyse minéralogique et chimique, a permis de confirmer la présence d'un minéral indicateur par deux échantillons en moyenne. Plusieurs zones où l'on a observé le regroupement de minéraux indicateurs (de la présence de kimberlite) ont été définies. D'autres analyses lithologiques, minéralogiques et géochimiques du till ont été utilisées pour en savoir plus sur l'origine des sédiments dans le substratum. Les sédiments composés de matériaux transportés généralement vers le sud-ouest par une glaciation pléistocène rayonnant à partir du Bouclier canadien se distinguent des sédiments pléistocènes au nord et au sud de Calgary, qui contiennent d'abondantes quantités de matériaux transportés par les glaciers à partir de la Cordillère. Les données géochimiques sur le sol ont une application moins directe en exploration minière que les données sur le till, étant donné la texture

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application moins directe en exploration minière que les données sur le till, étant donné la texture variable des sols et leur modification accrue par les processus pédologiques. Cependant, ces données fournissent des informations utiles en environnement et en agriculture.

INTRODUCTION

Rationale, scope, and objectives

Much of Canada is underlain by geological terrane which has a high potential for the presence of diamond-bearing rocks. Early diamond exploration focussed on the Great Lakes region (Brummer, 1978), but shifted west in recent years (Fipke et al., 1995). In 1988, kimberlite discoveries in central Saskatchewan were announced (Lehnert-Thiel et al., 1992; Scott-Smith, 1995), and in 1991, a dramatic increase in diamond exploration activity occurred in Alberta (Dufresne et al., 1994). In 1992, the Northwest Territories became the most active area of diamond exploration in Canada. This exploration activity, including the processing of sediment for indicator minerals, geophysical surveys, and drilling, was accompanied by a recognition of the need for regional government surveys that would place detailed industry data into context.

The work in Alberta summarized here is part of a survey covering the entire Canadian prairie region (Garrett and Thorleifson, 1995). The objectives of the work were: to map regional trends in indicator mineral frequency and chemistry; to seek evidence for the presence of gemstone and metallic mineral deposits; to demonstrate and compare various mineralogical and geochemical exploration methods; to map glacial sediment composition as an indicator of its transport history; and, to map regional soil geochemistry as an aid to exploration and environmental applications. Soil geochemical sampling was extended southward 100 km into the USA, in cooperation with the United States Geological Survey (USGS), in order to provide correlation to US regional surveys. The survey in Alberta was limited to contiguous agricultural land in the southern part of the province (Fig. 1), where road access permitted relatively inexpensive systematic coverage.

The prairie survey evolved from a 1990 proposal for a survey of southern Saskatchewan. In 1991, an orientation set of till and soil samples was collected at 40 to 50 km intervals along an orientation transect from Winnipeg to Calgary, and from Edmonton back to Winnipeg. Processing of these samples led to refinement of laboratory procedures and indicated that

well-defined regional trends could be mapped by ultra-low density sampling. In 1992, the southern Alberta survey was authorized, and coverage was extended across southern Manitoba as a cooperative effort with Manitoba Energy and Mines. All sampling for the regional survey was completed in 1992, and laboratory work progressed in stages over the ensuing three years.

Data obtained from the orientation samples were released in 1993 (Garrett and Thorleifson, 1993). Electron microprobe data for indicator minerals obtained from the regional survey, as well as till matrix geochemistry, were released later that year (Thorleifson and Garrett, 1993), prior to the release of proton microprobe indicator mineral data by Thorleifson et al. (1994).

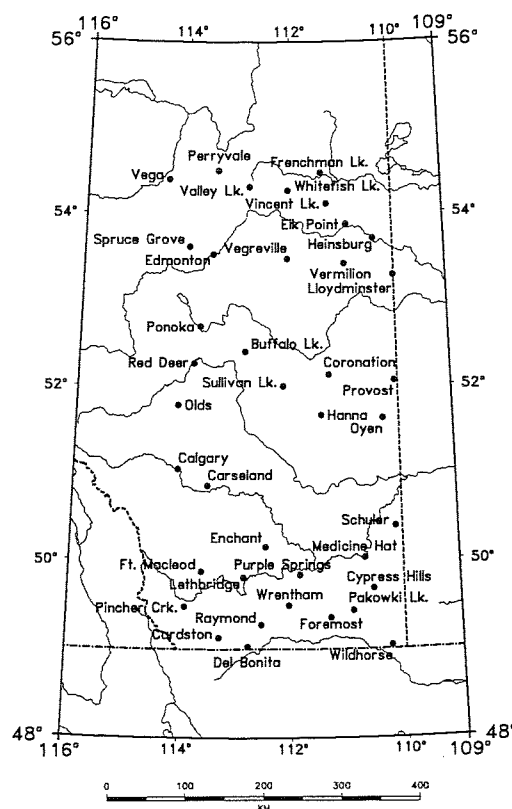


Figure 1. Location of geographic features discussed in the text.

Regional geology

The prairie region of southern Alberta is underlain by extensive Cretaceous to Paleocene sandstones, mudstones and coal, isolated occurrences of Oligocene, Miocene and early Pleistocene gravels, and, in southeasternmost Alberta, several small intrusions of Tertiary age (Dawson et al., 1994; Stott et al., 1993; Mossop and Shetsen, 1994). Outcrops of these pre-Quaternary deposits are generally limited to river valleys and areas of high relief. Northeast of the study area, in northeasternmost Alberta and to the east in Saskatchewan and Manitoba, are Precambrian igneous and metamorphic rocks of the Canadian Shield, as well as Paleozoic carbonate rocks which occur along the shield margin, mainly in Alberta and Manitoba. To the west in the Cordillera are extensive carbonate, metasedimentary, and other sedimentary rocks.

The oldest rocks that underlie the Quaternary sediments or outcrop in the study area are Cretaceous in age. They are the shale-dominated Milk River Formation, which outcrops along the Montana border southeast of Lethbridge, and Lea Park shale, northeast of the North Saskatchewan River. Sedimentary rocks which overlie the Milk River Formation elsewhere include the deposits of four progradational cycles of sand-dominated sedimentation associated with uppermost Cretaceous to Paleocene Laramide orogenesis: the Cretaceous Belly River, Horseshoe Canyon, and lower Scollard units, as well as the Paleocene Paskapoo and equivalent strata. Each of these sandstone units is underlain by mudstone and coal-dominated units, the Pakowki, Bearpaw, Battle, and upper Scollard strata respectively (Dawson et al., 1994).

Thermal maturity of coals and the elevation of the uppermost gravels indicate that the regional unconformity at the top of the Cretaceous-Tertiary sequence resulted from the removal, over most of the area, of 1 to 3 km of sediment by subaerial and glacial processes in post-Eocene time (Nurkowski, 1984; Bustin, 1992; Dawson et al., 1994). The subcrop pattern produced by this erosion generally consists of north-south belts. The Paskapoo sandstone dominates the western portion of the study area, extending from Calgary nearly to Edmonton (Mossop and Shetsen, 1994). The subcrop of the Horseshoe Canyon Formation, which underlies the City of Edmonton, is to the east. The Bearpaw shale is the next major subcropping or outcropping unit to the east, underlying a large area which bulges to the Saskatchewan border between Medicine Hat and Lloydminster. Northeast and southeast of the Bearpaw shale, the Lloydminster and Medicine Hat regions are underlain by the Belly River

Formation. Southeasternmost Alberta is underlain by Bearpaw shale, whereas the northeastern corner of the study area extends to the subcrop of Lea Park shale.

Most of the post-Eocene erosion which occurred in the area resulted from the action of eastward- and northeastward-flowing braided streams (Leckie and Cheel, 1989). Deposits of sand and gravel transported by these streams have been preserved across southern Alberta and Saskatchewan. The oldest preglacial gravels rest on the highest uplands, such as the Cypress Hills, and the youngest, deposits immediately preglacial in age such as the Empress Formation, fill in buried valleys. This succession of sand and gravel deposits can be divided into four groups (Dawson et al., 1994): 1) the Upper Eocene to Miocene Cypress Hills Formation and equivalents such as the Porcupine Hills Formation, which rest at an elevation close to the pre-existing surface indicated by coal maturity (Nurkowski, 1984; Bustin, 1992); 2) the Miocene to Pliocene Handhills Formation and equivalents on Del Bonita Upland and Wintering Hills, as well as on Wood Mountain in Saskatchewan; 3) Upland gravels, including the Willowbrook and Bredenbury Formation; and 4) the early Pleistocene Saskatchewan Gravels as well as the associated Grimshaw Gravels and the Empress Formation.

Throughout most of the area, pre-Quaternary deposits are overlain by Pleistocene glacial sediments. At the surface, and to a lesser extent in the subsurface, other Quaternary deposits such as glaciolacustrine clay and glaciofluvial sand and gravel also occur (Gravenor and Bayrock, 1961; Shetsen, 1987a, b). According to Fenton et al. (1994), sediments across most of the study area are less than 50 m thick, considerably thinner than values commonly exceeding 100 to 200 m which occur across southern Saskatchewan. Sediment exceeding 50 m in thickness occurs intermittently along the Alberta/Saskatchewan border and along the Montana border. The greatest thicknesses in the study area, over 100 m, occur between Medicine Hat and the Cypress Hills (Fig. 1), and midway between Calgary and the Montana border.

The complex Quaternary history of the study area may be summarized as three major glacial events of somewhat uncertain age: 1) an early, extensive Cordilleran ice advance; 2) a subsequent extensive advance of Laurentide ice which radiated outward from the Canadian Shield and overrode the glacial deposits of the earlier flow; and, 3) a less extensive coalescent Cordilleran and Laurentide ice flow which deposited a train of Cordilleran erratics along the foothills, passing through Calgary (Stalker, 1976; Stalker and Harrison, 1977; Jackson, 1980; Rutter,

1984; Fenton, 1984; Fulton et al., 1984; Bobrowsky and Rutter, 1992; Stalker and Vincent, 1993; Young et al., 1994; Evans and Campbell, 1995; Little, 1995).

The Quaternary stratigraphy of adjacent southern Saskatchewan has been described by Christiansen (1968), Whitaker and Christiansen (1972), Christiansen (1968, 1979), Schreiner (1990), Christiansen (1992), and Klassen (1992, 1994). The oldest tills are the Sutherland Group, consisting of the Mennon, Dundurn and Warman formations, of pre-Illinoian age. These are overlain by younger sediments of the Saskatoon Group, comprising the Floral and Battleford formations. The lower part of the Floral Formation is of Illinoian age, whilst the Upper Floral and Battleford Formations are Early and Late Wisconsinian age. In the Saskatoon area, where this stratigraphy was described by Christiansen (1992), at least six separate glacial events can be distinguished on the basis of till carbonate content. Varying composition at least implies unroofing of sources progressively lower in the bedrock stratigraphy, if not variation in distance as well as direction of transport. According to Schreiner (1990), ice flow directions ranging from westward to southeastward are indicated by the composition of Saskatchewan tills.

Survey design

The project originally was designed as an ultra-low density soil geochemical reconnaissance meant to define broad regional trends in geochemical baselines. Similar ultra-low density surveys based on 100 x 100 km grids have been carried out by the USGS (Severson and Tidball, 1979; Severson and Wilson, 1990) and are becoming increasingly applied elsewhere (Darnley et al., 1995). The sampling design for the present project, for which both soil and till would be sampled, had to fulfill two contrasting needs (Garrett, 1983). From the point of view of kimberlite/lamproite exploration, sample spacing had to be sufficient to intersect the glacial dispersal patterns from any significant clusters of kimberlites in the study area. With respect to estimating baseline levels, in order to characterize the different till units exposed at the surface, an essentially evenly distributed (i.e., random) sampling is required that gives all till and soil localities an equal chance of being selected (Garrett, 1994).

The sampling grid was designed using the 10 km UTM grid printed on 1: 250 000 topographic maps. The 80 x 80 cells stepped out both westward and eastward from the central meridian of each UTM zone. The southern boundary of the southernmost 80 x 80 km cell was at UTM northing 5 340 000 m. This

procedure led to some partially populated 80 x 80 cells at the UTM zone boundaries, however, the logistical convenience of this procedure was considered to outweigh this disadvantage.

The preferred site for soil sampling was the edge of agricultural land along a road allowance in or near the target cell. Inaccessible targets were relocated within the same 10 km cell if possible, or elsewhere in the same 20 km cell, or in one of the unsampled 20 km cells, if necessary. If only one 20 km cell within a 40 km cell was accessible, only one site was sampled. No preference for parent material or topographic position was permitted in soil sampling, except for avoidance of narrow stream valleys and sites inundated by water or peat. The objective was to collect an unbiased statistical sample of the soils in the study area. This would lead to a data subset, and subsequent statistics, weighted by the spatial frequency of the various till and soil environments across the study area, and so provide a valid basis for geochemical baseline level estimation.

All sites, including supplementary sites designed to characterize the variability of soil geochemistry on a hierarchy of scales, were to be sampled for A horizon and C horizon soil. Till, if present in the 40 km cell, was to be sampled at a nearby exposure such as a road cut at two sites per 40 km cell only.

Field procedures

Orientation sampling was carried out by the authors during August 1991. Survey sampling was completed on a contract basis by professional staff of the Alberta Research Council, during summer 1992. Sampling in the northeastern part of the area was completed in autumn 1992 by the first author.

The A and C horizons were chosen as the sampling media for soil geochemistry. The A horizon was readily identifiable as the blackish horizon at surface, typically a ploughed Ap horizon. The C horizon was sampled below the A horizon, and the B horizon, if present.

At 26 orientation transect sites and 352 survey sites, A horizon samples were obtained from an interval which ranged on average from 3 to 18 cm below surface, and C horizon samples from depths of 40 to 66 cm below surface. The A horizon sample was collected by making a small excavation through the entire A horizon with a shovel. After A horizon material was cleared from the pit, the C horizon sample was recovered with a Dutch auger. Soil samples were 1 to 2 l in size. Steel sampling tools were

sand-blasted at the start of the survey to remove coatings that could have contaminated sampled material. No contact of sample material with jewelry was permitted.

Till, unsorted Pleistocene glacial sediment, was chosen as the indicator mineral sampling medium, rather than more easily and inexpensively sampled and processed fluvial or glaciofluvial sediments. Till has a simpler transport history, more extensive occurrence, more uniform composition, and greater usefulness in the study of sediment provenance. A sampling depth below 0.8 m below surface was preferred in order to obtain material in which carbonate was less likely to have been precipitated or leached due to weathering. Till can be recognized in the field as a silty to sandy sediment which contains scattered pebbles and a clayey matrix. In the study area, the presence of very coarse sand grains in a silty matrix is diagnostic. These unsorted sediments are diamicts, regarded in most cases to be till, sediment deposited directly by glacial ice. No preference for any particular till type or stratigraphic affinity was applied. Such distinctions generally can only be made at large vertical exposures or in drill core.

Till samples were obtained at 16 orientation transect sites and 252 survey sites. In order to avoid laborious excavation from the surface, existing exposures, such as road cuts near the soil sites, were sampled. The exposure was cleared of a few tens of centimetres of material in order to sample undisturbed sediment. Rare deeper exposures, where unoxidized material might be exposed, were avoided in order to obtain till samples from which most or all of the sulphide fraction had consistently been lost to oxidation, thus simplifying the interpretation of heavy mineral geochemistry. Sand-blasted steel shovels and picks were used, and samples were homogenized in large plastic pans. Two samples, 2 and 3 l in size, weighing about 2 and 3 kg and intended for geochemical analysis and as a reserve respectively, were taken in plastic bags. A 25 l sample, which weighed 25 to 30 kg, from which heavy mineral and pebble fractions were to be recovered, was then placed in a plastic pail.

Most of the C horizon samples consist of oxidized till, however, many were derived from several other parent materials. Definitions of soil vary from the tendency of engineers to refer to all sediment as soil, to the view that only the A and B horizons are soil and the C horizon is sediment acting as parent material. Oxidation has had a profound effect on the geochemical behaviour of the near-surface glacial sediments by destroying virtually all sulphide mineral grains occurring above the water table (Shilts and

Kettles, 1990; Thorleifson and Kristjansson, 1993). Here, however, this material is referred to as till, rather than soil, in order to distinguish it from the A horizon and C horizon sets.

Field data were recorded at each site, and the actual sampling sites plotted on 1:250 000 topographic maps for later digitizing or manual UTM coordinate recovery. The field data provide information on the general sampling environment and observations on the colour, texture, moisture content, and composition of the soil and till.

Indicator mineral methods

Introduction

Indicator mineral tracing involves the sampling of sediments dispersed from bedrock sources by earth surface processes, the classification of mineral grains (in most cases by density and/or magnetic methods), and the recognition of mineral grains which indicate the presence of mineral deposits in the area from which the sediments were derived. Examples of indicator minerals include garnets, pyroxenes and oxides associated with potentially diamond-bearing kimberlites and lamproites, visible gold grains, sulphides in unoxidized sediments collected below the water table, and scheelite.

In Canada, the most common sediment available for indicator mineral sampling is till, which has, at least, been transported by glacial processes. In some cases, glacially transported mineral grains may also have been transported by fluvial action in preglacial or interglacial time, and material may have undergone multiple phases of glacial transport. Glaciofluvial sediments such as eskers, as well as fluvial sediments in modern rivers, have undergone an even more complex transport history involving the reworking of till and other sediments.

Ideally, indicator mineral analyses are used in three phases of diamond exploration, two using sediment and one using rock:

1. Following the selection of a region which is favourable for diamond potential with respect to tectonic context, sediment sampling at spacing on the order of 10 km is used to narrow the area of interest. Fluvial and glaciofluvial sediments, rather than till, may in some cases be favoured on the basis of ease of sampling and processing. Areas of interest on the order of 100 km across are

designated on the basis of elevated frequency and more favourable chemistry of recovered indicator minerals.

2. Geophysical surveys are conducted in the selected area. In areas where relatively thin till outcrops, sampling of till at spacing on the order of 100 m along several lines down-ice from the target and oriented perpendicular to ice flow may be used to test geophysical targets with respect to their lithology and indicator mineral chemistry.
3. Geophysical targets where the most favourable indicator mineral chemistry is obtained are chosen for drilling. A small sample of the intrusion, such as a diamond drill core, is processed for indicator mineral and petrological studies. Ideally, it is only on the basis of promising indicator mineral chemistry that a decision to extract an expensive bulk sample for diamond grade assessment would be made.

Most published literature on minerals derived from kimberlite relates to work on kimberlites themselves. Relatively little literature is available regarding the size, shape, and surface textures of minerals dispersed from kimberlite sources. Furthermore, clearly defined methods for the differentiation of likely-kimberlitic minerals from background minerals have not been published. Useful general discussions on the use of glacial sediments in mineral exploration programs have been presented by Shilts (1982, 1984), DiLabio (1989), Hirvas and Nenonen (1990) and Saarnisto (1990).

Kimberlite indicator minerals include: certain types of pyrope and almandine from the garnet group of silicate minerals; chrome-bearing forms of the relatively common pyroxene mineral diopside; and magnesian examples of the oxide minerals ilmenite and spinel. All of these minerals have specific chemical compositions which relate to conditions during crystallization in kimberlite or rocks such as peridotite or eclogite which were transported by the kimberlite. Perhaps the best known kimberlite indicator mineral is purplish Cr-pyrope garnet. In most cases, these garnets are derived from disaggregated peridotite xenoliths, which are the principal source of diamond in kimberlite (Deer et al., 1982; Fipke, 1989; Gurney and Zweistra, 1995). Dawson and Stephens (1975, 1976) and Gurney (1984) established protocols for the classification of kimberlitic garnets, with names derived from arbitrarily sequenced group numbers. For example, subcalcic to calcic, non-titanian Cr-pyropes were classified as Groups 10, 9, and 7 (respectively G10, G9, G7), and were attributed to harzburgites,

lherzolites, and wehrlite respectively. Titanian Cr-pyropes, of a distinctive rich orange to purple-orange colour, were classified as G1 and G2, on the basis of increasing TiO_2 content, and G11 in the case of pyropes rich in both TiO_2 and Cr_2O_3 . Pyropes with very high chrome content were classified as G12. Eclogite xenoliths, which also supply abundant diamonds to some kimberlites, contain titanian, calcic, and magnesian orange-coloured almandine garnets, which were classified as G3, G4, G6, and G8 by Dawson and Stephens (1975, 1976), on the basis of TiO_2 and CaO content. Crustal almandine garnets have the composition of the G5 group defined by these authors.

Diopsides with $>0.50\%$ Cr_2O_3 commonly occur in kimberlite (Deer et al., 1982; Fipke, 1989), as well as various other rocks. Hence the degree to which kimberlite indicator minerals are exclusive to kimberlite varies. From the oxide group of minerals, Mg-ilmenites with $>6\%$ MgO and Cr-spinels with $>60\%$ Cr_2O_3 and $>12\%$ MgO are also used as kimberlite indicators (e.g., Gurney and Moore, 1993).

Sample size is a critical issue in indicator mineral tracing (Craigie, 1993; Davison, 1993; Gregory and White, 1989; Clifton et al., 1969). The fundamental requirement is for a sufficient number of grains to be present in each sample, in areas where such grains occur, for regional trends in indicator mineral frequency to be mapped. A 25 l sample size was chosen for the orientation transect and confirmed for the survey on the basis of advice received regarding current activity in the region, as well as experience in northern Ontario (Thorleifson and Kristjansson, 1993). This sample size was considered marginally acceptable, but appropriate due to the logistical challenge and expense of larger samples.

Mineral processing methods: orientation

In the case of the orientation samples collected in 1991, experiments in the refinement of preconcentration procedures at the Saskatchewan Research Council (SRC) were followed by processing at CF Mineral Research of Kelowna, British Columbia. The till, washed of clay and fine silt, was separated at 2.96 specific gravity using tetrabromoethane. The >2.96 specific gravity fraction was subsequently separated at a specific gravity of 3.2 using methylene iodide (MI) diluted with acetone. The MI concentrate was screened at 0.25 mm (60 mesh) and 0.063 mm (230 mesh). Ferromagnetic minerals, mainly magnetite, were removed using a Carpcop top feed roll separator. The

almandine and ferro-ilmenite rich paramagnetic fraction was removed using a Carpc bottom-feed separator, followed by Frantz isodynamic separation at low amperage. A higher amperage Frantz pass was then used to remove the nonmagnetic fraction from the weakly paramagnetic fraction, which was subsequently visually examined for potential kimberlitic indicator minerals.

A total of 3457 grains, or an average of about 70 mineral grains per sample, were selected from the orientation samples, mounted, and polished by CF Minerals staff. About 75% of these mounted grains were regarded as potential eclogitic almandine garnets. Black opaque grains, considered possible Mg-ilmenites and Cr-spinels, as well as potential lamproitic tourmalines, each make up about 10%. The remaining grains were green clinopyroxenes, potentially Cr-diopsides, and a total of 6 purplish grains considered likely to be peridotitic garnets. Of the 3457 grains which were picked as potential indicator minerals, about 70% of the grains were from the 0.25 to 2.0 mm fraction. The remainder were recovered from the 0.063 to 0.25 mm fraction of five samples in order to test the viability of using this fraction. The grains, mounted and polished in four 25 mm epoxy cylindrical mounts, were analyzed by CF Minerals using multi-element EDS mapping followed by quantitative EDS analysis of selected grains. These grains were subsequently re-analyzed by electron microprobe at the GSC in order to test analytical procedures being developed for this application.

At the GSC, a reference set of non-kimberlitic grains which occur in abundance in all samples was selected from the orientation samples and analyzed to obtain comparative data for non-kimberlitic minerals in the area. A total of 1378 grains were mounted from four sites. Two of these sites were located in Alberta, near Suffield and Vegreville. The remaining two sites were located near Lanigan, Saskatchewan, and River Hills, Manitoba. The grains were mounted and polished in two 25 mm araldite cylindrical mounts. The grains were selected on the basis of the following preliminary visual identifications: 160 pink garnets, 160 orange garnets, 160 clinopyroxenes, 80 hornblendes, 80 orthopyroxenes, 50 epidotes, 10 barites, 20 rutiles, 160 black opaques, 80 grey ilmenites, 80 magnetites, 40 hematites, 10 goethites, 10 tourmalines, 10 apatites and gahnites, 10 leucoxenes, 40 staurolites, 40 sphenes, 30 weakly paramagnetic garnets, 30 weakly paramagnetic clinopyroxenes, 28 weakly paramagnetic black opaques, 30 paramagnetic garnets, 30 paramagnetic clinopyroxenes, and 30 paramagnetic black opaques.

Mineral processing methods: survey

The 25 l till samples collected for the 1992 regional survey were processed at the SRC. The material was disaggregated in a cement mixer with the aid of a sodium hexametaphosphate (calgon) solution (Fig. 2). In a few cases, repeated washings were required to prevent flocculation of sulphate- and carbonate-rich samples. The disaggregated till was screened at 10 mesh to remove the >2 mm fraction which was washed, dried, screened at 4, 8, and 16 mm, and weighed.

The -10 mesh (<2 mm) fraction was pre-concentrated at SRC by passing it over a shaker table twice to obtain large heavy mineral preconcentrates which were then transferred to Overburden Drilling Management in Nepean, Ontario. The concentrates were renumbered and randomized in order to avoid uncertainty in distinguishing trends related to spatial distribution from those related to analysis order. The material was screened at 0.5 mm and all >0.5 mm material was submitted directly to heavy liquid separation. The <0.5 mm fractions were inspected for visible gold on a shaker table. Samples in which three or more gold grains were seen were panned in order to count and size the gold. Following panning, the gold was returned to the table concentrate which was dried and further concentrated using methylene iodide diluted with acetone to 3.2 specific gravity. The ferromagnetic fraction, averaging 4 g in the Alberta samples, was removed using a hand magnet. The concentrates were then also screened at 0.25 mm in preparation for indicator mineral analysis.

The coarse heavy mineral concentrates were returned to the SRC and examined for potential indicator minerals under a stereoscopic microscope. An average of 15 minutes were spent examining an average of 3 g of 0.5 to 2.0 mm nonferromagnetic concentrate from each sample. The 0.25 to 0.50 mm nonferromagnetic fraction, which averaged 5 g in total mass, was sorted by magnetic susceptibility using a Frantz isodynamic separator. The strongly paramagnetic fraction, rich in ferro-ilmenite, was not examined. The moderately paramagnetic fraction, which in this area contains abundant Fe-rich almandine garnet, was visually scanned for Mg-ilmenite and Cr-spinel. The weakly paramagnetic to nonmagnetic fraction was visually scanned for indicator garnets and pyroxenes. An average of 20 minutes were spent examining each 0.25 to 0.50 mm fraction.

All visually selected grains, an average of 30 per site, were subsequently re-examined by the mineralogical staff of Consorminex Inc. of Gatineau, Quebec, and unwanted minerals such as staurolite and

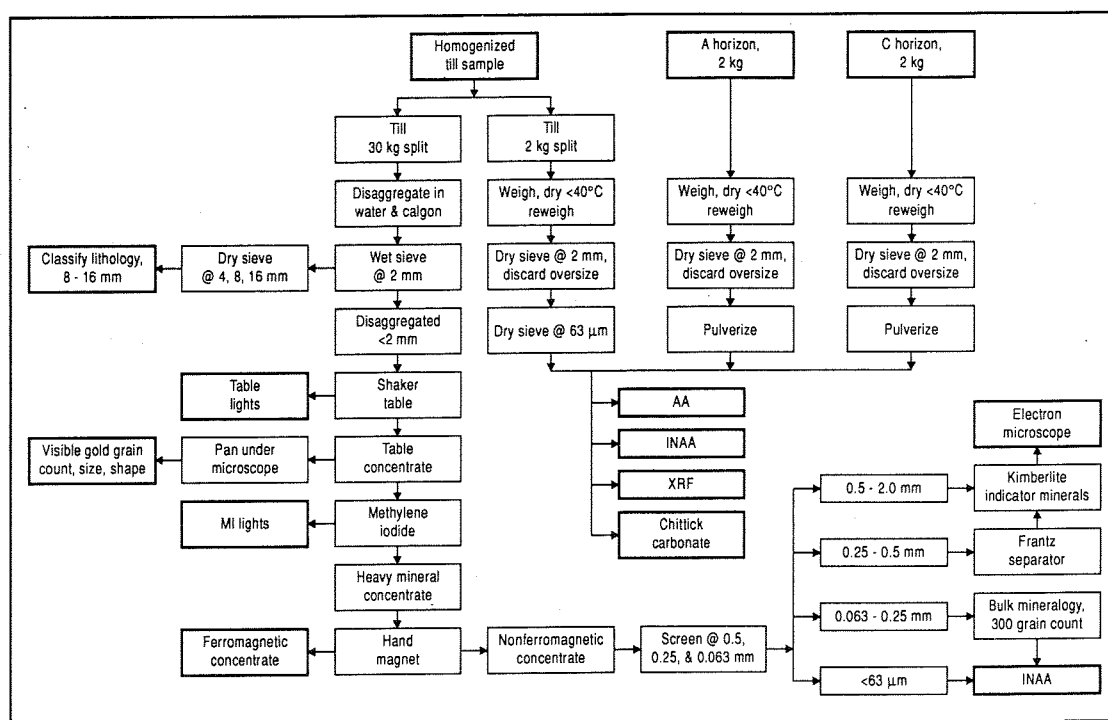


Figure 2. Sample processing flow-sheet.

hornblende were removed on the basis of properties such as birefringence. An average of 8 grains per sample, averaging 4 from the 0.25 to 0.50 and 4 from the 0.25 to 0.50 mm fraction, were selected for analysis.

Minerals were mounted in 25 mm cylindrical araldite mounts, with grains arranged in rows within 9 cells per mount. Grains from the 0.5 to 2.0 mm fraction were arranged in 5 rows of 6 grains per cell, to yield a total of 270 grains per mount. Grains from the 0.25 to 0.5 mm fraction were placed in 8 rows of 10 in each cell, resulting in a total of 720 grains per mount. The mounts were polished using diamond paste. Maps recorded the site number and identification number of each grain.

Microprobe analysis

In the case of the orientation sampling, coordinates of points to be analyzed were entered using an optical microscope. One point in the core of each grain was analyzed at the GSC, with care to avoid inclusions, fractures, or pits. A second point was analyzed at the end of the batch for one grain in every 20, in order to assess analytical variability. In order to make possible the analysis of a very large number of grains, high amperage (200 nA, 20 kv) and short counting times were used. Values reported for potassium and sodium by this method are of low reliability. Background

counts were included in the routine for each element. Detection limits were estimated by calculation to be about 0.01 wt. % for SiO_2 , Al_2O_3 , CaO , FeO , MgO , Cr_2O_3 , TiO_2 , Na_2O , and K_2O ; 0.02 wt. % for MnO , NiO , ZnO , and CoO ; 0.04 wt. % for Nb_2O_5 ; and 0.05% for V_2O_5 .

Chemical analyses of a total of 7813 grains from the 1992 regional survey samples were carried out in the Canada Centre for Mineral and Energy Technology (CANMET) laboratories in Ottawa, using a JEOL 8900 electron microprobe operating at 40 nA and 20 kV. Peak counting times of 10 seconds were used for Na_2O , K_2O , CaO , total Fe as FeO , MgO , Al_2O_3 , MnO , and SiO_2 , and 40 seconds for TiO_2 and Cr_2O_3 . Calibration was confirmed at the beginning and end of each batch. In order to reduce machine time, background determinations were made on every 50th grain and used for the 50 grains which followed. Hence detection limits were elevated above the levels normally used in research work. The analyses were completed in 11 automated runs which were driven by a set of x-y-z coordinates for one point per grain, selected to avoid inclusions, fractures or pits. At the end of each batch, every 45th grain, on average, was re-analyzed at another similar point to monitor precision related to grain heterogeneity, calibration drift, or unusual background measurements. These replicates indicate good reproducibility at levels above 0.1% for all elements, with a few exceptions attributed to heterogeneity.

Subsequent to the initial microprobe analyses, a total of 156 eclogitic garnets and garnets which only marginally failed to surpass the definition being used for eclogitic garnets were re-analyzed at CANMET using detection limits which were reduced by the inclusion of background measurements with every analysis. These analyses were carried out to obtain acceptable Na₂O sodium data used to assess the potential association of eclogitic garnets with diamond (Gurney and Moore, 1993), and to enhance TiO₂ data which were being used for the recognition of eclogitic garnets. A total of 233 Cr-pyropes and 136 Cr-spinels were analyzed by proton microprobe at the University of Guelph for Ni and several other elements in order to utilize classification methods developed by Griffin and Ryan (1993). Nickel temperatures were calculated for Cr-pyropes using the equation presented by Griffin et al. (1989).

Geochemical methods

The <2 mm fraction of soil samples was utilized for geochemical analysis in order to conform with accepted agricultural and environmental analytical protocols. As has been done elsewhere for till geochemical studies (e.g., Eden and Bjorklund, 1995), the <0.063 mm fraction of till was prepared. This fraction, from which the silica-dominated sand fraction is excluded, provides a greater reflection of regional bedrock composition and hence provenance.

The 2 l soil and till samples were air dried below 40°C, gently disaggregated, avoiding the crushing of rock and mineral grains, and screened using a 2 mm stainless steel sieve. The oversize was discarded. Approximately 50 g of the <2 mm soil was ground to <0.150 mm in an agate pestle and mortar and stored for analysis. In the case of till, enough of the retained <2 mm material was screened using a 0.063 mm stainless steel sieve to yield approximately 50 g of material that was stored for analysis. The remaining <2 mm soil and till was archived.

Prior to analysis, 33 quality assurance samples were added to the 252 field till samples to be analyzed. These quality assurance samples consisted of 22 randomly selected sample preparation duplicates (second cuts of 50 g of the <0.063 mm fraction) intended to monitor precision, as well as 11 aliquots of certified reference materials (coded as sample 7) intended to monitor accuracy. The soil samples, consisting of two sets of 352 A and C horizon soil samples, were augmented with 32 sample preparation duplicates consisting of material from code 5 sites split after preparation, the resulting sample being coded as

sample 6. Sixteen control samples consisting of certified reference materials and material from bulk samples prepared as project references were added to each soil batch.

The A horizon, C horizon, and till sample sequences for the entire prairie survey were each randomized and renumbered prior to analysis in order to prevent the mistaken attribution of analysis order trends to spatial patterns.

All samples were submitted to Becquerel Laboratories, Inc., Mississauga, Ontario, for instrumental neutron activation analysis (INAA) which produced data for 34 elements. A fixed volume of prepared material, averaging 7.3 g (4.82 to 10.12 g), was encapsulated, sealed and irradiated with neutron flux monitors in a 2 MW pool-type reactor. Following a 7 day decay period, the samples were analyzed using a high-resolution Ge detector system. Gamma radiation was counted for approximately 500 seconds. Usable data were obtained for the elements indicated in Table 1.

Table 1

Elements for which geochemical data were obtained, with lower limit of detection indicated

INAA		AAS		XRF	
As	0.5 ppm	Ag	0.2 ppm	SiO ₂	0.01%
Au	2 ppb	Cd	0.2 ppm	Al ₂ O ₃	0.01%
Ba	50 ppm	Co	2 ppm	CaO	0.01%
Br	0.5 ppm	Cu	2 ppm	MgO	0.01%
Ce	5 ppm	Fe	0.02 %	Na ₂ O	0.01%
Cs	0.5 ppm	Hg	10 ppb	K ₂ O	0.01%
Co	5 ppm	Mn	5 ppm	Fe ₂ O ₃	0.01%
Cr	20 ppm	Mo	2 ppm	MnO	0.01%
Eu	1 ppm	Ni	2 ppm	Cr ₂ O ₃	0.01%
Fe	0.2 %	Pb	2 ppm	P ₂ O ₅	0.01%
Hf	1 ppm	V	5 ppm	TiO ₂	0.01%
La	2 ppm	Zn	2 ppm	LOI	0.01%
Lu	0.2 ppm			Ba	10 ppm
Na	0.02%			Nb	10 ppm
Rb	5 ppm			Rb	10 ppm
Sb	0.1 ppm			Sr	10 ppm
Sc	0.2 ppm			Y	10 ppm
Sm	0.1 ppm			Zr	10 ppm
Ta	0.5 ppm				
Tb	0.5 ppm				
Th	0.2 ppm				
U	0.2 ppm				
W	1 ppm				
Yb	1 ppm				

At Barringer (Alberta) Laboratories, Ltd., a 1 g aliquot from each of the same vials already subsampled for INAA was decomposed, with a fuming mixture of HF, HClO₄, and HNO₃, to near dryness on a hot plate. The residue was taken into solution with concentrated HCl and, following dilution to a 1 M concentration, was analyzed by flame atomic absorption spectrophotometry (AAS) for elements indicated in Table 1. Mercury was determined on a separate 0.5 g aliquot by flameless AAS after an aqua-regia dissolution.

The till and C horizon soil samples also were analyzed for major elements by X-Ray Fluorescence (XRF) following fused disk preparation at XRAL Laboratories, Don Mills, Ontario, for elements indicated in Table 1.

The <0.25 mm nonferromagnetic heavy mineral concentrates were screened at 0.063 mm in preparation for mineralogical as well as geochemical analysis. After a few milligrams of the 0.063 to .25 mm fraction were obtained for mineralogical analysis by coning and quartering, 0.063 to 0.25 mm fractions averaging 21 g and <0.063 mm fraction averaging 3 g were analyzed by nondestructive INAA at Becquerel Labs. The <0.25 mm concentrate was divided at 0.063 mm in order to permit the comparison of sand and silt sized material, including comparison of the geochemical data to visual mineralogical counts of the 0.063 to 0.25 mm fraction. The entire concentrate was analyzed. Data for samples split into multiple INAA vials were recombined by weighted average. Due to variable and frequently small sample sizes, detection limits vary. Data for the 0.063 to 0.25 mm and <0.063 mm fraction were retained separately, as well as being combined by calculation of a weighted average in order to obtain data for the <0.25 mm heavy mineral fraction.

Lithological methods

The texture of the <2 mm matrix of till samples collected along the orientation transect was determined by GSC staff using methods described by McDonald and Kelly (1968). A 50 g split was used for textural analysis. An additional 10 g sample was tested for moisture content. The subsample was disaggregated by freeze-drying and subsequently by treatment with 0.5N sodium hexametaphosphate. The sample was then mechanically mixed, heated to boiling, cooled, stirred and subjected to an ultrasonic probe for 20 seconds. Sand fractions were determined by dry sieving. The material finer than 0.063 mm was analyzed by pipette analysis.

The carbonate content of the <0.063 mm till matrix was analyzed using a technique for the Chittick gasometric apparatus described by Dreimanis (1962). Because of the contrasting reaction rates of calcite and dolomite in HCl, two readings of the amount of carbon dioxide produced by these reactions could be taken and the contributions of each of these minerals to total carbonate in the sample could be estimated.

The 8 to 16 mm fraction of till samples was classified with respect to lithology. The 4 to 8 mm and 2 to 4 mm fraction for selected samples were classified in order to compare fractions.

Bulk mineralogy of the 0.063 to 0.25 mm nonferromagnetic heavy mineral concentrates was determined by the staff of Consorminex Inc. on the basis of visual identification, under a stereoscopic microscope, of 300 grains in an araldite mount. This size fraction corresponds to that used in similar surveys elsewhere (Parfenoff et al., 1970; Karrow, 1976; Gwyn and Dreimanis, 1979; Paré, 1982; Peuraniemi, 1990), where the objective has been to determine the bedrock source of sediments.

KIMBERLITE INDICATOR MINERALS

The mean total moist weight of the 25 ℓ till samples from the prairie survey was 28 kg. The 2 ℓ till samples, which had been stored in sealed pails, were weighed before and after being air dried at <40°C. The resulting moisture content determinations averaged 10%, hence the mean air dry weight of the large till samples was 25 kg. The samples contained an average of 2 kg of gravel (>2 mm). The mean sand content of the <2 mm fraction of the orientation samples was found to be 35% (Garrett and Thorleifson, 1993), so the total amount of sand in the samples was about 8 kg. About 3 kg consisted of medium to very coarse sand, the fraction eventually used for indicator mineral analysis.

Electron microprobe data were used to assign mineral identifications. The data are considered clearly adequate for the recognition of Cr-pyroxene, Mg-ilmenite, and Cr-spinel, adequate for the selection of Cr-diopsides, and marginally adequate for the distinction of eclogitic Ti-almandines (>0.2% TiO₂). Garnets were classified using a scheme based on those of Dawson and Stephens (1975, 1976), Gurney (1984), and Gurney and Zweistra (1995). Diopsides with >0.50% Cr₂O₃ were regarded as Cr-diopside (Deer et al., 1982; Fipke, 1989). Mg-ilmenites in every case contained well in excess of 6% MgO. Cr-spinels exceeding 60% Cr₂O₃ and 12% MgO were regarded as

compositions comparable to those reported for diamond inclusions by Gurney and Moore (1993).

Among the 252 survey samples, a total of 148 mineral grains were judged to be kimberlite indicator minerals, which also serve as the principle indicator for lamproites, despite their lower abundance in the latter rocks. This frequency can be approximated as one indicator mineral in every second sample.

A total of 67 Cr-pyropes were recovered. The majority of these grains have non-titanian, peridotitic compositions. One grain is a calcium-rich G7, 33 are lherzolitic or G9, and one grain, recovered near Provost, at the Saskatchewan border in the east-central part of the area (Fig. 1; Table 2), was classified as a subcalcic G10. The remaining 32 Cr-pyropes are titanian in composition (G1, G2, G11). These pyropes show a nonrandom distribution (Fig. 3), with the

Table 2
G7, G9, G10, and G11 garnets recovered from till (approx 25 kg) in southern Alberta

Site	NTS sheet	Location name	UTM coordinates	Mineral ID	CaO %	Cr ₂ O ₃ %	TiO ₂ %	Temp C	Ni ppm	Zr ppm
5-2-2	83J	Vega	11 670100	6031800 G9	5.72	5.34	0.23	894	26	20
15-4-2	83H	Spruce Grove	12 305300	5946000 G9	5.01	4.34	0.26	1008	39	194
16-3-1	83A	Ponoka	12 316900	5842600 G9	6.05	4.95	0.03	781	16	5
16-3-1	83A	Ponoka	12 316900	5842600 G9	6.09	4.97	0.03	932	30	6
19-4-1	82I	Carseland	12 321900	5637500 G9	5.09	4.61	0.20	950	32	31
20-3-1	82H	Ft. Macleod	12 311900	5528700 G9	4.84	2.46	0.01	583	5	16
21-3-1	82H	Cardston	12 332900	5444200 G9	5.82	7.28	0.04	852	22	152
24-2-2	83I	Perryvale	12 344500	6042900 G9	5.75	5.94	0.07	na	na	na
24-4-2	83I	Valley Lake	12 383000	6020500 G9	5.44	5.44	0.22	1111	53	18
27-2-1	83A	Buffalo Lake	12 373500	5808500 G11	6.20	7.99	0.45	959	33	37
30-1-2	82H	Lethbridge	12 365700	5519600 G11	5.90	6.39	0.78	1323	88	112
30-4-2	82I	Enchant	12 394700	5557800 G9	6.20	7.79	0.17	1016	40	122
31-3-2	82H	Raymond	12 387800	5459500 G9	5.42	3.43	0.03	768	15	14
34-2-2	73L	Whitefish L	12 432900	6015000 G9	4.23	2.67	0.21	1131	56	13
34-3-1	73L	Vincent L	12 482000	5997300 G9	5.69	6.08	0.25	1008	39	47
34-4-2	73L	Frenchman L	12 475000	6037200 G9	4.57	2.79	0.19	1016	40	19
34-4-2	73L	Frenchman L	12 475000	6037200 G9	5.07	5.72	0.14	818	19	22
37-1-2	83A	Sullivan Lake	12 421600	5762700 G9	4.88	4.82	0.17	841	21	15
37-3-1	73D	Coronation	12 480900	5776800 G9	4.61	3.02	0.08	739	13	12
38-3-1	72M	Oyen	12 497200	5685900 G9	6.43	7.39	0.06	1039	43	7
38-4-1	72M	Hanna	12 470200	5724900 G9	4.60	2.51	0.30	1170	62	16
40-1-1	72E	Purple Springs	12 439300	5521600 G9	5.28	3.87	0.08	884	25	61
41-2-1	82H	Wrentham	12 424100	5483600 G9	5.36	2.89	0.04	400	0	18
41-4-2	72E	Foremost	12 478100	5467500 G9	5.97	6.56	0.24	984	36	34
44-1-1	73E	Vermilion	12 503200	5919400 G9	5.63	5.46	0.07	950	32	4
44-2-2	73E	Elk Point	12 506700	5970100 G9	4.79	3.73	0.00	794	17	42
44-4-2	73E	Heinsburg	12 541600	5951800 G9	4.52	2.67	0.22	950	32	23
46-3-2	73D	Provost	12 564900	5768200 G10	4.68	6.56	0.01	894	26	88
47-1-1	72M	Oyen	12 530300	5697100 G11	5.87	6.39	0.86	1295	83	112
47-1-1	72M	Oyen	12 530300	5697100 G11	6.14	6.95	0.86	1317	87	112
47-4-1	72M	Oyen	12 549100	5720100 G9	5.00	4.03	0.13	894	26	22
47-4-2	72M	Oyen	12 542600	5734200 G7	7.35	6.11	0.18	884	25	8
48-1-1	72L	Suffield East	12 535000	5581400 G9	4.83	3.78	0.18	806	18	20
48-3-1	72L	Schuler	12 562900	5582900 G9	4.53	3.08	0.18	806	18	22
48-3-1	72L	Schuler	12 562900	5582900 G11	5.92	6.09	0.89	1448	112	140
48-3-2	72L	Suffield East	12 552200	5590000 G9	6.39	7.89	0.08	830	20	1
49-1-1	72E	Cypress Hills	12 533900	5504000 G9	5.19	6.24	0.22	1350	93	68
50-2-1	72E	Pakowki Lake	12 507100	5475800 G9	5.00	4.27	0.03	781	16	22
50-3-2	72E	Wildhorse	12 555300	5432500 G9	4.55	3.46	0.22	1024	41	20
50-3-2	72E	Wildhorse	12 555300	5432500 G9	4.66	3.48	0.24	1016	40	23
50-3-2	72E	Wildhorse	12 555300	5432500 G11	5.83	7.58	0.43	923	29	32

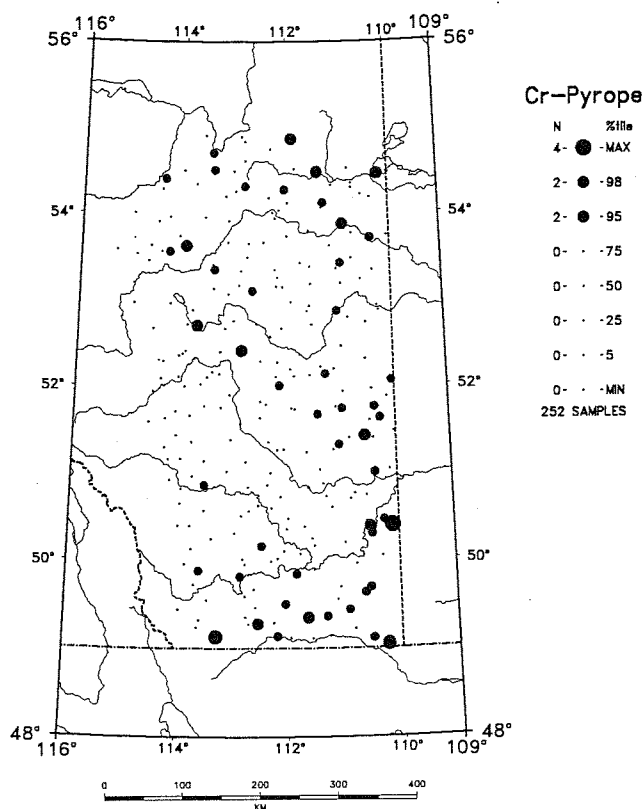


Figure 3. Cr-pyropes (0.25–2 mm) recovered from 25 l till samples.

highest concentrations in the southern, east-central, and northern parts of the survey area. The most noteworthy cluster is located 50 km north of Medicine Hat, east of Canadian Forces Base Suffield.

Ni determinations by proton microprobe on a total of 40 garnets classified as G7, G9, G10, and G11 were used in a geothermometry study. Although there is some uncertainty regarding precision of the method and validity of the assumptions (e.g., Kjarsgaard, 1992, 1995), tentative conclusions may be made by assuming a 40 mW/m² geotherm (Griffin et al., 1989) and acceptable calibration to other instruments. On that basis, 12% of the garnets, mostly G11, report temperatures above the diamond stability field (>1250°C, >75 ppm Ni), 38% are in the diamond stability field (32–75 ppm Ni), and 50% are cooler (<950°C, <32 ppm Ni). The G10 at Provost reported a Ni concentration of 26 ppm, implying a low temperature of formation (~890°C). The grains indicating temperatures in the diamond stability field are scattered across the area. Six grains occur along a belt of Cr-pyrope occurrences across the northern part of the study area (Fig. 3), five in the central portion of the study area, and four in the south. Of the grains in the Griffin diamond window (950–1250°C, 32–75 ppm Ni), 87% contain <50 ppm Zr, a positive sign

regarding diamond grade, according to Griffin and Ryan (1993) and Griffin et al. (1994a, b). Among the diamond stability field Cr-pyropes, only one in the central belt and one in the southern belt contained >50 ppm Zr.

Using a minimum TiO₂ value of 0.25%, Thorleifson and Garrett (1993) identified 4 titanian, calcic, and magnesian, hence eclogitic, almandines (G3, G4, G6) from the survey samples. At a lower cutoff of 0.2%, Thorleifson et al. (1994) reported the occurrence of 16 eclogitic garnets on the basis of re-analysis data. These grains were obtained from sites in the southeastern, east-central, and north-central portions of the area. None of these grains was found to contain anomalous concentrations of Na₂O.

A total of 51 Cr-diopsides were recovered from the survey samples (Fig. 4). These occurrences show a tendency toward east-west alignment, similar to the pattern shown by Cr-pyropes (Fig. 3). A cluster of occurrences north of Medicine Hat coincides with occurrences of Cr-pyropes (Fig. 3). Clusters in Cr-diopside frequency also are apparent near Oyen and Red Deer, as well as elevated frequency in the northern portion of the study area.

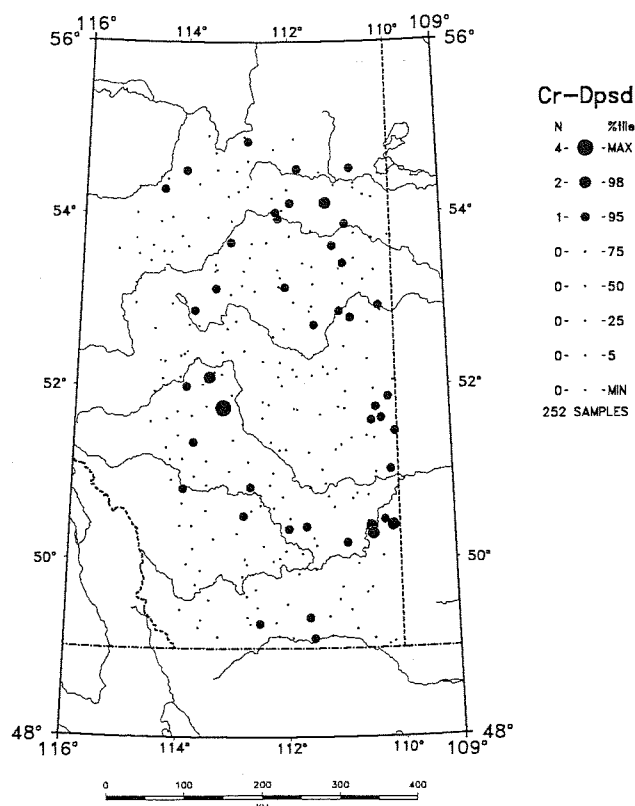


Figure 4. Cr-diopsides (0.25–2 mm) recovered from 25 l till samples.

A total of 26 Mg-ilmenites were recovered from the survey samples (Fig. 5). Two were recovered from the sample that yielded a G10, near Provost. Occurrences of Mg-ilmenites also are relatively concentrated in the Red Deer area.

A total of 18 Cr-spinels were recovered from the Alberta survey samples (Fig. 6), with occurrences tending to occur in the western half of the area. None of these grains exceeds 60% Cr₂O₃ and 12% MgO, values characteristic of diamond inclusion spinels. The prairie-wide Cr-spinel data are readily divisible into two clusters separated at 53% Cr₂O₃. Above this value, Ni concentrations cluster between 200 and 800 ppm. This group is comparable to the P1 cluster from kimberlites reported by Griffin and Ryan (1993, 1995). Below 53% Cr₂O₃, Ni values are more variable, ranging from 200 to 2000 ppm. This compositional range is comparable to the P3 and P4 clusters of Griffin and Ryan (1993, 1995). High-Cr grains preferentially occur in the eastern half of the prairie region, including eastern Saskatchewan, whereas grains recovered in Alberta tend to be low-Cr grains.

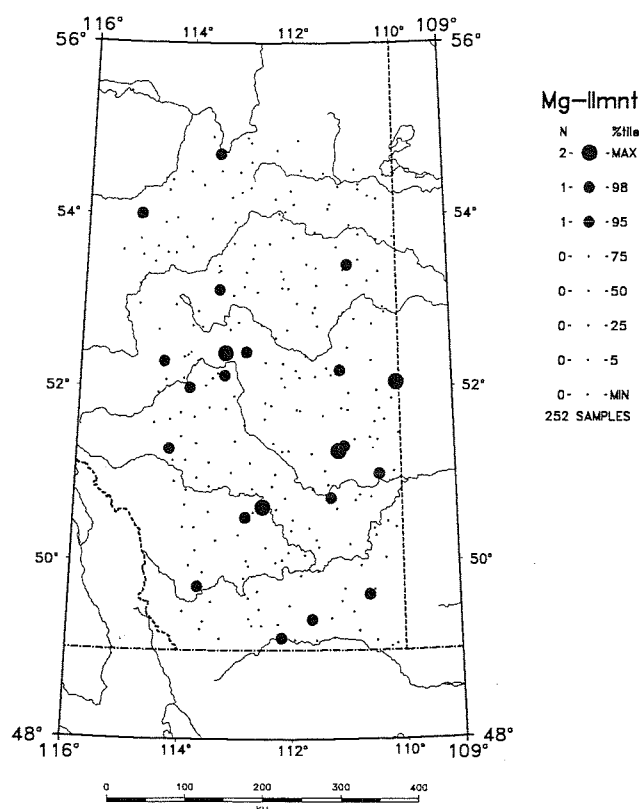


Figure 5. Mg-ilmenites (0.25–2 mm) recovered from 25 l till samples.

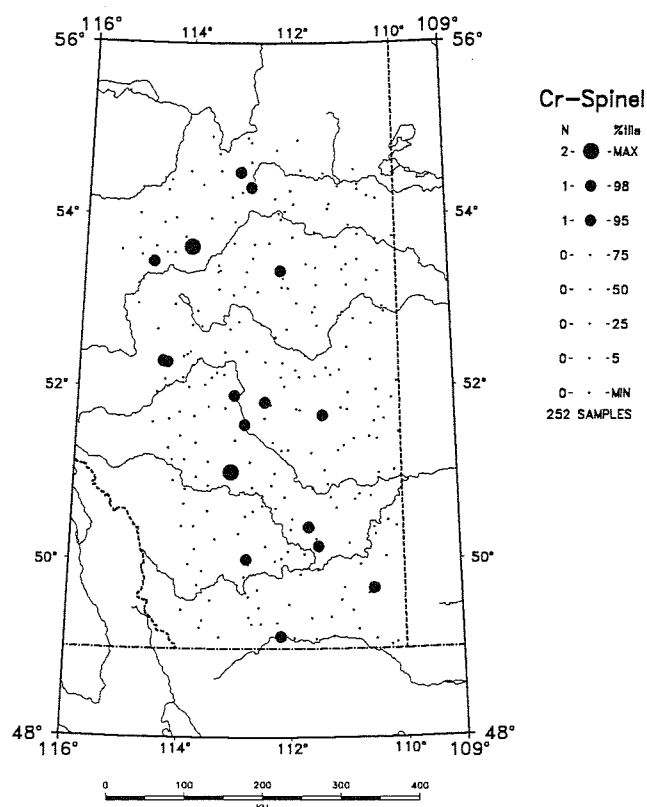


Figure 6. Cr-spinels (0.25–2 mm) recovered from 25 l till samples.

VISIBLE GOLD

The 25 l till samples contained as many as 19 visible gold grains per sample (Fig. 7). The highest counts were obtained in the Edmonton area, an area of former placer gold production (Halferdahl, 1965; Romaniuk, 1981; Giusti, 1986, 1987; Day and Fletcher, 1987; Edwards, 1990). At least one visible gold grain was recovered in 75% of the samples, and of these grains, approximately 70% are about 0.075 mm or smaller (i.e., silt sized). The remainder are sand-sized grains with dimensions exceeding 0.3 mm in only a few cases. In the opinion of the staff of Overburden Drilling Management Ltd., the majority of the grains exhibit characteristics typical of glacially transported gold, such as tool marks and folding. A few of the grains exhibit characteristics more typical of placer deposits, such as raised rims.

Provenance of the grains in Alberta is thought to be primarily from the Cordillera, by some combination of eastward fluvial transport in Cretaceous, Tertiary, or interglacial time, Cordilleran ice flow, and at least one phase of Laurentide glacial transport. In addition, intrusions penetrating the Phanerozoic sequence may be contributing visible gold (Harris and Ballantyne,

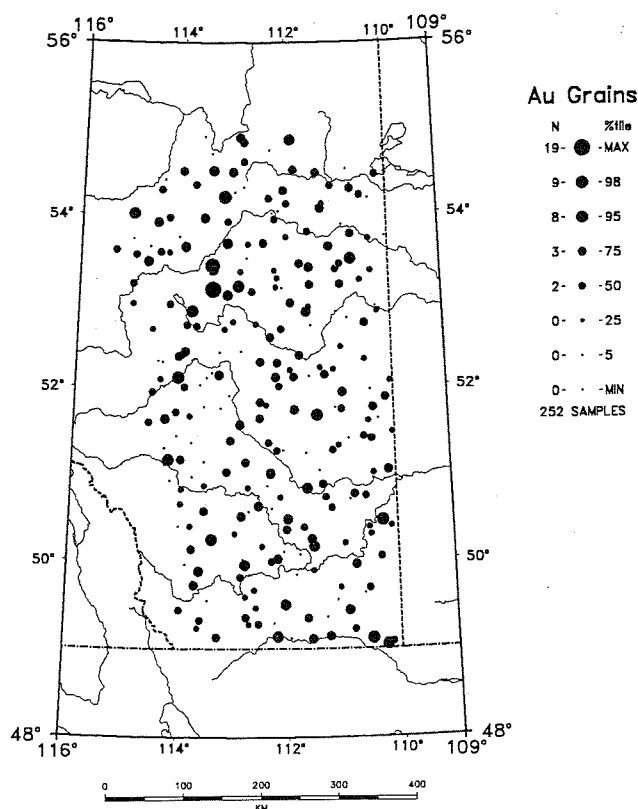


Figure 7. Visible gold grains recovered from 25 l till samples.

1994; Ballantyne and Harris, 1997), and long distance transport from the Canadian Shield is likely the source for some of the grains. Paleoplacers in Early Cretaceous rocks of the Foothills Ranges, such as the McDougal-Segur conglomerate (Leckie and Craw, 1997), may be the source for some of the gold.

GEOCHEMISTRY

Till matrix geochemistry

As was previously documented by Bayrock and Pawluk (1967), geochemical data for the fine grained matrix of till across Alberta reveal broad-scale patterns that can be related to regional provenance. In addition, a number of elements exhibit patterns that may be related to mineral occurrences, even though they are of low geochemical contrast. The broadest division that can be delineated in the geochemical data is the distinction between an area extending north and south from Calgary and the remainder of the area. For example, As values in the <0.063 mm fraction are depressed around Calgary (Fig. 8), whereas Cd values are elevated (Fig. 9). In addition, As values are elevated in the south-central part of the study area, in the Brooks region, which may be due to an area of more metalliferous shale, perhaps the Bearpaw. A

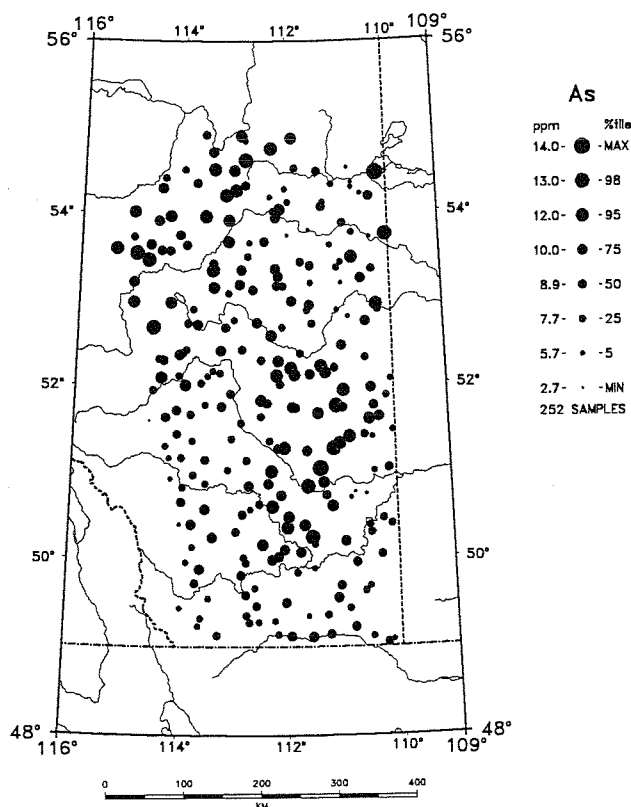


Figure 8. As in the <0.063 mm fraction of till.

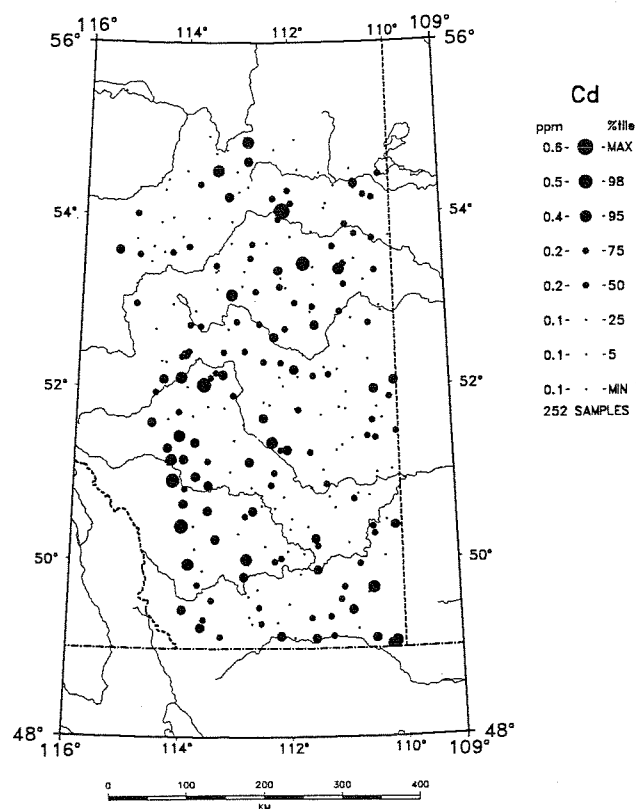


Figure 9. Cd in the <0.063 mm fraction of till.

number of elements increase in abundance to the northwest in Alberta relative to the area to the south [e.g., Fe, V, Cu (Fig. 10), Ni, Cr, Th, Sc, Rb and As]. This is likely a lithological control being exerted on the till composition. Shales are more widespread to the north and northwest in comparison to the Tertiary sandstones and Foothills carbonates in the west, which are likely poorer in trace elements. Some elements, such as Th (Fig. 11), are most abundant in the northeast, apparently reflecting proximity to the Canadian Shield.

The Calgary area, which has already been noted as being distinct with respect to trace elements, stands out as an area of elevated CaO (Fig. 12). As discussed below, this is attributed to carbonate derived by glacial transport from the Cordillera. Elevated values for P_2O_5 in the Calgary area (Fig. 13) raise the possibility that phosphatic rocks may play a role with respect to the elevated Cd levels in that area.

Heavy mineral concentrate geochemistry

Analyses of the <0.063 and 0.063 to 0.25 mm heavy mineral concentrates were combined into a composite <0.25 mm value. These data reveal many of the same

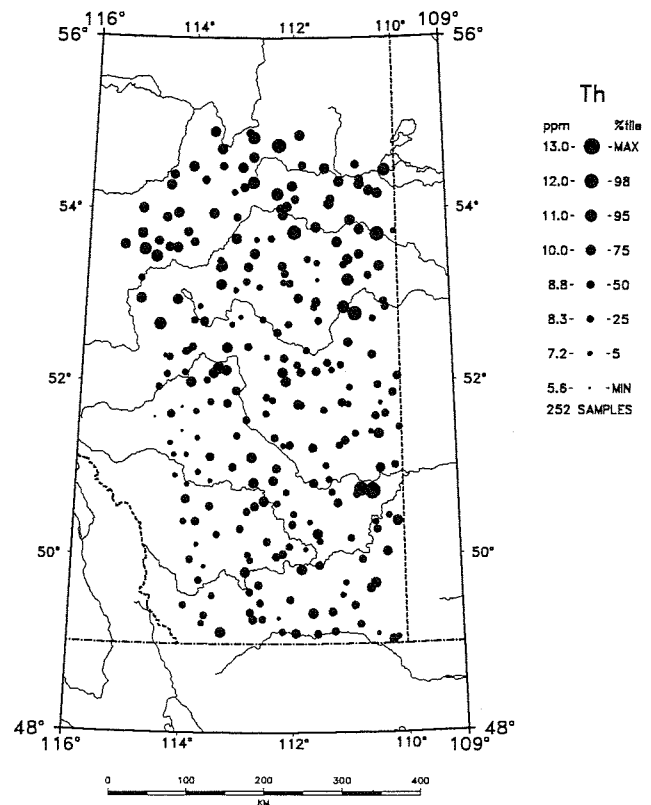


Figure 11. Th in the <0.063 mm fraction of till.

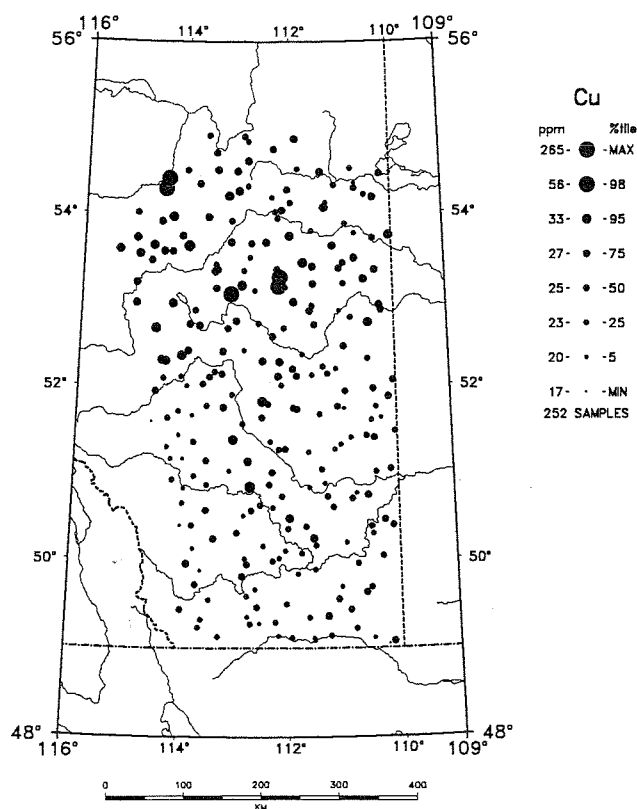


Figure 10. Cu in the <0.063 mm fraction of till.

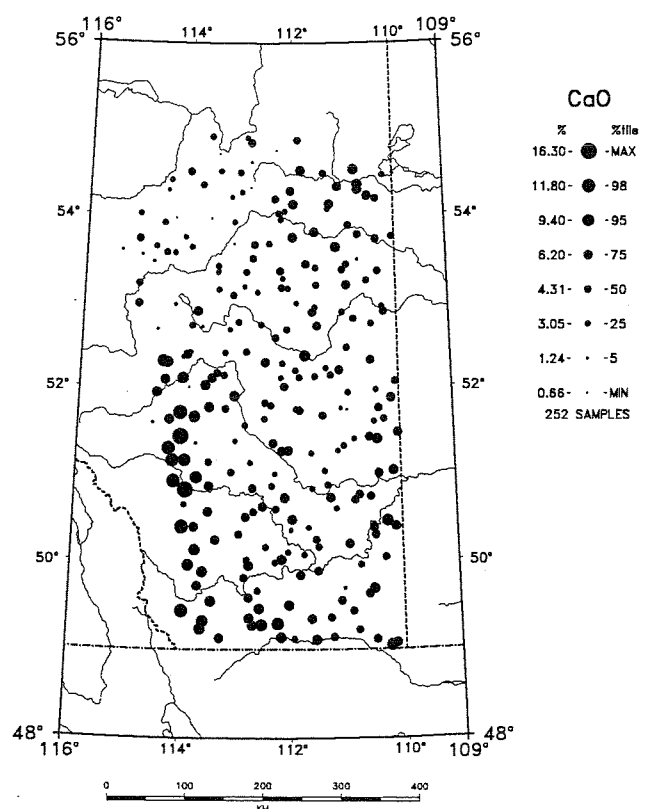


Figure 12. CaO in the <0.063 mm fraction of till.

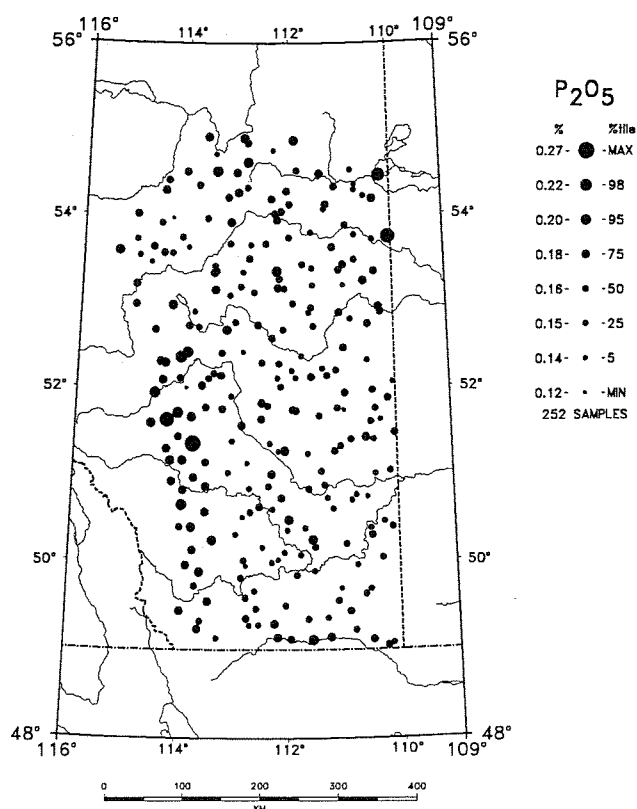


Figure 13. P₂O₅ in the <0.063 mm fraction of till.

features as the till matrix data that appear to divide the surface till data into two geochemical domains. In the Calgary area, As is elevated in the concentrates, (Fig. 14), the reverse of its behaviour in the <0.063 mm fraction (Fig. 8), perhaps reflecting dilution by abundant <0.063 mm carbonate material in the till matrix. However, Sc (Fig. 15) and Ta (Fig. 16), occur at concentrations in this fraction which are elevated to the northeast.

Soil geochemistry

The geochemical patterns in the soil data closely follow those observed for the tills. However, as soils were collected on all parent materials, some patterns relate to fluvial derivatives of till, such as quartz-rich fluvial and aeolian sand, and clay-sized material of glacio-lacustrine sediments. These two groups are characterized by generally lower trace-element values in the case of coarse, quartz-rich sediments and higher values for many elements in fine grained parent materials. The A horizon samples have been influenced by pedological processes that have led to a modification of the C horizon patterns through concentration and depletion, with relationships varying between areas and soil regimes. For example, As is relatively concentrated in light brown chernozemic surface soils in the south of the survey area.

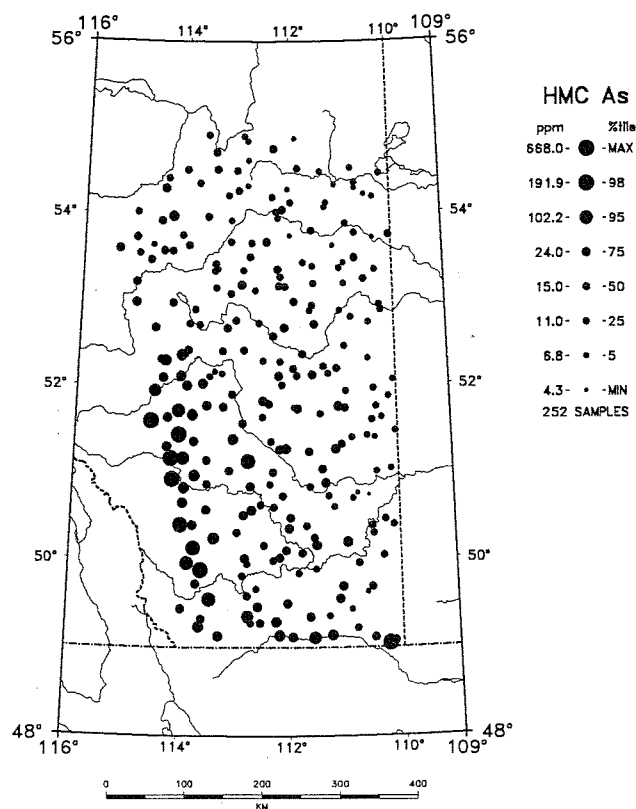


Figure 14. As in the <0.25 mm, nonferromagnetic, >3.2 specific gravity fraction of till.

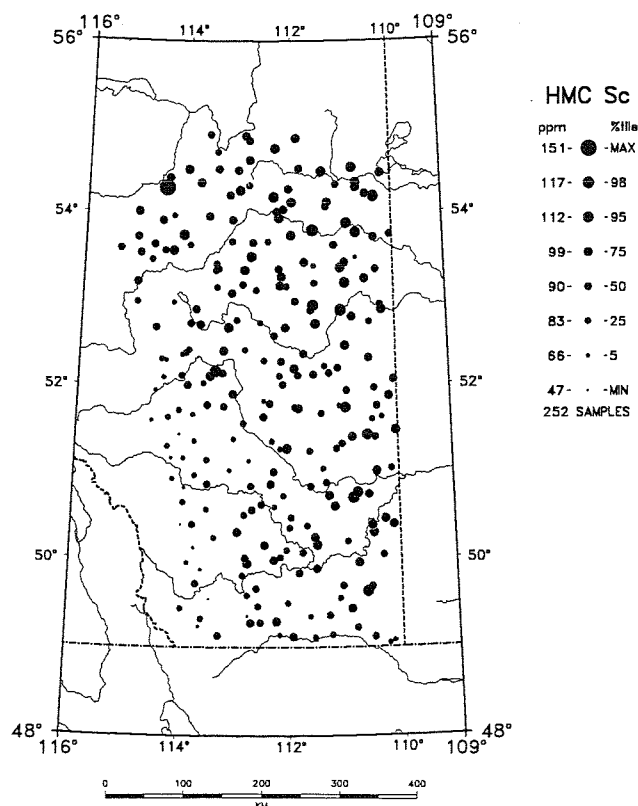


Figure 15. Sc in the <0.25 mm, nonferromagnetic, >3.2 specific gravity fraction of till.

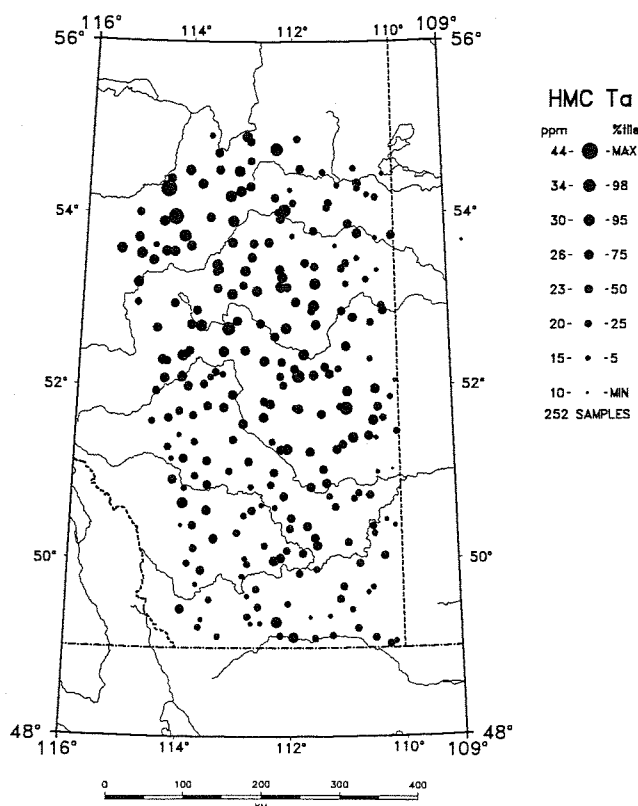


Figure 16. Ta in the <0.25 mm, nonferromagnetic, >3.2 specific gravity fraction of till.

The distribution of Cd in the soils is of particular interest in environmental and agricultural studies because certain compounds of this element were regulated under the Canadian Environmental Protection Act (CEPA) in 1994. A discussion of the close relationship of the Cd data for A horizon soils to glacial sediment parent materials has been presented by Garrett (1994). Similarly, toxic Hg compounds are regulated in Canada, and a discussion of the distribution of Hg in surface and C horizon soils has been presented by Garrett and Thorleifson (1994). Again, the dominant controls on Hg distribution are the chemistry of the soil parent materials, glacial sediments, and in turn, their provenance.

Comparison of gold analyses

INAA analyses of the <0.063 mm fraction of the till samples indicate clusters of elevated Au values in the southern and northeastern portions of the study area (Fig. 17). This fraction seems to be responding to the presence of gold in silts and clays, the origin and significance of which differs from the visible gold grains and other gold detected in the heavy mineral concentrates. Perhaps this gold was chemically dispersed in shales. The highest count of visible gold grains, which does not take the mass of this gold into

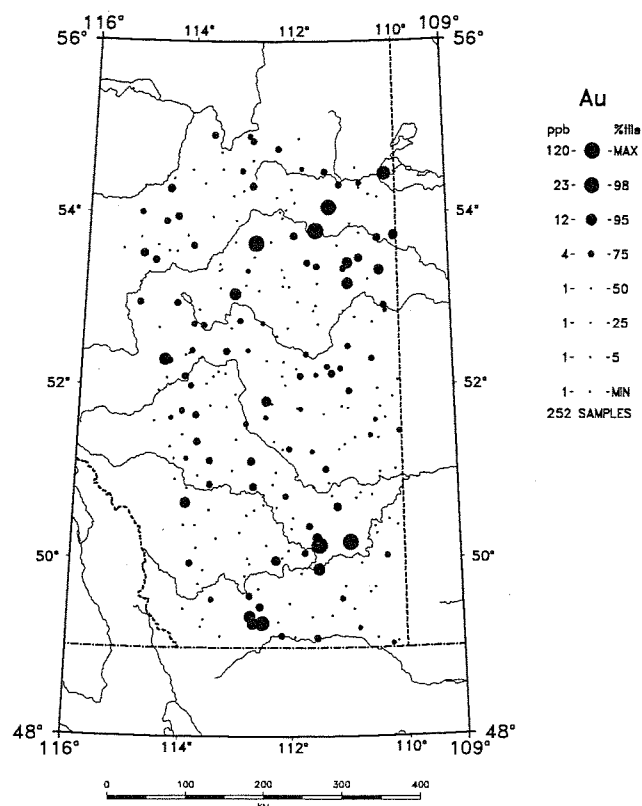


Figure 17. Au in the <0.063 mm fraction of till.

account, is in the Edmonton area (Fig. 7). However, INAA analyses of heavy mineral concentrates (Fig. 18), which do take the mass of the gold into account, but which are referred to as the mass of the concentrate, clearly show a pattern of elevated values parallel and adjacent to the Foothills.

Gold analyses for A and C horizon soil samples indicate lower concentrations and less systematic variability than the till data. This is attributed to dilution by sterile sand due to analysis of the <2 mm fraction, as well as to the fact that many of the samples were taken on glaciolacustrine and glaciofluvial clay and sand. Data for this size fraction are more susceptible to the nugget effect.

SEDIMENT TRANSPORT HISTORY

Introduction

Only till was processed for indicator minerals in this survey, so all the minerals reported here were transported by the continental ice sheet during the Pleistocene. These mineral grains may have undergone multiple phases of reworking by glacial processes, and may also have been transported by fluvial processes in interglacial and preglacial time.

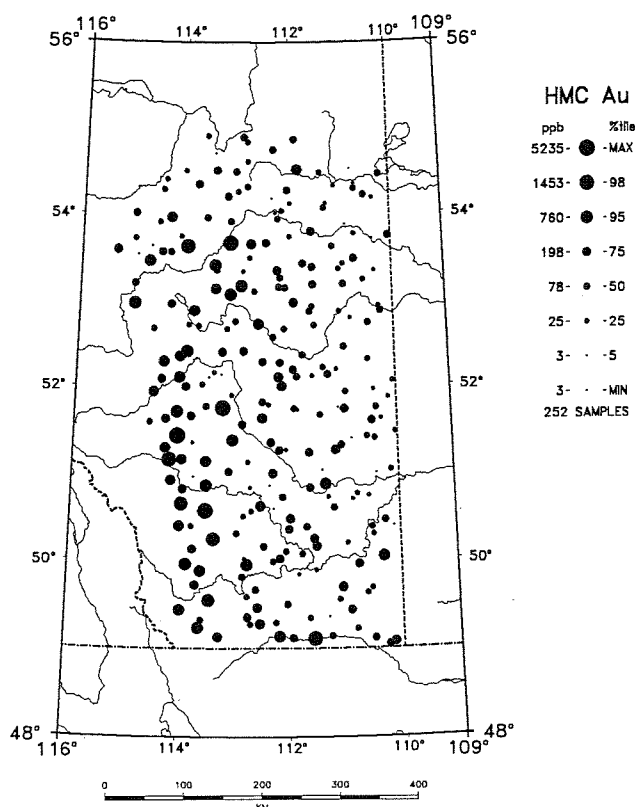


Figure 18. Au in <0.25 mm heavy mineral concentrates.

Furthermore, determination of the relative contributions of natural or anthropogenic processes to soil chemistry in environmental studies is dependent on an understanding of the transport history of a sediment. In southern Alberta, till is the most available sediment and the material with the greatest influence on soil geochemistry.

Hence the tracing of glacial transport history is required for the interpretation of data collected by this and other soil and till sampling surveys. Previous efforts to examine regional trends in the provenance of Alberta glacial sediments include work by Pawluk and Bayrock (1969).

Depositional processes

Previous research on processes of glacial sedimentation in the prairie region have focussed on landforms (e.g., Gravenor and Kupsch, 1959) and sedimentary structures in diamicts released from stagnant ice (Shaw, 1982). Discussion of sedimentation by active ice has been influenced by work elsewhere (e.g., Boulton, 1974) which emphasized high-stress lodgement of sediments from sliding ice. Recent research has indicated, however, that till sedimentation in areas of thick, extensive, fine grained till may be related to

subglacial deformation, rather than entrainment in the ice. Seismic surveys of the bed of Ice stream B in the west Antarctic have indicated a 10 m thick sediment layer, the seismically determined shear strength of which is less than the shear stress exerted by the overriding ice (Alley et al., 1986, 1987a, b). The implied deformation and hence transport of the sediments is analogous to deformation observed in Iceland by Boulton and Jones (1979) and discussed by Boulton (1982, 1987) and Boulton and Hindmarsh (1987). Thick exotic diamicts of the prairie region, therefore, may represent deposits of sediments transported by shear below a very thin glacier (Mathews, 1974). In this context, preservation of carbonate clasts and indicator minerals susceptible to abrasion could be attributed to protection by the enclosing fine grained deforming matrix.

Texture

Processing of till samples for indicator minerals presented an opportunity to determine gravel content of till in the area. The mean gravel (>2 mm) content of air dry till in the study area was determined to be 5%. Values of 15 to 20% occur in the Calgary area. Only the orientation samples were processed for detailed textural analysis of the <2 mm fraction. Among these 14 samples, sand content ranged from 27 to 47% and averaged 37%, silt ranged from 31 to 58% and averaged 39%, and clay ranged from 14 to 32% and averaged 24%. A bimodal grain size distribution is consistently apparent, with modes centred on fine sand and medium silt. Whereas silt content of the <2 mm fraction was consistently between 30 and 40% for most of the samples, values well over 40% were obtained in the Calgary area, where several variables indicate the presence of material derived from the Cordillera.

Matrix carbonate content

The <0.063 mm fraction of the survey till samples contains, on average, 9% carbonate, as indicated by the Chittick gasometric method. This average composition is made up of near equal contributions of calcite and dolomite. Values range from less than 1% each to highs of 22% calcite and 19% dolomite. Several samples which clearly stand out as outliers at over 20% carbonate occur in the Calgary area, ranging from Olds in the north to Pincher Creek in the south.

Pebble lithology

Pebbles recovered in the 8 to 16 mm fraction were classified with respect to lithology. Till in the area contains an average of 10 g of 8 to 16 mm pebbles per

kg of dry <16 mm till. On average, this amount is made up of about 2 g each of intrusive and high-grade metamorphic rocks ('granite'), quartz sandstone, and brown carbonate. At about 1 g or less each, on average, are grey carbonate, immature sandstone, quartzite, ironstone, and low grade metasedimentary and metavolcanic rocks. Small quantities of shale and coal are present in some of the samples.

The bedrock source of these rock types has been determined by previous work on gravel lithology in the area by Gravenor and Bayrock (1955, 1956), Stalker and Craig (1956), Rutter (1972), Metz (1968), Vohnhof (1965, 1969), Whitaker (1980), Shetsen (1981, 1984), Shaw and Kellerhals (1982), and Little (1995). The Precambrian Shield is considered the source for virtually all of the intrusive and high-grade metamorphic rocks as well as the low-grade metasedimentary and metavolcanic rocks. Brown carbonate, in general, is attributed to long distance transport from the outcrops which occur along the shield margin in northeastern Alberta and Manitoba. Quartz sandstone was likely derived from the Cordillera as well as the Athabasca sandstone of northern Saskatchewan, grey carbonate from the Cordillera, immature sandstone from local Cretaceous and Tertiary bedrock, quartzite from Tertiary gravels and the Cordillera, and ironstone, shale and coal from local bedrock.

Concentrations of Precambrian rocks in general increase to the northeast (Fig. 19). Enhanced concentrations of low-grade metasedimentary and metavolcanic rocks in the southwesternmost portion of the area are attributed to Proterozoic rocks of the Waterton area.

Anomalous values for grey carbonate (Fig. 20) occur in an area extending north and south of Calgary. This area, which has already been noted as being distinctive with respect to geochemistry, texture, and carbonate, is the site of what has been referred to as the Foothills Erratics Train (Stalker, 1956; Mountjoy, 1958; Roed et al., 1967; Morgan, 1969; Tharin, 1969). This narrow zone extends from Jasper, west of Edmonton, along the mountain front, to the Montana border as a narrow strip of compositionally distinct till and large conglomeratic boulders. The train is attributed to coalescence of the Cordilleran and Laurentide ice sheets, and southward transport of material from the Athabasca valley along the mountain front.

Quartzite is abundant in the Foothills Erratics Train (Fig. 21). Other areas where preglacial gravels have contributed quartzite to the till are apparent in the south-central and southern portion of the area. These abrupt increases in quartzite concentration are

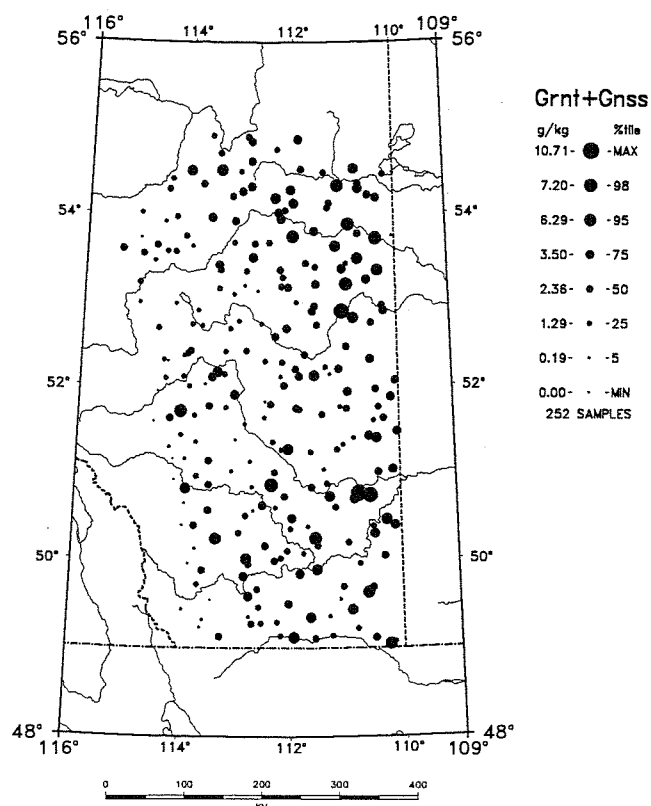


Figure 19. Intrusive and high-grade metamorphic clasts in the 8 to 16 mm fraction of till.

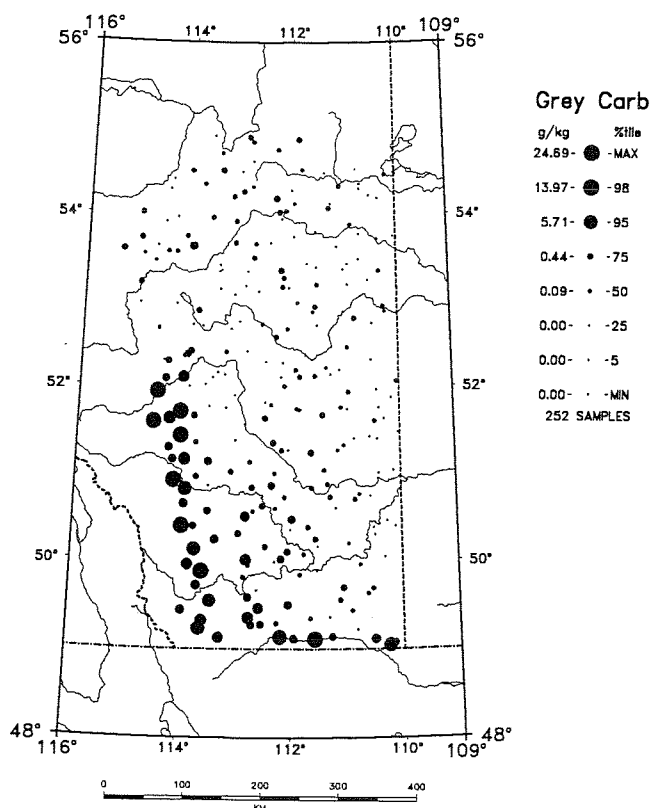


Figure 20. Grey carbonate clasts in the 8 to 16 mm fraction of till.

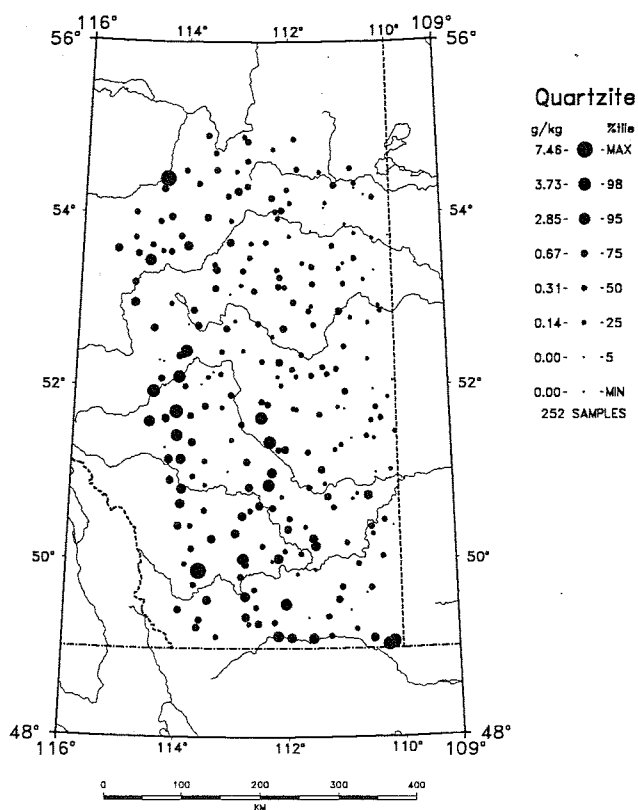


Figure 21. Quartzite clasts in the 8 to 16 mm fraction of till.

examples of a distinguishable local component, confirming that surface till provides information about nearby bedrock geology and, therefore, mineral potential.

Heavy minerals

The bulk mineralogy of heavy mineral concentrates provides another indicator of sediment transport history. For example, garnet (Fig. 22) increases in abundance to the northeast, probably indicating that the Canadian Shield is the principal source. Despite the presence of heavy minerals in local Cretaceous and Tertiary sandstones (Vonhof, 1965, 1969; Rahmani and Lerbekmo, 1975), Bayrock (1962) concluded that the vast majority of heavy minerals in surface till in east-central Alberta were derived from the Shield. In contrast, barite is more abundant to the southwest, implying a local, Cordilleran, or authigenic source (Fig. 23).

CONCLUSIONS

This reconnaissance has provided the first systematic data on the distribution of till matrix, soil mineralogy, geochemistry, and kimberlitic and lamproitic indicator minerals in the region. It has demonstrated that:

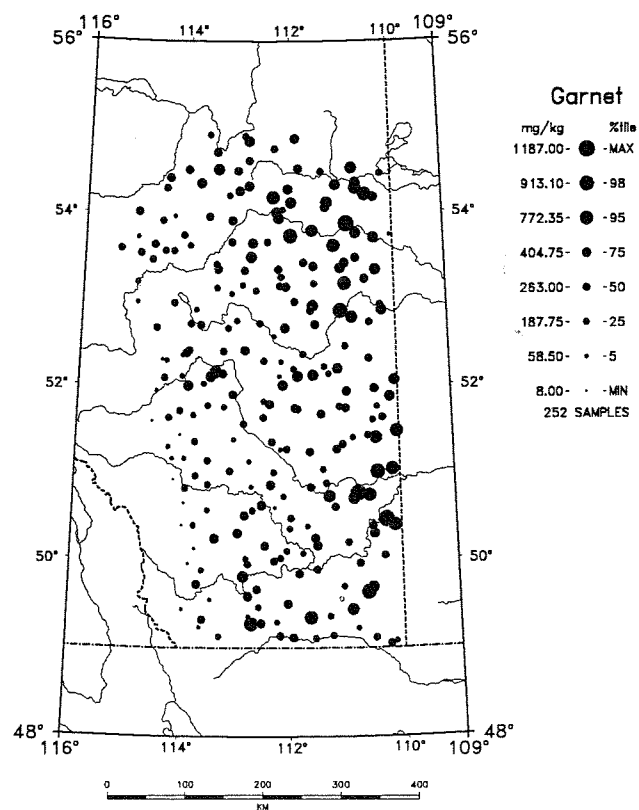


Figure 22. Garnet in the 0.063 to 0.25 mm, nonferromagnetic, >3.2 G fraction of till.

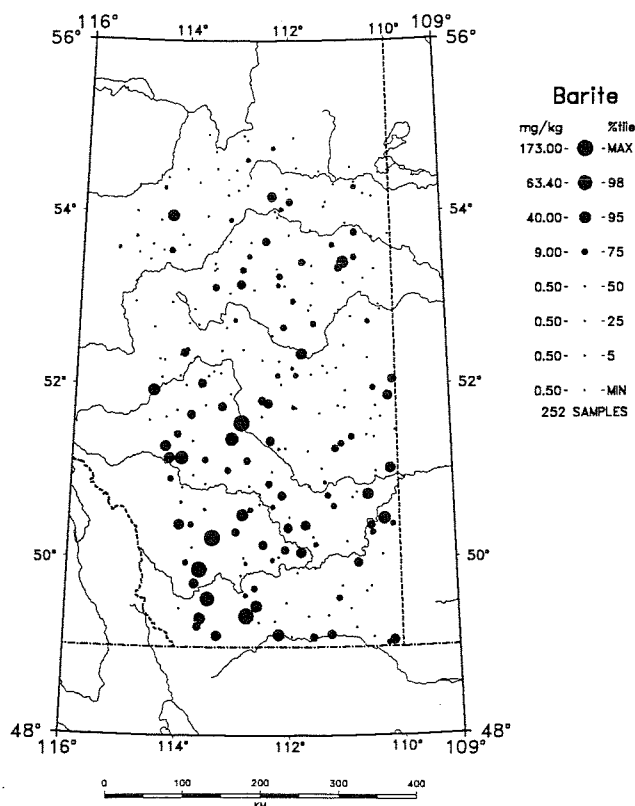


Figure 23. Barite in the 0.063 to 0.25 mm, nonferromagnetic, >3.2 G fraction of till.

1. Kimberlite indicator minerals, including Cr-pyroxene, Cr-diopside, and Mg-ilmenite, as well as gold in various forms, are present in surface till of southern Alberta in a nonrandom distribution;
2. Till geochemistry, pebble lithology, and bulk mineralogy of heavy minerals vary systematically across the region, indicating derivation generally from the northeast over most of the area, but also from the Cordillera in the Calgary area; and
3. Ultra-low density soil geochemical data show patterns which are relevant to environmental and agricultural investigations.

Acknowledgments

We wish to acknowledge with appreciation the effort by a large number of people who contributed to this project: Walter Nassichuk and Roger Macqueen of GSC for coordination and facilitation of the project; colleagues Mark Fenton, Lionel Jackson, Erik Nielsen, Rudy Klassen, Bryan Schreiner, and Archie Stalker for discussions on the Quaternary history of the region; John Pawlowicz and Mark Fenton of the Alberta Geological Survey, who directed most of the field sampling; Chuck Fipke for valuable advice regarding indicator mineral tracing; staff of the Saskatchewan Research Council under the leadership of Alan Holsten and Bernard Gartner, who prepared the samples; Bruce Kjarsgaard of GSC for stimulating discussions on the alkaline igneous rocks of the Montana Alkaline Province; Irena Shetsen and Lawrence Andriashek of the Alberta Research Council, who provided very useful advice regarding lithological analyses; staff at Becquerel Labs, CANMET, CanTech Labs, CF Minerals, Consorminex, GSC, Overburden Drilling Management, XRAL and the University of Guelph for laboratory services; and Arlene Drake, Alexander FitzPatrick, Leanne Forman, Susan Lambert, and Dan Roberts, for assistance in the field and the office. We gratefully acknowledge the contribution that all these people, and others, made to the success of the project. However, we stress that the ideas presented here are those of the authors, for which we accept full responsibility.

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