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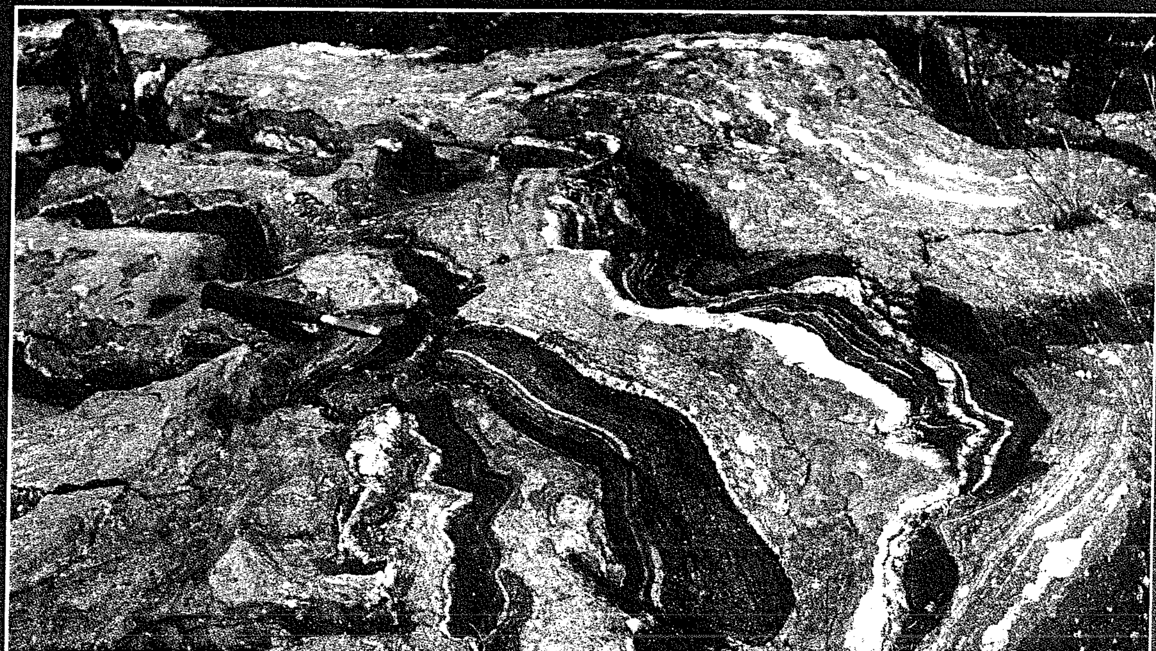

INVESTIGATIONS COMPLETED BY THE SASKATCHEWAN GEOLOGICAL SURVEY AND THE GEOLOGICAL SURVEY OF CANADA UNDER THE GEOSCIENCE PROGRAM OF THE CANADA-SASKATCHEWAN PARTNERSHIP AGREEMENT ON MINERAL DEVELOPMENT (1990-1995)

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Canada

Kimberlite Indicator Mineral and Till Geochemical Reconnaissance, Southern Saskatchewan

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SUMMARY

A systematic ultra-low density (1 site per 800 km^2) till (390 sites) and soil (526 sites) survey was undertaken in southern Saskatchewan in order to provide baseline information useful to diamond exploration. The survey revealed the wide dispersal of kimberlitic indicator minerals, which outline areas northwest of Prince Albert and in the southwest of the Saskatchewan as having the greatest incidence of indicator minerals. However, a number of other sites and smaller areas contain varying assemblages of indicator minerals. The matrix and heavy mineral geochemical, mineralogical and pebble lithology data permit the surface tills of southern Saskatchewan to be divided into three broad domains. Diamond exploration in these three domains requires different approaches in recognition of the different development histories of the surficial materials in these areas. The soil geochemical data are of less direct application in diamond exploration due to pedological processes that have altered the non-heavy mineral components of the soil. However, these data provide useful information relevant to environmental and agricultural issues.

INTRODUCTION & OBJECTIVES

The recognition of potentially diamondiferous kimberlites in central Saskatchewan in 1988, led to a significant increase in mineral exploration in southern Saskatchewan, and the Canadian prairies became a target for diamond exploration.

The region is predominantly covered by Quaternary sediments, mainly tills, glacio-lacustrine deposits, and moraine complexes. A few small areas remained unglaciated. Heavy mineral and, to a lesser extent, geochemical surveys form a major part of the exploration activity. There was a notable lack of systematic data on the mineralogical and geochemical composition of prairie surficial materials in the public domain. This was particularly true for the glacial tills sampled in diamond exploration projects. The availability of systematic data would assist explorationists in recognizing mineralogically and geochemically abnormal areas within the prairies, and thus help direct exploration to the areas of highest potential.

In 1990, a project was proposed for funding under the (1990-1995) Canada-Saskatchewan Partnership Agreement on Mineral Development (PAMD) with the objectives of:

1) Providing geochemical, mineralogical and pebble lithology information that would permit the provenance of the till units occurring at the surface to be determined, and preparing maps indicating the boundaries of distinctive till units, in order to better understand their sources of origin and transport;

2) Providing baseline information on the above compositions in order to assist the minerals industry in establishing expected background ranges in areas actively being explored;

3) Determining the down-ice extent of kimberlitic or lamproitic indicator mineral dispersion trains in tills from pipe/dyke swarms (i.e., not individual kimberlites or lamproites);

4) Determining the pattern of gold distribution in the tills and C horizon soils and correlating them with known placer gold occurrences;

5) Interpreting the till and C horizon soil trace element data to determine if there are indications of undiscovered base-metal (Pb-Zn) and other (e.g., Ba-Sr-F) mineral resources;

6) Comparing geochemical data for soils and tills in order to assess their relative merits as exploration sampling media (soils being cheaper to collect than tills); and comparing geochemical and mineralogical data for till heavy mineral concentrates in order to assess their relative merits in till provenance studies (geochemical data being cheaper to acquire than mineralogical data); and

7) Providing data on the background (baseline) levels and spatial variability of a wide range of major, minor and trace elements in A and C horizon soils that would be

of interest to those concerned with epidemiology and the agricultural sciences.

This proposal was accepted and an orientation survey, consisting of sampling at 40 km (soil) and 50 km (till) intervals along two cross-prairie traverses, was completed in 1991 (Garrett and Thorleifson, 1993) and yielded encouraging results. A G10 garnet was recovered from till in southwestern Manitoba, and prairie-wide variations were observed for several mineralogical (e.g., garnet and epidote) and geochemical variables (e.g., total carbonate and Ba).

In the spring of 1992, a proposal for a similar survey in Alberta was submitted, and accepted, for funding under the (1992-1995) Canada-Alberta PAMD. At about the same time Manitoba Energy and Mines offered to support a prairie-wide survey by undertaking sampling within the province of Manitoba to the same survey specifications. It was agreed that the Geological Survey of Canada would provide the funds to process and analyze the Manitoba samples. In order to facilitate trans-border geochemical mapping, the soil sampling was extended some 80-90 km south into the U.S.A. with the cooperation of the United States Geological Survey.

This report describes the major findings of the Saskatchewan component of the prairie-wide survey, with a focus on the results of the glacial till survey as it relates to mineral development activities.

METHODS

Survey Area and Geological Framework

The survey area was defined by the limits of Saskatchewan on the west, south and east, and in the case of soils, the northern limit of farmland, or in the case of tills, the Phanerozoic limit south of 55° N. The soil survey limit roughly follows, from east to west, the Carrot River, the Sipanok Channel, the Saskatchewan River to Prince Albert, then along a line northwest to Cold Lake on the Alberta border. Till sampling was extended by highway traverses along the Northern Woods and Water Route and roads to the north and northeast towards the Precambrian Shield margin.

Southern Saskatchewan is covered by extensive Quaternary deposits. Outcrops of Pre-Quaternary deposits are generally limited to river valleys, the Missouri Coteau, and higher relief areas in the southwest, including the Cypress Hills and Wood Mountain (Fig. 1). The bedrock

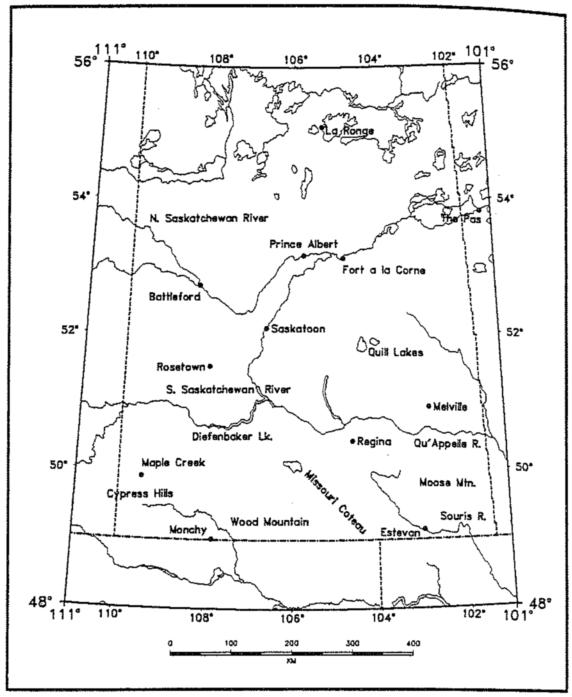

Figure 1. Location of geographic features, etc., discussed in the text

consists dominantly of shales and sandstones of Lower Cretaceous (Mannville) to Paleocene (Ravenscrag) age, including some coal measures, and isolated outcrops of Oligocene and Miocene gravels (Mossop and Shetsen, 1994). Of these units, the shales of the Upper Cretaceous Colorado Group, Riding Mountain and Lea Park formations, and laminated shales and siltstones of the Bearpaw Formation dominate the survey area (Fig. 2a). Two additional factors of major importance that influence the composition of Quaternary glacial deposits of southern Saskatchewan, include: 1) the presence of Colorado Group equivalent Lower Cretaceous Ashville Formation and Upper Cretaceous Favel (including Morden and Niobrara) to Pierre Formation shales in Manitoba; and still further east, in Manitoba, Ordovician and Silurian limestones and dolomites; and 2) Precambrian Shield igneous and metamorphic rocks north of the survey area.

Between Eocene and Pleistocene times it is estimated that some one to three km of pre-Eocene sediments were eroded as a result of the uplift of the Rocky Mountains to the west (Dawson et al., 1994). East and northeasterly flowing streams eroded these rocks and redeposited their coarse clastic component to the east. Remnants of these coarse clastic sediments have been preserved as Oligocene and Miocene gravels of the Cypress Hills and Wood Mountain formations. The Willowbrook and Bradenbury

AGE	GROUP	FORMATION
Pleistocene		Empress
Pliocene		Bradenbury
		Willowbrook
Miocene		Wood Mtn.
Oligocene		Cypress Hills
Paleocene		Ravenscrag
Upper Cretaceous	Montana	Bearpaw Lea Park Riding Mtn.
	Upper Colorado	Morden Favel
Lower Cretaceous	Lower Colorado	Colorado
	Mannville	Mannville
Silurian	Interlake	Cedar Lake

Figure 2a. Preglacial subcrop stratigraphic sequence for the study area. Several units not referred to in the text omitted to preserve simplicity (after Dawson et al., 1994; Mossop and Shetsen, 1994)

formations are probably younger and consist of finer grained sands that occur more distally from the source and to the east (Schreiner, pers. comm.). River channel sands and gravels of immediate pre-glacial age have been preserved in the Empress Formation. The Willowbrook, Bradenbury and Empress formations do not outcrop and have only been observed in drill holes.

Laurentide glaciations deposited sediments over the entire survey area except the Cypress Hills and Wood Mountain. Sediment thicknesses are highly variable; in the south and southwest they are mostly thin, as they are on some of the higher ground east of the survey area along the Manitoba Escarpment. The line of the Missouri Coteau, extending northwestwards to the Battlefords, defines the southwest edge of a zone where sediment thicknesses generally exceed 50 m, commonly exceed 100 m, and can exceed 200 m (Fenton et al., 1994). There is a significant extension of this deeper sediment zone to the southwest along an axis from Saskatoon to Maple Creek (Fig. 1), where sediment thicknesses exceed 50 m along the valley of the proto-South Saskatchewan River.

The Quaternary stratigraphy of relevant parts of Saskatchewan has been described by 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 (Fig. 2b). 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, while the Upper Floral and Battleford Formations are Early and Late Wisconsin age, respectively (Fig. 2b). In the Saskatoon area where this stratigraphy was described by Christiansen (1992) at least six separate glaciation events can be distinguished on the basis of till carbonate content.

AGE	STRATIGRAPHY		CARBONATE	CALCITE/ DOLOMITE	V	Zn
Wisconsin	Saskatoon Group	Battleford	·	+	−	·
		Upper Floral	+	++	−	−
Illinoian		Lower Floral	++	−	·	·
Pre - Illinoian	Sutherland Group	Warman	−−	−	++	++
		Dundurn	·	−	+	+
		Mennon	−	?	+	++

Figure 2b. Quaternary stratigraphy after Christiansen (1992); mineralogical and geochemical characterization after Schreiner (1990). (Symbols: + = high; · = medial; - = low; ? = insufficient data)

Important to this study, Schreiner (1990) describes a number of geochemical characteristics of till recognized in several drill holes, including carbonate, V and Zn contents, calcite/dolomite ratio. Other trace element concentrations (i.e., Pb, Cu, Ni and Co), were not as well differentiated between the different tills. Figure 2b includes a synopsis of Schreiner's findings (Tables 5a and b, and Fig. 20, op. cit.) and reflects the relative level of the most useful discriminating measurements in the different sediments.

From these findings it is clear that the Warman Formation at the top of the Sutherland Group stands out as being uniquely low in carbonate and high in V and Zn. Schreiner (1990) postulates that this unit is derived largely from the Morden Shale that is exposed along the Manitoba

Escarpment. The Saskatoon Group as a whole was found to be higher in carbonate and lower in V and Zn in comparison with the older Sutherland Group. Meanwhile, the Battleford Formation is generally characterized by lower carbonate, V and Zn levels than the other units. The limited dolomite/calcite data indicate that the younger glacial sediments of Wisconsin age are generally richer in dolomite than the older sediments.

In the context of this regional study, it is important to note: 1) the surface samples collected and described below were believed at the time of sampling to be almost entirely Saskatoon Group tills from the Upper Floral and Battleford Formations; and 2) dilution effects must be taken into account: the key geochemical features described above are inherited from Paleozoic carbonate rocks and trace element-rich Upper Cretaceous black shales to the east and northeast. As the tills derived from them were transported westward they were diluted by carbonate and trace element deficient local materials of younger Cretaceous and Tertiary ages, either directly, or more likely via an earlier glacial sediment.

Sampling Design

Low density soil geochemical surveys based on 100x100 km grids have been used by the United States Geological Survey (USGS) since the mid-1970's to estimate geochemical baseline levels (Severson and Tidball, 1979). The sampling design for the present project had to fulfil two contrasting needs. From the point of view of kimberlite/lamproite exploration, the sample grid had to be sufficiently fine to intersect the down-ice heavy mineral dispersal patterns from any significant clusters of pipes or dykes in the study area. However, for estimating baseline levels, and 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. Sampling designs to meet these requirements have been discussed in more detail by Garrett (1983).

On the basis of the 1991 orientation survey data and work by the USGS (Severson and Tidball, 1979; Severson and Wilson, 1990) an 80x80 km grid was selected as the basic sampling cell. This sampling grid cell size would be both sufficient to detect major heavy mineral dispersal trains, and to characterize the geochemical variability of the tills and soils and quantify their spatial variability. The basic 80x80 km cell was successively subdivided into 40x40 km, 20x20 km and finally 10x10 km grid cells for sampling with randomly selected 1x1 km target cells. This leads to an 80x80 km cell containing 12 geochemical samples for analysis. The effective sample density of the prairie grid is best expressed as 2 sites per 1600 km^2 for soils and tills where they outcrop.

Field Procedures

All sample sites were randomly chosen as 1x1 km target cells before the commencement of fieldwork within the framework of the overall design structure. Alternate 1x1 km cell selection rules were prepared for use if the pre-selected target cell could not be sampled in the field (i.e., the cells fell in lakes and restricted access areas, or no exposure of till suitable for sampling could be found). Tills were collected only in Canada, however, soils were collected at all sites as far south as UTM northing 5,340,000 m, some 80-90 km south of the Canada-U.S.A. border along the 49th parallel. This report describes the results for the southern Saskatchewan part of the prairie-wide survey (850,000 km^2) that extended over the provinces of Alberta, Saskatchewan and Manitoba (735,000 km^2), and in the states of Montana, North Dakota and Minnesota (115,000 km^2). In addition a suite of till samples was collected along a number of highway traverses in order to extend coverage to the Precambrian Shield margin to the north of the grid based soil and till sampling area in Manitoba and Saskatchewan. The field sampling in southern Saskatchewan was undertaken between June and early October, 1992, by Saskatchewan Research Council staff. During the period June to August, 93% of the field work was completed. In southern Saskatchewan, a total of 390 till sites were sampled, 350 from the prairie grid and an additional 40 on the northern road traverses; and 526 soil sites were sampled for two horizons.

Three till samples were collected at each site, including: 1) two and three kg samples for geochemical analysis and a reserve, respectively; and 2) a 25 litre sample for recovery of the heavy mineral and gravel fractions. The samples were collected from road cuts, or other existing excavations, at approximately 1-2 m below surface in order to minimize the effects of weathering on the carbonate content of the till and maximise heavy mineral preservation. In a few instances samples were taken from depths as shallow as 0.5 m, and as deep as 4 m. Samples were collected into large plastic wash pans for homogenization using sand-blasted steel shovels and picks. The 2 and 3 kg samples were then placed in plastic bags, and the large till sample was placed into a 25 litre plastic pail. Two 2 kg soil samples were collected at all sites: an A horizon sample collected on average from between 3 and 18 cm below surface, and a C horizon sample collected on average from between 40 to 66 cm below surface with a Dutch auger. Field data were recorded at each site, and the actual sampling site 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 soils and tills.

Sample Preparation, Analysis and Quality Assurance

Indicator Heavy Minerals

At the Saskatchewan Research Council, the mean total moist weight of the 25 litre till samples was found to be 28 kg. The 2 kg till samples, which had been stored in sealed pails, were weighed before and after being air dried (<40° C). The resulting moisture content determinations averaged 10%, hence the mean air dry weight of the large till samples was 25 kg.

The 25 litre till samples were disaggregated in a cement mixer with the aid of a sodium hexametaphosphate (calgon) solution (Fig. 3). 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, screened at 4, 8, and 16 mm, weighed and retained. The samples contained an average of 2 kg of gravel (>2 mm). The mean sand content of the <2 mm fraction of till in this region was found to be 35% by Garrett and Thorleifson (1993). The -10 mesh (<2 mm) material was passed twice over a shaker table to obtain a large heavy mineral preconcentrate.

The heavy mineral separations were completed by Overburden Drilling Management Ltd. of Nepean, Ontario, using methylene iodide diluted to a specific gravity of 3.2 using acetone. The table concentrates were screened at 0.5 mm. All >0.5 mm material was submitted directly to heavy liquid separation. Some of the <0.5 mm fractions were re-tabled to reduce their mass prior to heavy liquid separation. The ferromagnetic fraction was removed using a hand magnet.

The >0.25 mm heavy mineral concentrates were returned to the Saskatchewan Research Council and examined for potential indicator minerals, including garnets, pyroxenes and oxides, under a stereoscopic microscope. An average of 15 minutes were spent examining each 0.5-2.0 mm non-ferromagnetic concentrate. Selected grains were subsequently examined by the mineralogical staff of Consorminex Inc. of Gatineau, Québec, and minerals such as staurolite and hornblende, that can be mistaken for kimberlitic indicator minerals, were removed. An average of 4 potential kimberlitic indicator mineral grains from this fraction were selected for analysis. The 0.25-0.50 mm non-ferromagnetic fraction was sorted by magnetic susceptibility at the Saskatchewan Research Council using a Frantz isodynamic separator. The strongly paramagnetic fraction rich in ferro-ilmenite was not visually examined. The

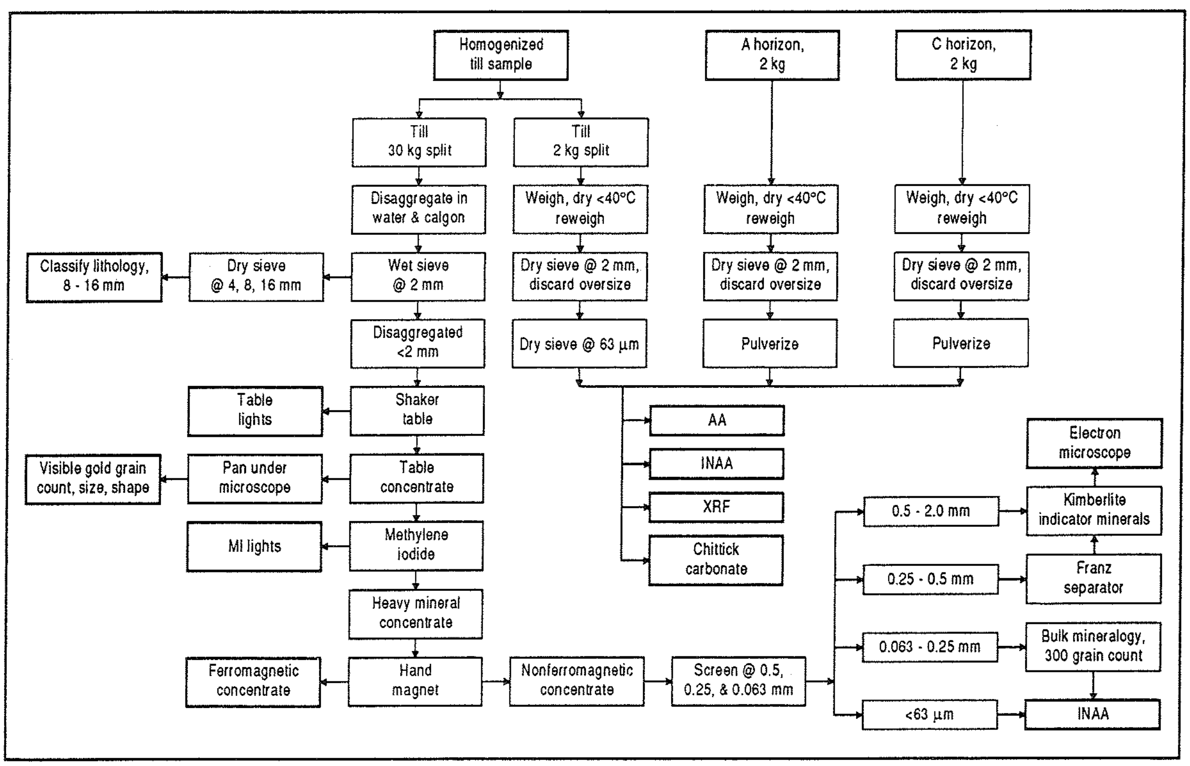

Figure 3. *Flow-sheet illustrating sample processing and analysis*

moderately paramagnetic fraction, which is rich in almandine garnet, was visually scanned under a microscope for magnesian-ilmenite and chromite. The weakly paramagnetic to nonmagnetic fraction was visually scanned for indicator garnets and pyroxenes. An average of 20 minutes were spent examining this fraction. Following further selection at Consorminex, an average of 4 grains per sample were selected for analysis. Minerals were mounted in 25 mm cylindrical epoxy mounts, with grains arranged in rows within 9 cells per mount. Grains from the 0.5-2.0 mm fraction were arranged in 5 rows of 6 grains per cell, to yield a total of 270 grains per mount (i.e., 6 grains X 9 cells X 5 rows). Grains from the 0.25-0.5 mm fraction were placed in 8 rows of 10 in each cell, to give 720 grains per mount (i.e., 10 grains X 9 cells X 8 rows). The mounts were polished using diamond paste. Maps recorded the sample number and identification number of each of the 7813 grains selected for further study.

Chemical analyses of the grains were carried out in the CANMET laboratories in Ottawa, using a JEOL 8900 electron microprobe operating at 20 kV and 40 nA. 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, and background determinations were made on every 50th grain. The analyses were completed in eleven 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 reanalysed at another similar point to monitor precision related to grain heterogeneity, calibration drift, or unusual background measurements. These replicates indicate good reproducibility above 0.1% for all elements, with a few exceptions attributed to heterogeneity.

The resulting data were used to select and classify the minerals, and determine which were kimberlite indicators (Gurney and Zweistra, 1995). The data are considered clearly adequate for the recognition of peridotitic garnets and kimberlitic oxides, adequate for the identification of chrome-diopsides, and marginally adequate for the distinction of titanian almandines (>0.2% TiO_2). Garnets were classified using the Dawson and Stephens (1975, 1976), Gurney (1984), and Gurney and Moore (1993) classifications. Diopsides with >0.50% Cr_2O_3 (Fipke, 1989) were regarded as chrome-diopsides. Magnesian-ilmenites in every case contained well in excess of 6% MgO. The classification procedures employed are detailed by Thorleifson et al. (1994).

Subsequent to the initial microprobe analyses a number of additional studies were undertaken. Eclogitic and near-eclogitic garnets were re-analyzed by electron microprobe at reduced detection limits, by using the electron microprobe routine described above with the inclusion of background counts with all determinations. These analyses were carried out to obtain acceptable sodium data for diamond grade prediction (Gurney and Moore, 1993), and to enhance titanium data used for the recognition of eclogitic garnets. All G7, G9, G10, and G11 peridotitic garnets and chrome-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, 1995). Nickel temperatures were calculated for peridotitic garnets using the equation presented by Griffin et al. (1989).

Lithology and Mineralogy

Other studies were completed on materials retained during the till processing described above. The 8-16 mm gravel was classified with respect to lithology and each fraction weighed. Identified classes included: brown carbonate; intrusive and high-grade metamorphic; low-grade metasedimentary and metavolcanic; gray carbonate; quartzite; quartzitic sandstone; shale; immature sandstone; and ironstone. The table concentrates were panned by Overburden Drilling Management Ltd. in order to recover any visible gold grains. After these had been measured and their morphology described they were returned to the heavy mineral concentrates. The 63-250 μm fraction of the heavy minerals was submitted to Consorminex Inc. of Gatineau, Québec, for a quantitative mineralogical assay based on a 300 grain count.

Geochemistry

Following air drying at <40° C, the 2 kg soil and till samples were gently disaggregated to avoid crushing rock and mineral grains, and screened using a 2 mm stainless steel sieve (Fig. 3). The oversize was discarded. In the case of tills, sufficient of the retained fraction was screened using a 63 μm stainless steel sieve to yield approximately 50 g of material that was stored for analysis. In the case of soils, approximately 50 g of the <2 mm material was ground in an agate pestle-and-mortar to <150 μm and stored for analysis. The remaining unscreened <2 mm materials were retained as archive samples.

Prior to analysis, the 816 till samples, 71 sample duplicates (i.e., second cuts of 50 g of the <63 μm fraction), 44 aliquots of GSC internal till control samples, and 2 aliquots each of the CANMET/GSC international reference materials Till-2 and Till-3, were randomized at the GSC, Ottawa. The purpose of the randomization was to destroy any relationship between the order of analysis and the spatial location of the samples. The two sets of 1273 A and C horizon soil samples, augmented with 116 prepared sample duplicates (i.e., second cuts of 50 g of the <2 mm fraction ground to <150 μm), 50 (A horizon) or 46 (C horizon) aliquots of GSC internal soil control samples, and 6 aliquots of the CANMET/Agriculture Canada international reference materials (i.e., SO-3 or SO-4), were randomized at the GSC, Ottawa.

XRF analyses for major and some minor elements were completed by XRAL Laboratories, Don Mills, Ontario, for the tills and C horizon soils. Instrumental Neutron Activation Analysis (INAA) for a suite of 34 elements was completed by Becquerel Laboratories, Inc., Mississauga, Ontario, for all soil and till samples, and the <63 and 63-250 μm heavy mineral concentrates. A suite of trace elements and Fe and Mn were determined for all soil and till samples by CanTech Laboratories Ltd., Calgary, using Atomic Absorption Spectrophotometry (AAS), following total (HF-$HClO_4$-HNO_3) decomposition of 1 g of sample material. In addition, Hg was determined in the A and C horizon soils, and Se in the A horizon soils. Total carbonate, and an estimate of the weight percent calcite and dolomite, were determined for till and C horizon soil samples using the Chittick gasometric apparatus in the Terrain Sciences Division laboratories at the GSC, Ottawa.

An estimate of the accuracy and precision of the analyses was facilitated by: 1) the insertion of both international and internal GSC standard reference materials; and 2) preparation and analysis of duplicate samples.

RESULTS

The salient features of the survey data are described below. Locations of sites where kimberlitic indicator mineral were recovered are reported in the text or Table 1 and 2 as UTM coordinates. Geographic features discussed in a regional context are plotted on Figure 1. The data for the till sampling components have been released as digital Open Files in Garrett and Thorleifson (1993) and Thorleifson et al. (1994). A full graphical presentation of all the data is planned in both monochrome hard copy form, and as a digital atlas in colour with accompanying till and soil digital databases.

Indicator Minerals in Tills

All the minerals described here were recovered from tills deposited by continental Laurentide glaciation. Hence the indicator mineral grains were carried to the sampling sites by at least the final ice flow in the region. The dominant ice flow was towards the west and southwest, as indicated by drift composition in the region (e.g., Schreiner, 1990). This was overprinted in many areas by southeastward flow in late glacial time (Prest et al., 1968; Dyke and Prest, 1987). In most cases, the mineral grains are likely to have undergone a complex transport history involving repeated glacial, and possibly interglacial and/or pre-glacial fluvial, transport.

A total of 1384 kimberlite indicator minerals were recovered from 401 (49%) of the 816 sites in the prairie-wide survey. A total of 390 (48%) of the till sites were in Saskatchewan, and 814 (59%) of the kimberlitic indicator minerals were recovered from 233 (58%) of those sites. In the following paragraph describing the results for southern Saskatchewan the percentages in brackets indicate the Saskatchewan contribution to the total prairie-wide recovery.

The most abundant class of kimberlite indicator minerals consisted of 435 (56%) chrome-diopsides. A total of 171 (73%) peridotitic garnets (G7, G9, G10, G11), including 6 (50%) G10 subcalcic chrome-pyropes, 74 (67%) magnesian-ilmenites, 42 (32%) chrome-spinels, 77 (71%) megacryst or, strictly speaking, kimberlitic garnets (G1, G2), and 15 (60%) titanian, calcic, magnesian eclogitic almandines (G3, G4, G6) were also identified. The indicator minerals are concentrated in southwestern and central Saskatchewan, for example the chrome-diopsides (Figs. 4 and 5), with the low-chrome-diopsides showing a particularly high abundance in the Wood Mountain area. The G10 garnets (Fig. 6), the best known indicator of potential high diamond grade, are scattered across southern Saskatchewan. Two grains were recovered in the northeast of the survey area just west of an area of chrome-diopside abundance in west-central Manitoba (i.e., near the Pas). The majority of the chrome-spinels, not originally included by Garrett and Thorleifson (1993), are located in Manitoba, but 39 lie in a southeast-northwest band across Saskatchewan (Fig. 7). The distribution of magnesian-ilmenites indicates a greater abundance in the western half of the survey area, dominantly southwest of the Missouri Coteau (Fig. 8).

After re-analysis 156 eclogitic garnet grains were identified and four were found to contain anomalous concentrations of sodium (>0.06% Na_2O), two of which were from Saskatchewan. The first grain, a G3, is from Monchy in southwestern Saskatchewan close to the Montana border (Site 76-3-2, NTS 72G, UTM 13 303803 5443639). The second, also a G3, from Broadview (Site 114-2-1, NTS 62L, UTM 13 676048 5572612) 75 km SSE of Melville forms a loose cluster with the other two high soda grains in southwestern Manitoba.

The Ni determinations by proton microprobe of

Table 1. G10 peridotitic garnets recovered from till (approximately 25 kg samples) in southern Saskatchewan

Site	NTS Sheet	Location	UTM Coordinates			CaO %	Cr_2O_3 %	Temp. °C	Ni ppm	Zr ppm
58-2-2	72K	Tunstall	12	587103	5555112	1.57	5.75	1328	89	55
75-4-2	72J	Hak	13	302806	5551213	6.02	12.16	1360	95	20
98-2-2	72P	Gregherd	13	522080	5650673	5.09	7.55	1448	112	49
103-4-1	63E	Smoky Burn	13	634000	5899400	4.63	9.47	1289	82	4
KIM-92-57	73H	Bittern Lake	13	440537	5979106	4.64	8.25	941	31	20
KIM-92-63	63E	Red Earth Creek	13	640372	5916228	4.96	6.98	913	28	152

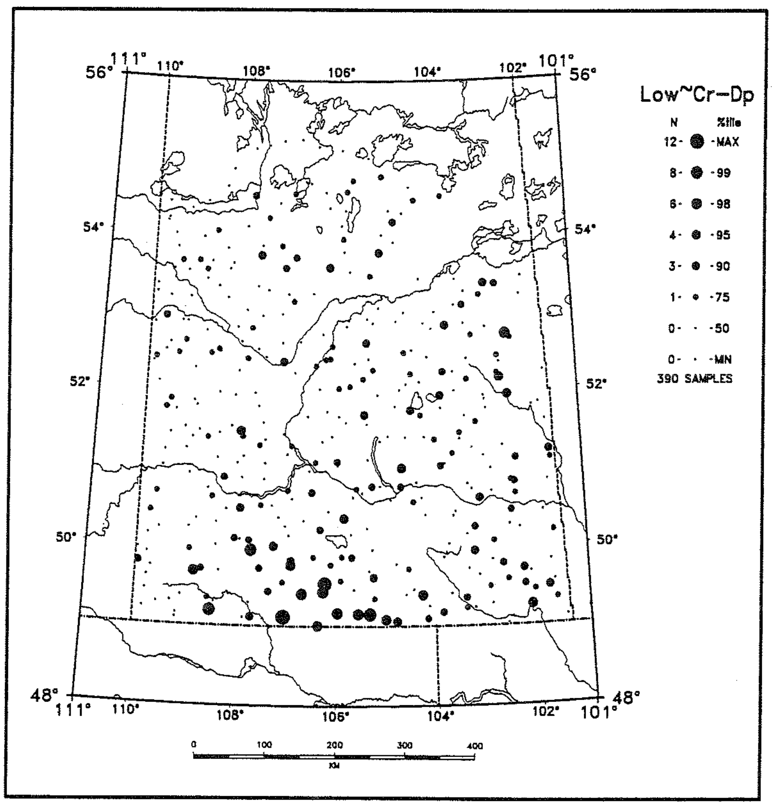

Figure 4. Chrome (<1%) diopsides (0.25-2 mm) recovered from till (approximately 25 kg samples).

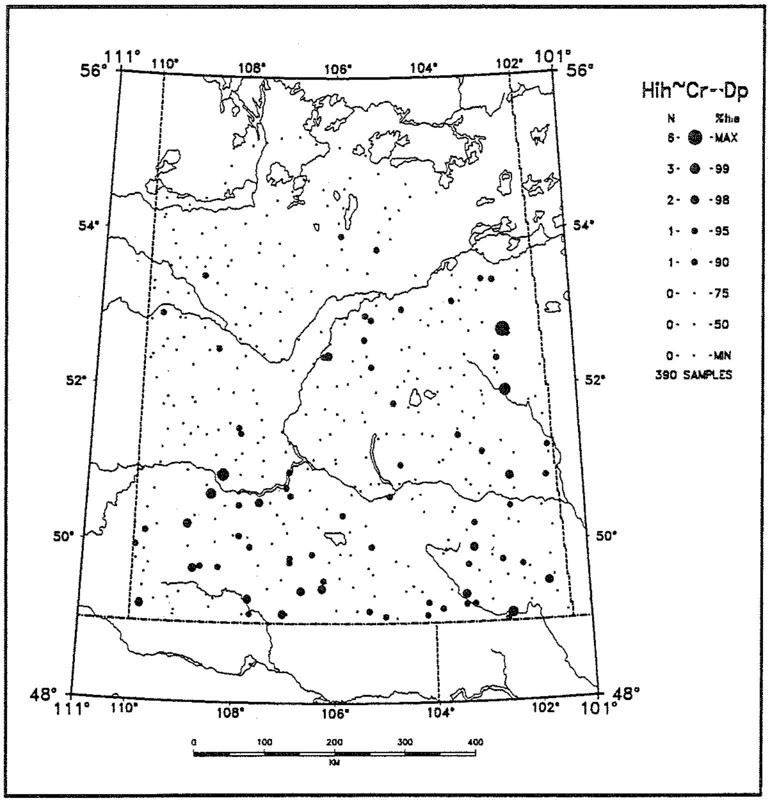

Figure 5. Chrome (>1%) diopsides (0.25-2 mm) recovered from till (approximately 25 kg samples).

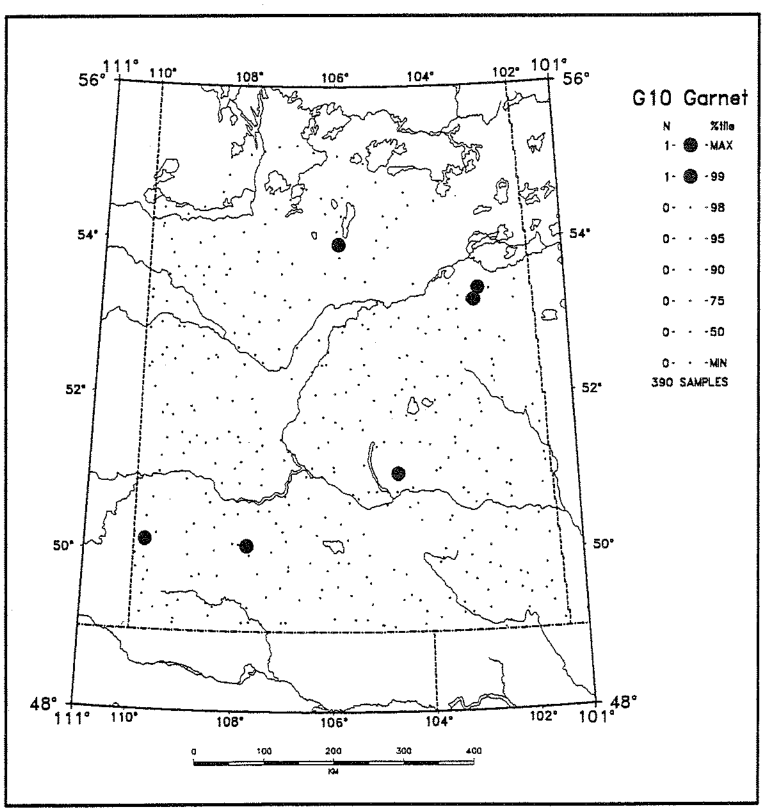

Figure 6. G10 harzburgitic garnets (0.25-2 mm) recovered from till (approximately 25 kg samples).

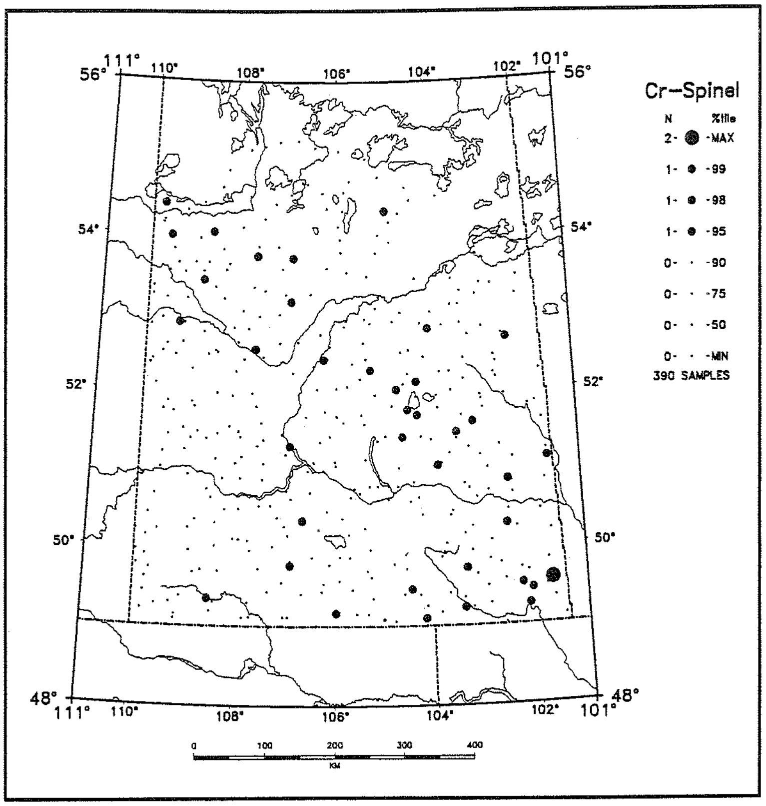

Figure 7. Chrome (>30%) spinels (0.25-2 mm) recovered from till (approximately 25 kg samples).

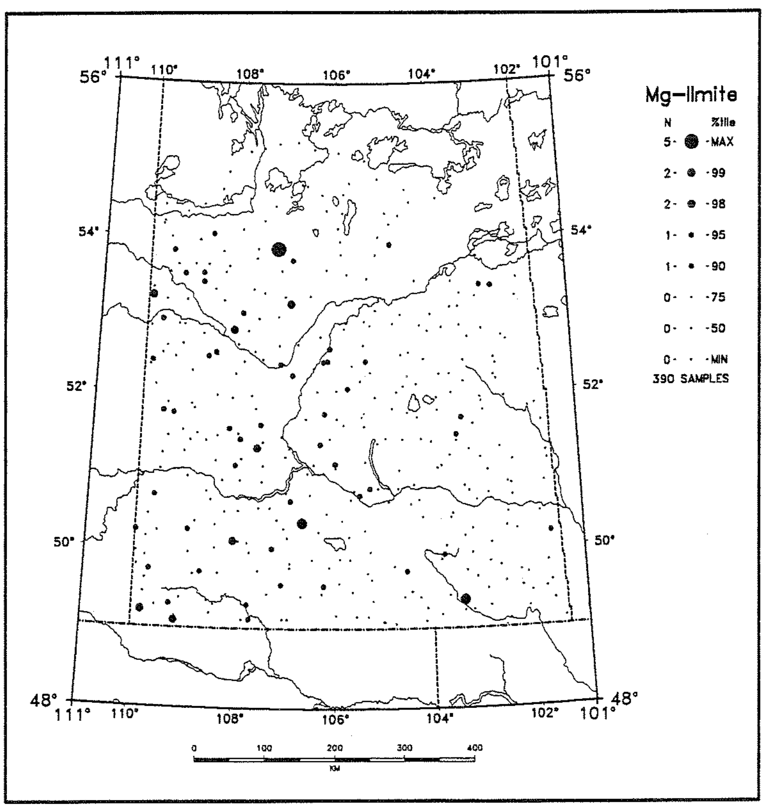

Figure 8. Magnesian-ilmenites (0.25-2 mm) recovered from till (approximately 25 kg samples).

chrome-pyropes were used in a geothermometry study. Using the assumption of a 40 mW/m^2 geotherm (Griffin et al., 1989; Griffin and Ryan, 1995) and assuming acceptable calibration to other instruments, 13% of the prairie-wide garnets, mostly G11s, report temperatures above the diamond stability field (>1250° C or >75 ppm Ni), 31% are in the diamond stability field (32-75 ppm Ni), and 56% have temperatures below the diamond stability field (<950° C or <32 ppm Ni). Of the grains in the Griffin diamond window (32-75 ppm Ni), 80% contain <50 ppm Zr, a positive sign regarding diamond grade (Griffin and Ryan, 1993 and 1995). These grains occur across southern Saskatchewan, but cluster around Diefenbaker Lake and Prince Albert.

Six southern Saskatchewan garnets were classified as harzburgitic G10s (Fig. 6, Table 1). Two are from southwestern Saskatchewan, near Tunstall and Hak. One grain each was recovered at Bittern Lake and Gregherd. In the northeast of the study area, two G10 chrome-pyropes were found at closely spaced sites near Red Earth Creek and Smoky Burn, west of the Pas (Manitoba). The Tunstall G10 is strongly subcalcic, under 2% CaO. The other five contain about 5% CaO, but have Cr_2O_3 concentrations sufficiently high to warrant a G10 designation. The chrome-rich character of the Hak G10, over 12% Cr_2O_3, indicates a composition similar to G12; and the titanian nature of the Gregherd grain indicates a composition similar to G11.

Using the Ni temperature guidelines mentioned above, none of the six G10s recovered from southern Saskatchewan fall in the diamond preservation window. Those recovered from tills at Tunstall, Hak, Gregherd, and Smoky Burn give higher temperatures, whilst those recovered at Bittern Lake and Red Earth Creek give lower temperatures. However, four of the G10 pyropes, at Hak, Bittern Lake, Gregherd and Smoky Burn, contain <50 ppm Zr.

Two chrome-spinel grains marginally stand as outliers in the prairie-wide data above or near 60% Cr_2O_3 and 11% MgO. This composition has been identified as typical of diamond inclusion chrome-spinels and hence presumably the composition of chrome-spinels derived from diamondiferous xenoliths (Gurney and Moore, 1993; Gurney and Zweistra, 1995). One of these grains is from Booth in southern Saskatchewan (Site 97-1-2, see Table 2).

The prairie-wide chrome-spinel data are readily divisible into two clusters separated at 53% Cr_2O_3. 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); while chrome spinels with > 900 ppm Ni fall within the P2 field. Below 53% Cr_2O_3, Ni values are more variable, ranging from 200 to 2000 ppm. This compositional range is comparable to Griffin and Ryan's (1993; 1995) P3 and P4 clusters. High-Cr grains preferentially occur in the eastern half of the prairie region, including eastern Saskatchewan, whereas low-Cr grains are present at several sites in Alberta.

Griffin and Ryan (1993, 1995) report that chrome-spinels with high-Zn values are unlikely to have been derived from kimberlite or lamproite; 28 (67%) of the 42 chrome-spinels recovered from southern Saskatchewan contain <2000 ppm Zn. Griffin and Ryan (1993) also reported an association between low-Zn, high-Ni chrome-spinels and high temperature, and hence high pressure, conditions as indicated by co-existing garnets. Using an arbitrary cutoff of 800 ppm for both variables, 8 low-Zn and high-Ni chrome-spinels were identified from the survey area (Table 2). Seven of these occur in a zone running from Prince Albert to Regina, and a single grain was recovered at Redvers in the far southeast of the survey area. Of these 8 grains seven fall within Griffin and Ryan's P3 classification, and one is a P2, indicating that they could have been derived from Group 2 kimberlites and lamproites.

Griffin and Ryan (1993, 1995) also report that chrome-spinels from kimberlite and lamproite commonly contain >6 ppm Nb or Zr. No grains meeting this criterion were identified.

Multiple indicator mineral sites and districts are clearly of particular interest in diamond exploration; a number of these deserve mention. Firstly, the Smoky Burn and Red Earth Creek sites, together with one site to the east form a G10, chrome-diopside and magnesian-ilmenite cluster. Both the Hak and Tunstall sites in southwestern Saskatchewan are characterized by a G10, kimberlitic garnet, chrome-diopside association. On a regional scale, the abundance of chrome diopsides in the south of the province is, together with the occurrence of kimberlitic and eclogitic garnets, magnesian-ilmenites and chrome-spinels, well known in the Wood Mountain region and demonstrated by these data,. Of perhaps greater interest is the region of kimberlitic and peridotitic garnet abundance, with the presence of chrome-spinels, magnesian-ilmenites and chrome-diopsides, west and northwest of Prince Albert. North of Lake Diefenbaker, in the Rosetown-Elrose region, a number of sites show a pattern of peridotitic garnet, chrome-diopside and magnesian-ilmenite occurrence. Further to the north, southwest of Battleford,

Table 2. Chrome-spinels recovered from till (approximately 25 kg samples) in southern Saskatchewan

Site	NTS Sheet	Location	UTM Coordinates			Chrome-spinel classification after Griffin and Ryan (1993, 1995)				Zn ppm	Ni ppm
						P1	P2	P3	P4		
43-4-2	73K	Northern Pine	12	580750	6029000	1	0	0	0	907	549
52-1-2	73F	Worthington Lake	12	593250	5983250	1	0	0	0	887	155
54-1-2	73C	Carruthers	12	613280	5859450	1	0	0	0	2362	441
68-2-1	72F	Eastend	12	679250	5469031	1	0	0	0	1037	568
71-3-2	73B	Maymont	13	318000	5823450	1	0	0	0	1502	145
88-4-1	73A	Carmel	13	481850	5790750	1	0	0	0	3182	203
96-1-1	73A	Leroy	13	519264	5762454	1	0	0	0	5915	522
97-1-2	72P	Booth	13	527284	5694449	1	0	0	0	336	679
100-2-1	72H	Brooking	13	539209	5479022	1	0	0	0	4299	128
105-4-2	62M	Sheho	13	628304	5717133	1	0	0	0	1304	375
110-1-1	63D	Etomami	13	677578	5838139	1	0	0	0	955	275
114-2-1	62L	Broadview	13	676048	5572612	1	0	0	0	744	668
115-3-2	62E	Oxbow	13	708111	5459461	1	0	0	0	1021	295
115-4-1	62E	Auburnton	13	712146	5481114	1	0	0	0	992	396
KIM-92-44	73I	Nipekamew Lake	13	504944	6019431	1	0	0	0	1631	284
81-1-2	72O	Tichfield	13	364800	5683550	0	1	0	0	492	988
107-1-2	62E	Griffin	13	618258	5509342	0	1	0	0	2654	1086
121-4-2	62F	Redvers	14	306392	5493192	0	0	1	1	409	1303
121-4-2	62F	Redvers	14	306392	5493192	0	0	1	1	1497	558
53-3-1	73F	Turtleford	12	643800	5921350	0	0	1	0	2473	1008
64-1-1	72N	Duperow	12	697280	5757250	0	0	1	0	1579	1650
76-3-1	72G	Rosefield	13	321750	5440750	0	0	1	0	5187	2013
78-2-1	73G	Dumble	13	373031	5953277	0	0	1	0	570	1300
80-4-1	73B	Aberdeen	13	414700	5806500	0	0	1	0	291	1755
83-4-1	72J	Droxford	13	381332	5577398	0	0	1	0	339	900
95-3-2	73A	Tisdale	13	565052	5850083	0	0	1	0	666	1258
96-3-2	73A	Quill Lake	13	547664	5773820	0	0	1	0	561	1670
97-4-2	72P	Kandahar	13	548659	5726145	0	0	1	0	542	1264
98-4-2	62M	Enid	13	577663	5654356	0	0	1	0	932	1089
100-3-1	72H	Lake Alma	13	559369	5438074	0	0	1	0	2216	1547
105-2-1	62M	Tuffnell	13	612164	5726234	0	0	1	0	3884	2219
113-2-1	62L	Waldron	13	678135	5635188	0	0	1	0	3000	947
115-2-2	62E	Wordsworth	13	698081	5488434	0	0	1	0	1461	889
118-3-1	62N	MacNutt	14	314608	5665265	0	0	1	0	947	1014
52-3-2	73K	Morin Creek	12	653180	5990850	0	0	0	1	1045	716
70-4-1	73G	Chitek Lake	13	322500	5957650	0	0	0	1	9489	123
79-2-2	73G	Avebury	13	369398	5890691	0	0	0	1	1828	401
83-1-2	72G	Royer	13	362655	5514520	0	0	0	1	3891	144
92-1-1	72H	Rockglen	13	428690	5446218	0	0	0	1	1130	538
97-2-2	72P	Dafoe	13	534755	5733207	0	0	0	1	2296	250
105-2-2	62M	West Bend	13	604802	5701737	0	0	0	1	10131	117
108-1-1	62E	Torquay	13	615203	5453652	0	0	0	1	1249	468

a group of three sites are characterized by a chrome-diopside, kimberlitic garnet, magnesian-ilmenite and peridotitic garnet pattern, which is similar to that observed northwest of Prince Albert and to the north of the Battleford site. These results demonstrate the true multiple mineral nature of the Wood Mountain region low-chrome-diopside pattern, an observation that has tended to be overlooked. However, what is perhaps most remarkable is the generally broad distribution of kimberlitic indicator minerals across the entire survey area.

Visible Gold in Tills

Visible gold grains were recovered at 246 (63%) of the sites where till was collected in the survey area. It is hard to discern any obvious patterns in the southern Saskatchewan data, however, there is some clustering (Fig. 9). Three sites containing 7-12 grains, supported by sites containing >2 grains, occur in the area north and northeast of Saskatoon in close proximity to the North and South Saskatchewan Rivers. Single sites containing >12 grains, and supported by several sites containing >2 grains, occur north of the Quill Lakes, southwest of Melville, and northeast of Rosetown. North of the Saskatchewan River towards the Shield margin sites containing >3 gold grains are not uncommon, and one site, west of La Ronge, contained 11 grains. There is a diffuse pattern of gold grains along a north-northwest trend from the southeast corner of the province through the Melville and Quill Lakes patterns mentioned above, and another west of the Missouri Coteau and south of the South Saskatchewan River.

Bulk Mineralogy of Till Concentrates

The 63-250 μm mineralogy data outline three general regions as having characteristic till compositions. The southwest part of the survey area (i.e., southwest of the Missouri Coteau) is not marked by any particular pattern, except for a tendency to exhibit lower ferromagnetic mineral and amphibole levels, and increased clinopyroxene (including diopside) levels in the far south and southwest.

The area north of the North Saskatchewan River exhibits a unique assemblage marked by high levels of ferro-magnetic minerals, ilmenite, garnet, ortho- and clinopyroxene, amphibole (Fig. 10) and zircon. Low levels of siderite are present in these tills, and the amphibole/siderite ratio clearly delineates this region.

The region south of the Saskatchewan River and east of the Missouri Coteau is characterized by mineralogy somewhat intermediate between the two patterns described above. Tills here have elevated concentrations of ortho- and clinopyroxene, epidote, and to a lesser extent garnet and amphibole, relative to the area to the southwest. Notably, kyanite was observed relatively frequently in tills from this region, but relatively infrequently to the southwest and rarely to the north.

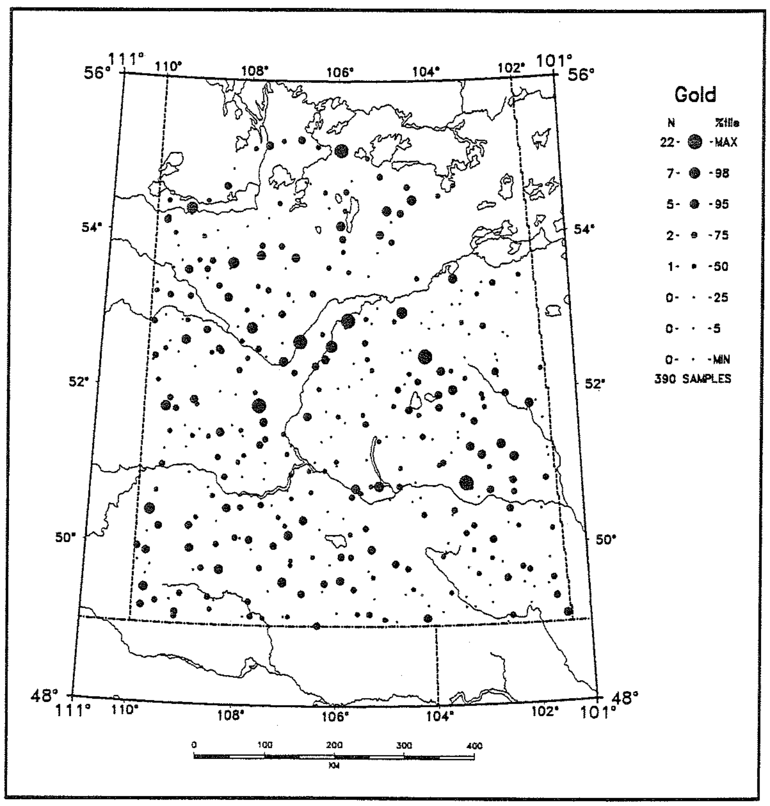

Figure 9. Visible gold grains recovered from heavy mineral concentrates of till.

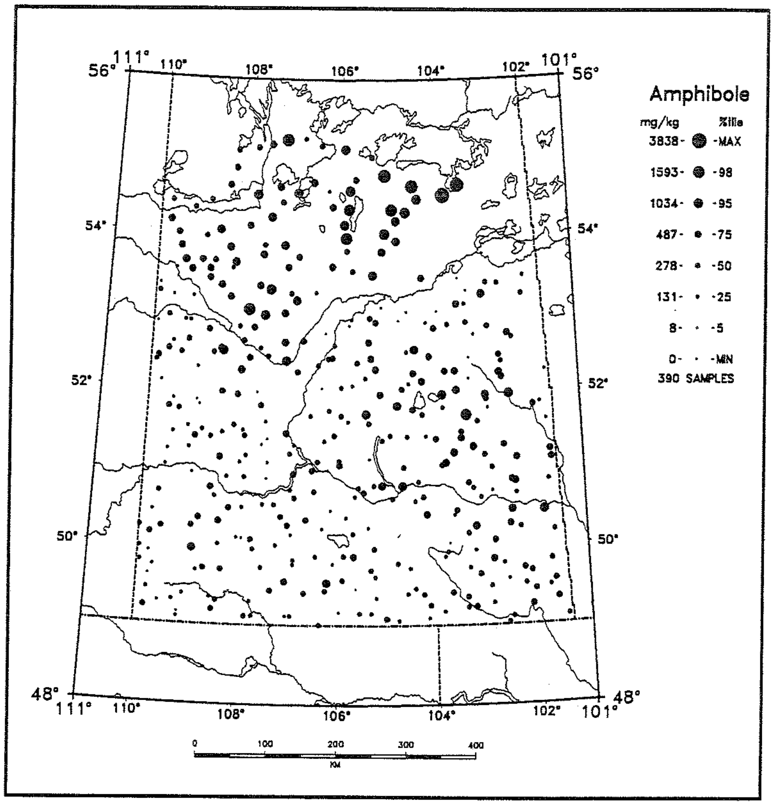

Figure 10. Amphibole recovered from the 63-250 µm heavy mineral fraction of till

8-16 mm Till Clast Lithology

Brown carbonate clasts, derived from the Paleozoic carbonates in Manitoba, are most frequent in the eastern half of the survey area, particularly in the Pasquia Hills area closest to their source (Fig. 11). Unlike the chemical carbonate data (described below) these clasts do not as noticeably drop in abundance west of the Missouri Coteau and north of the Saskatchewan River. Intrusive and high-grade metamorphic clasts (predominantly granites and granite-gneisses) are most abundant north of the Saskatchewan River and Latitude 52° N (Fig. 12). In contrast, Shield derived metavolcanic and metasedimentary clasts are abundant across the entire survey area, but are highest in the southeast and lowest in the southwest.

Gray carbonate clasts derived from the Rocky Mountains are rare, but most frequently occur in the southwest. The same area in the southwest, around the Cypress Hills and Wood Mountain, is characterized by the greatest abundance of quartzite clasts (Fig. 13). Quartzitic sandstone clasts (not shown) are most frequent west of the Missouri Coteau, and northwest of a line running northeast-southwest through the Battlefords. Shale clasts are largely restricted to the area south of the Saskatchewan River and east of the Missouri Coteau; however, there are a notable number of clasts extending some 150 km southwest beyond the Coteau south of the South Saskatchewan River.

Geochemical Analyses of Till Samples

The geochemical data for tills reveal broad-scale patterns that can be related to their provenance on a prairie-wide scale. The prairie-wide features of these multi-element patterns are briefly described by Garrett and Thorleifson (1995b). A more detailed discussion of these data is presented below in the context of the southern Saskatchewan survey area. In addition, a number of elements exhibit single element patterns that, even though they are of low geochemical contrast, may be related to mineral occurrences.

The most notable feature in the data is the high abundance of carbonate in eastern and central Saskatchewan (Fig. 14) that can be traced back to the Paleozoic carbonates in Manitoba. These data define an area delimited by the Missouri Coteau, in a 300 km line from Estevan, through Regina to Saskatoon, on the southwest, and the Saskatchewan River on the north. The carbonate levels are highest in the northeast of the survey area closest to Paleozoic outcrop, and generally decrease in a southwestwards direction towards the Coteau. Interestingly a number of other elements and ratios follow this trend and define this same region as having a characteristic till geochemistry. All of CaO, MgO, As (Fig. 15), Sb, Mn, V (Fig. 16), Mo (Fig. 17), Zn (Fig. 18) and Cd tend to decrease sympathetically; Na_2O (Fig. 19), K_2O and

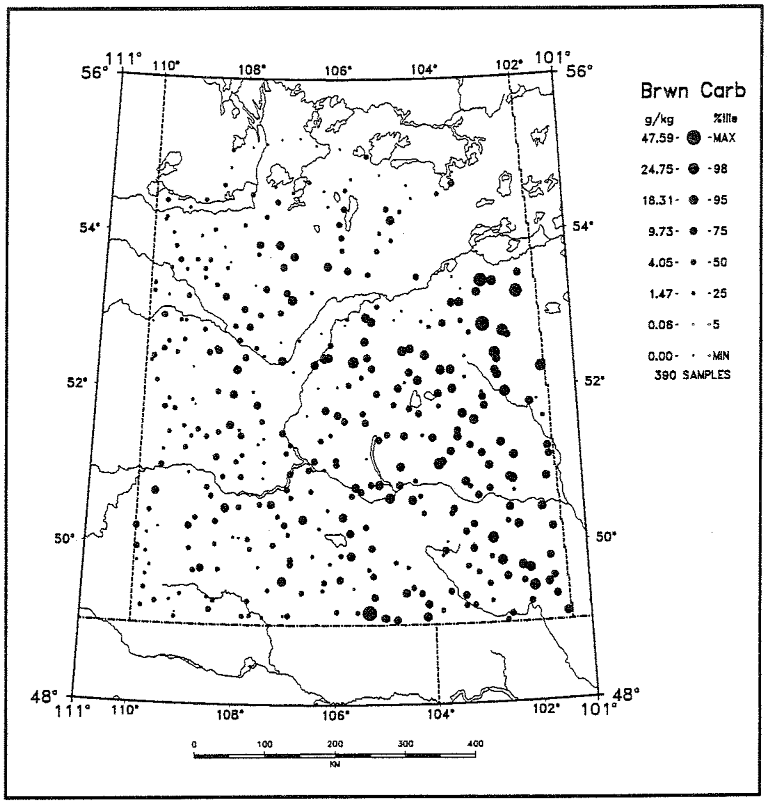

Figure 11. Brown carbonate clasts in the 8-16 mm fraction of till

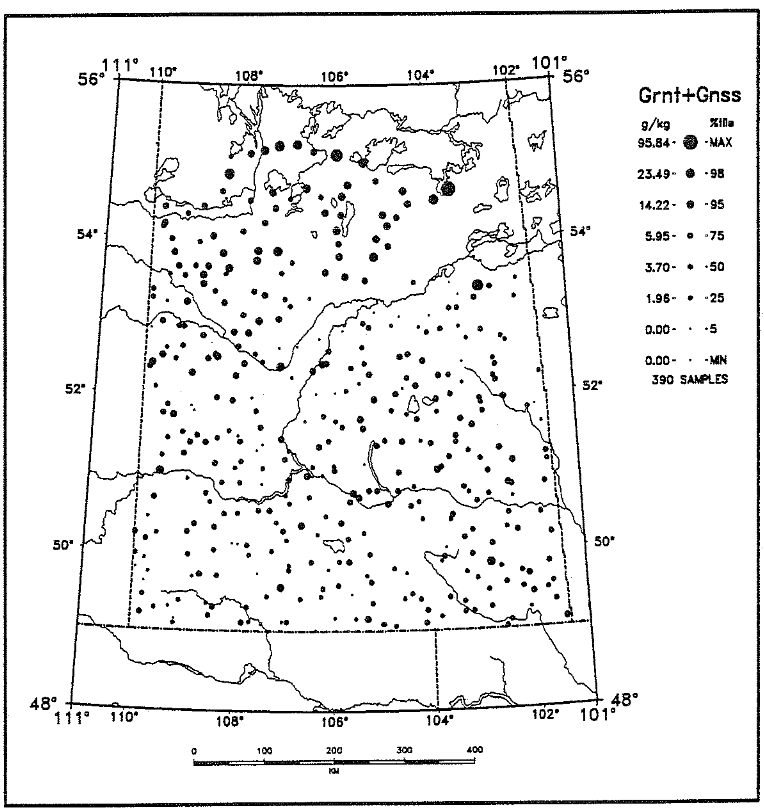

Figure 12. *Intrusive and high-grade metamorphic clasts in the 8-16 mm fraction of till*

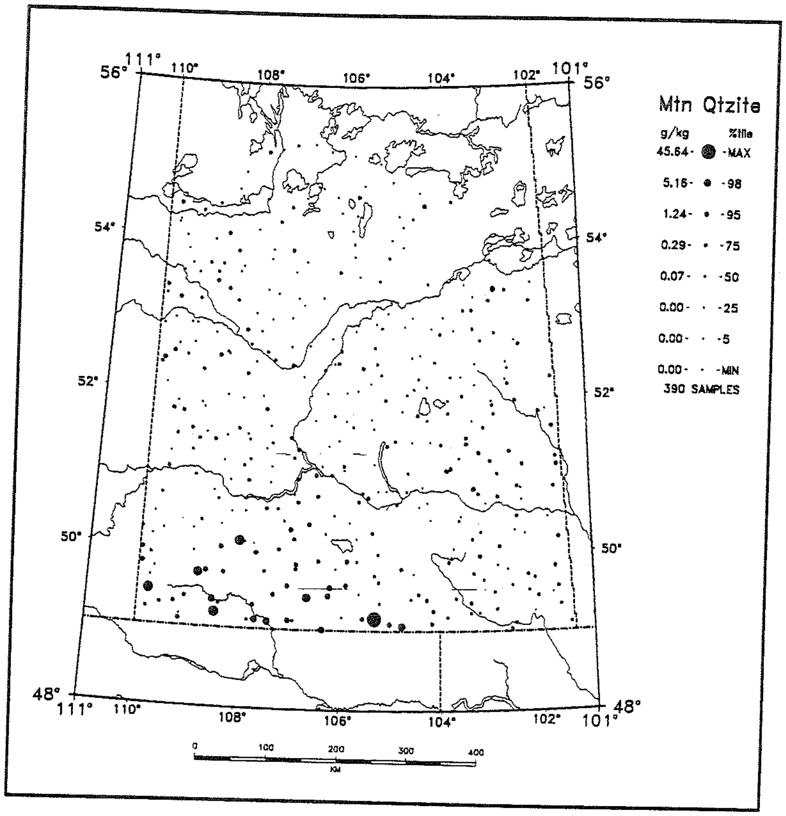

Figure 13. *Quartzite clasts in the 8-16 mm fraction of till*

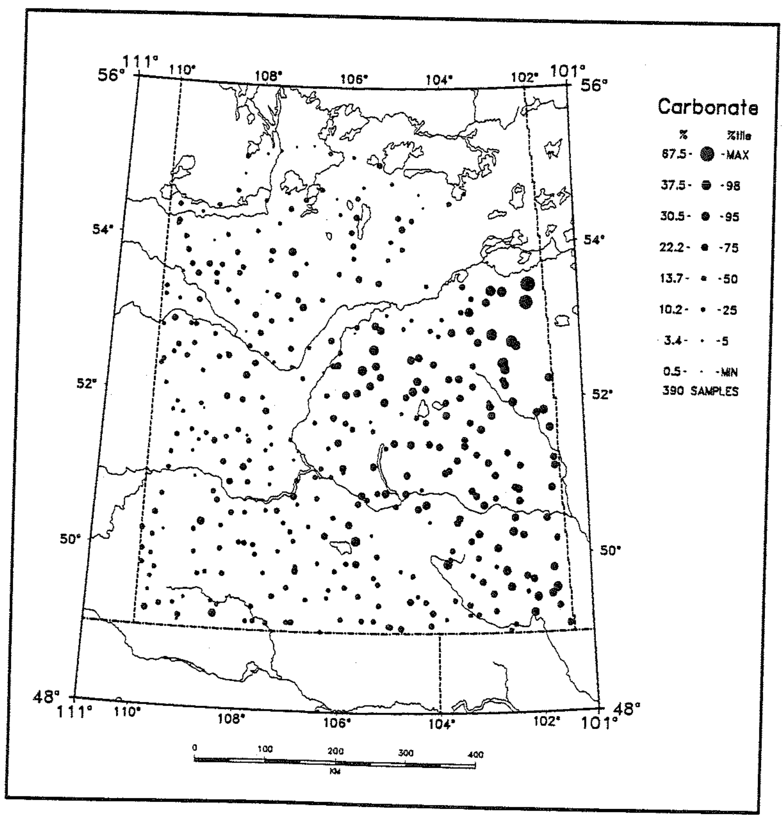

Figure 14. *Carbonate (Chittick) in the <63 μm fraction of till in southern Saskatchewan*

SiO_2 tend to increase; and Al_2O_3 (Fig. 20), Mo and the Al_2O_3/Carbonate ratio take on unique levels, in relation to other parts of the survey area. The role of metal-rich Cretaceous shales, now exposed in the Manitoba Escarpment, in developing these patterns is discussed later.

The region north of the North Saskatchewan River, also limited by the northwesterly extension of the Missouri Coteau, exhibits a characteristic geochemical signature. Most notable are the low levels of As (Fig. 15), Sb and U/Th, together with Zn (Fig. 18) to a lesser extent; in contrast, Na_2O (Fig. 19), K_2O and SiO_2 levels all tend to be higher.

The area southwest of the Missouri Coteau is characterized by lower carbonate, CaO and MgO levels, and increased Al_2O_3 (Fig. 20), K_2O, Na_2O, SiO_2, Ti, Sc, As (Fig. 15), Sb, Zn (Fig. 18) and V (Fig. 16) levels. High values of the Al/Carbonate and Na/Carbonate ratios are characteristic of this region of dominantly shallow, locally derived, tills.

The distribution of a number of elements of economic interest is discussed below. Cadmium is geochemically useful because of its relationship to Zn, and levels are disproportionately high, relative to Zn, in the northern tills in the Porcupine and Pasquia Hills areas. The Br data are of interest as they are highest in an arcuate belt from the Estevan area northwest through Saskatoon. Intriguingly this area overlies the Prairie Evaporite. Levels of Ba generally increase towards the southwest and are highest southwest of the Missouri Coteau; a feature clearly demonstrated in the <250 μm heavy mineral concentrate data, which suggests that the Ba is likely present in the form of barite.

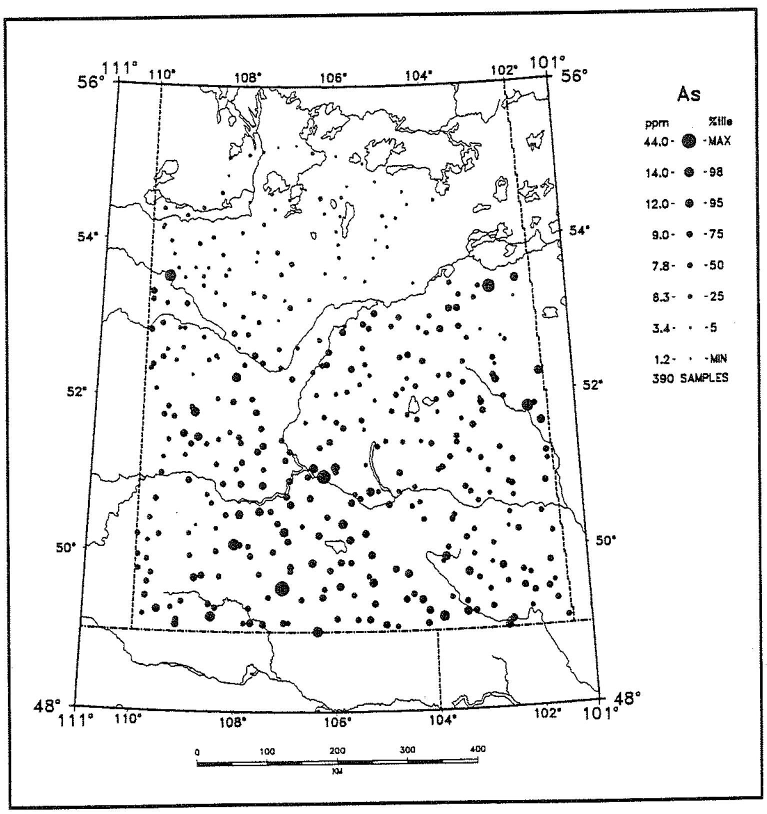

Figure 15. As in the <63 μm fraction of till

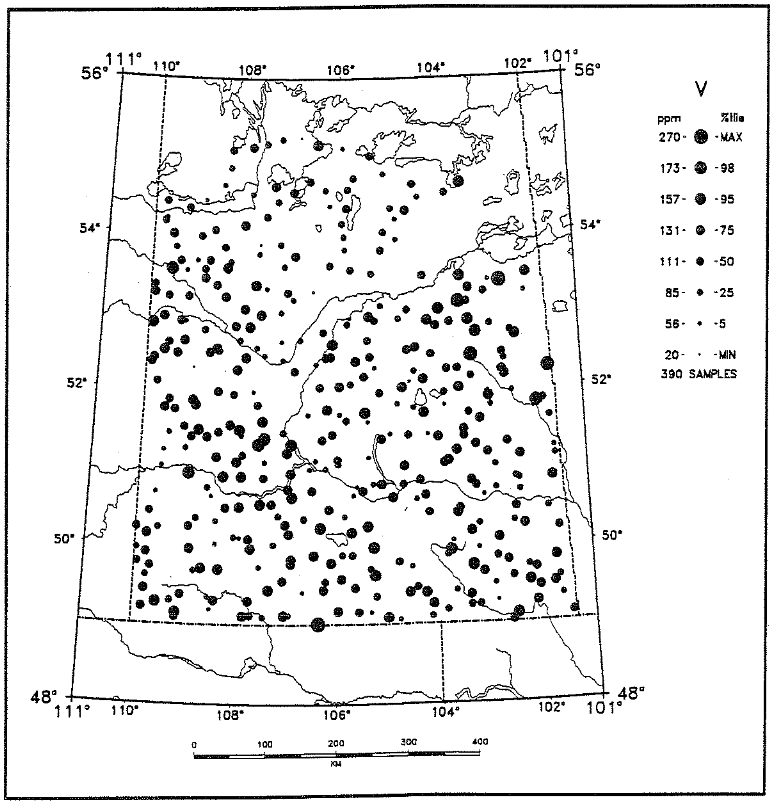

Figure 16. V in the <63 μm fraction of till

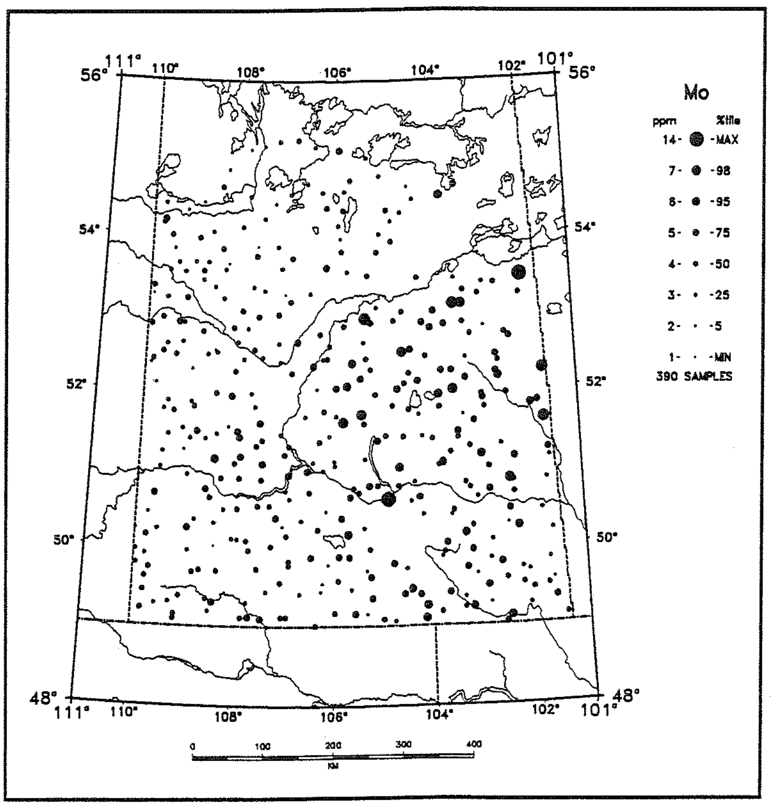

Figure 17. Mo in the <63 μm fraction of till

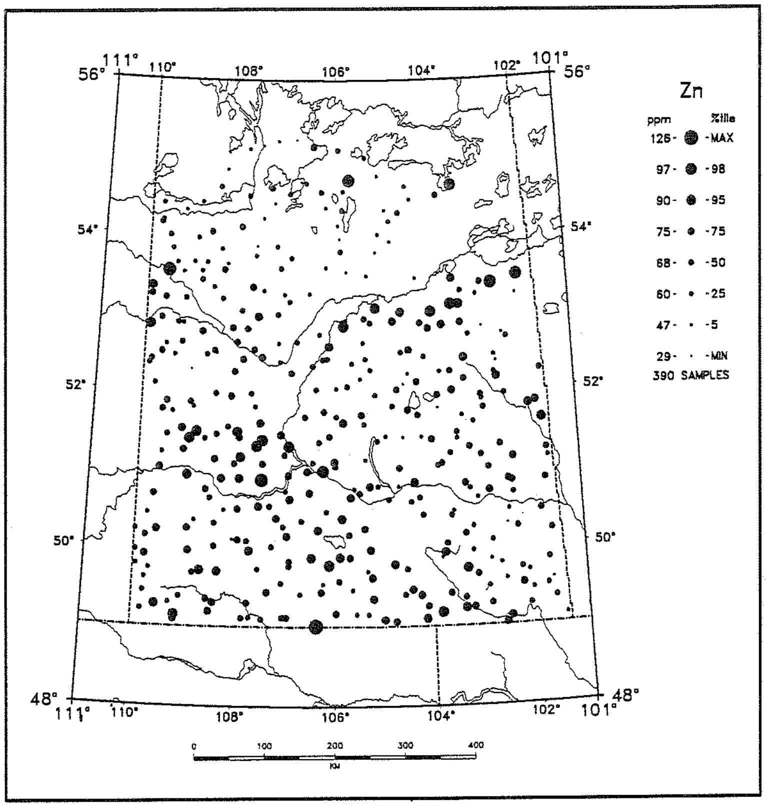

Figure 18. Zn in the <63 μm fraction of till

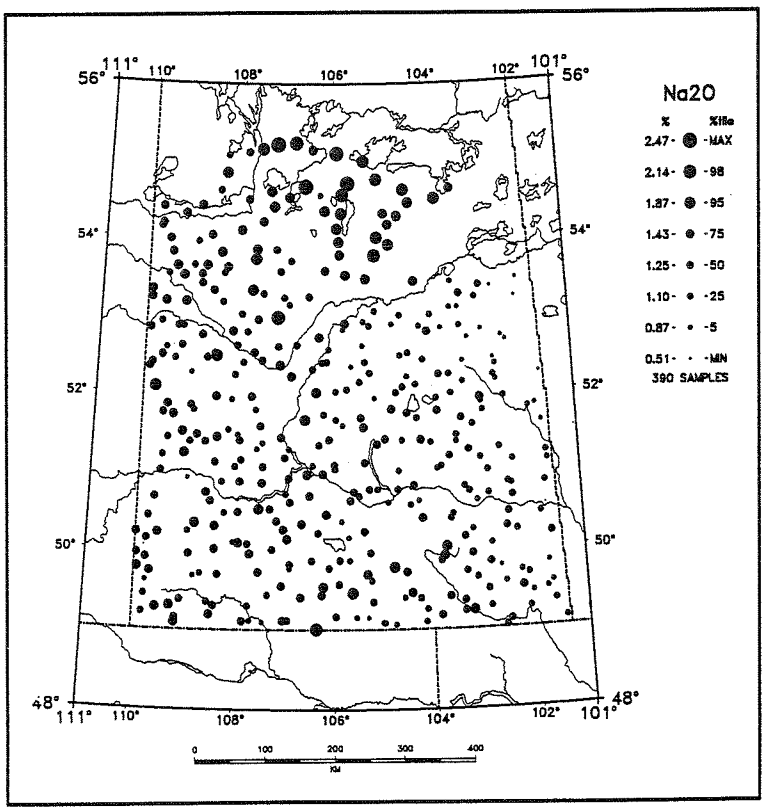

Figure19. Na_2O in the <63 μm fraction of till

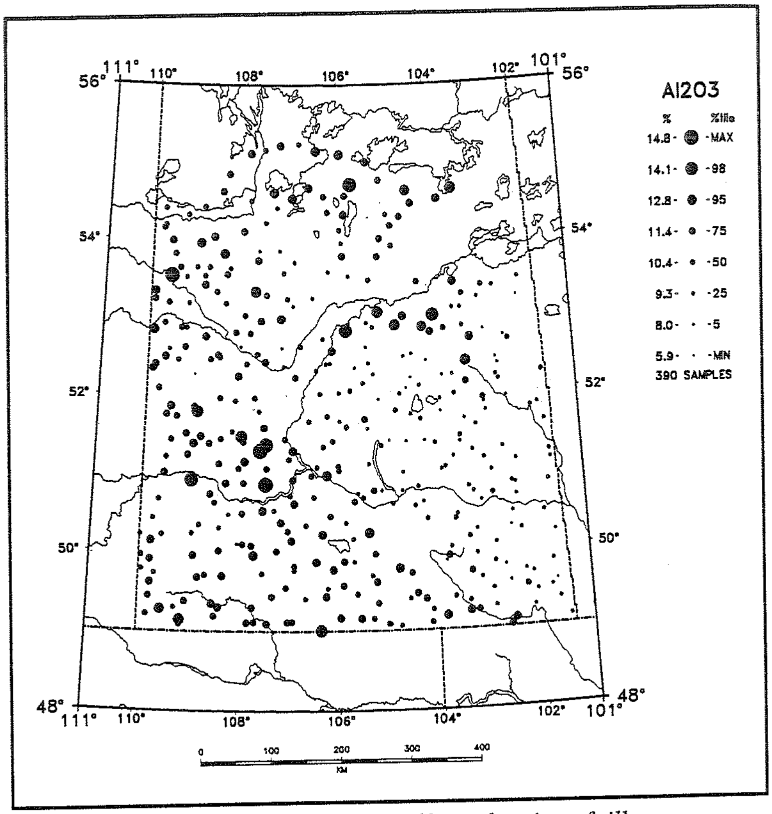

Figure 20. Al_2O_3 in the <63 μm fraction of till

Gold levels in the <63 μm fraction of the tills (Fig. 21) are highest in the western part of the survey area, but clearly detectable amounts of Au occur widely; though the distribution pattern does not always agree with the observations of visible gold in the heavy mineral concentrate (Fig. 6). The highest levels occur in proximity to the North and South Saskatchewan Rivers and the Cypress Hills and Wood Mountain. The Au in <63 μm heavy mineral concentrate (HMC) data, when normalized for the amount of concentrate in each till sample, indicate a generally similar pattern to the till data. Features that are characteristic of the <63 μm HMC data are elevated Au levels south of the Wood Mountain, in the Melville-Quill Lakes area, and north and northeast of Prince Albert towards the Shield margin. The coarser 63-250 μm corrected HMC Au data reveals a somewhat different pattern of 6 clusters that occur: 1) along the Wood Mountain; 2) along a line through Moose Mountain between the Souris and Qu'Appelle Rivers; 3) north of Quill Lakes; 4) around the elbow of the North Saskatchewan River; 5) Pierceland in the northwest corner of the survey area; and 6)north of Prince Albert.

The analyses of the <63 and 63-250 μm heavy mineral concentrates were combined into a composite <250 μm value. These data reveal many of the same features as the raw till data that appear to divide the surface till data into three domains. Firstly, Ba and Cr levels are highest southwest of the Missouri Coteau; secondly levels of Fe, Co and Sc are highest northeast of the Coteau; and lastly levels of Na, Th, Tb, Sm, Ce and La are highest north of the North Saskatchewan River. Of interest is a group of 5 sites to the south of the South Saskatchewan River above its confluence with the North Saskatchewan River that are characterized by higher levels of Th, U, Tb, Yb (Fig. 22), La, Lu, Sm, Ce, Hf, Zr, Ta, Cr and Au. The possible significance of these will be discussed later.

Geochemical Analyses of Soil Samples

The geochemical patterns in the soil data closely follow those observed for the tills. However, in some instances, soil patterns are related to fluvial derivatives of the tills (i.e., coarser grained quartz-rich fluvial and aeolian sands, and finer grained clay-particle sized richer glacio-lacustrine sediments). These soil fractions are characterized by generally lower trace-element levels in the coarser sediments and higher levels in the fine-grained sediments. The C horizon data bear a greater similarity to the till data than the A horizon data, since to a large extent, C horizon samples consist of weathered till and other glacial sediments. While A horizon samples have been influenced by eolian and pedological processes that have led to a modification of the C horizon patterns through the concentration and depletion of different elements in different areas and soil regimes.

The distribution of Cd and Hg in the A (and/or) C horizon soils is of particular interest in environmental and agricultural studies as compounds of this element were declared toxic under the Canadian Environmental Protection Act (CEPA) in 1994. A discussion of the close relationship of the Cd data for surface soils to

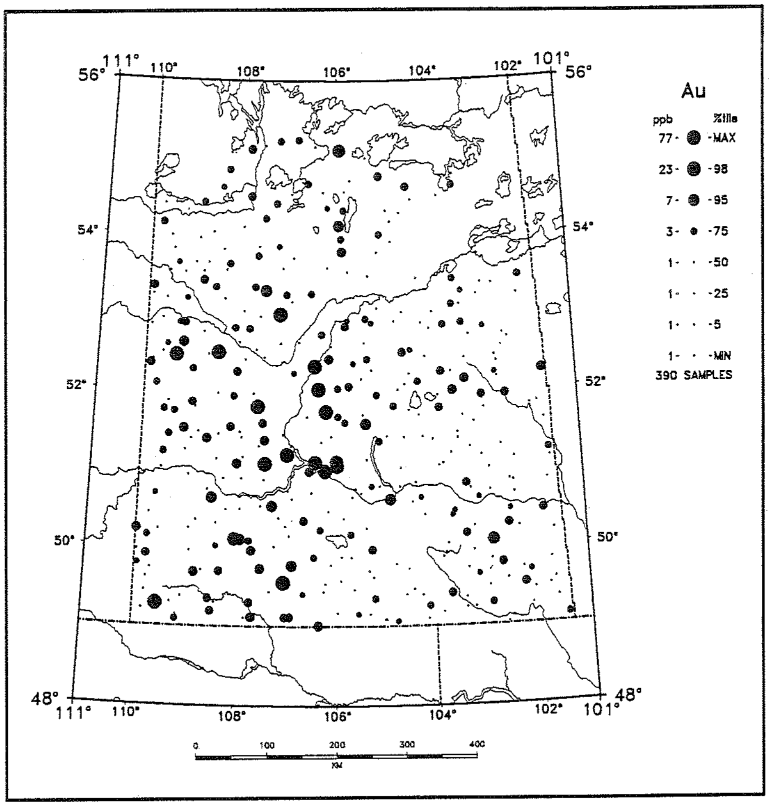

Figure 21. Au in the <63 µm fraction of till

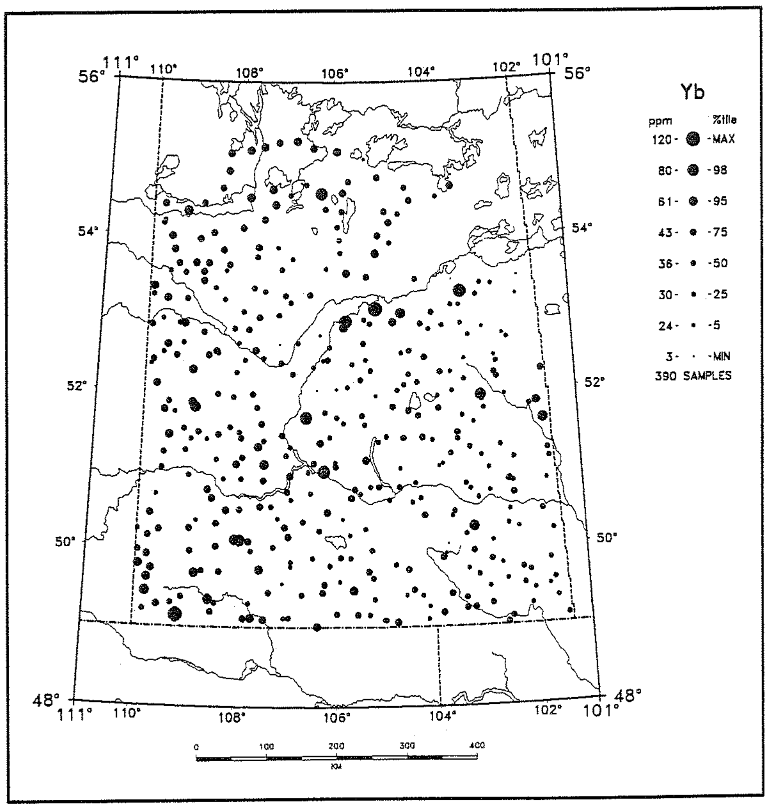

***Figure 22.** Yb in the <250 µm heavy mineral fraction of till*

glacial sediment parent materials has been presented in Garrett (1994). Similarly, a discussion of the distribution of Hg in A and C horizon soils has been presented by Garrett and Thorleifson (1995a). The dominant controls on Hg distribution are the chemistry of the soil parent materials, glacial sediments, and in turn their provenance.

DISCUSSION

Chrome-Diopside Distribution

The distribution of chrome-diopsides in glacial tills is worth further note. The data were split into two groups using a 1% Cr_2O_3 cut off. The spatial distribution of these two groups is quite different (Figs. 4 and 5). High chrome-diopsides are most concentrated in the northeast portion of the survey area, southwards along the Manitoba border, and in a general pattern in the southwest. In contrast, whilst there are low chrome-diopsides scattered throughout southern Saskatchewan there is a marked concentration of these heavy minerals in southern Saskatchewan in the vicinity of, and down ice from, the Miocene Wood Mountain Formation gravels.

In the eastern part of the survey area there is an increased chance that at least some of the chrome-diopsides might be derived from Churchill or Superior Province ultramafic rocks in the Shield. Thus, a two provenance model, with both Cretaceous (?) kimberlitic and older Shield sources, is appropriate.

Work by Kjarsgaard (1995) has indicated that chrome-diopsides from Phanerozoic intrusives in southern Alberta and northern Montana are characterized by low Cr_2O_3. Again a multiple provenance model may be appropriate for southwestern Saskatchewan, since the chrome-diopsides may be derived from either local intrusions, or from the Wood Mountain gravels. The latter suggests that the transport history of the kimberlitic/lamproitic indicator minerals in this area is complex. The indicator minerals may have been removed from their original bedrock source by Tertiary fluvial events, stored in Miocene river gravels, and later released and dispersed by Pleistocene glacial processes. If this is the case, and long-distance fluvial transport was involved, the data can only be considered a favourable regional indicator. It should be remembered that if indicator grains were originally transported in rock fragments the post-depositional weathering of these, or the heavy mineral recovery processing of rotten fragments, would release fresh looking indicator minerals that do not necessarily reflect a local bedrock source.

Till Provenance

The geochemical, mineralogical and pebble data for the 390 till samples collected across southern Saskatchewan indicate that the surface tills can be divided into three main domains. For the purpose of this discussion these can be defined as the: 1) western (i.e., southwest of the Missouri Coteau and its extension northwest of Battleford); 2) eastern (i.e., east of the Coteau and south of the South Saskatchewan River); and 3) northern (i.e., the remaining area east of the Coteau and north of the South Saskatchewan River) domains.

The eastern domain clearly shows the influence of Paleozoic carbonates and Cretaceous shales from Manitoba in controlling till composition. This influence decreases in a southwesterly direction as more locally derived material is incorporated into the surface till sheet, as pointed out by Schreiner (1990). However, it must be remembered that this till sheet was introduced not over bedrock, except along and immediately to the west of the Manitoba Escarpment, but over earlier till sheets. It is in this part of the survey area that total till thicknesses can exceed 200 m. For example, if Floral Formation till is present at the surface it may contain entrained Warman Formation, and possibly interglacial, material. The geomorphic features in much of this domain indicate a north or northwest ice source. This appears to be in conflict with the compositional evidence. One possible explanation is that although locally surface tills derived from the north and northwest may exist, the last ice advance was more of a re-sculpting event that modified the surface geomorphic features of the pre-existing easterly and northeasterly derived materials.

The compositional data for northern domain tills indicates a major component of Shield provenance material. This is well demonstrated by the low As, V, Zn and U/Th, and high Na/Carbonate levels. The abundance of granite and granite-gneiss clasts and the suite of rare-earth elements concentrated in the heavy minerals recovered from the tills, described above, all point to a Shield provenance. Interestingly a number of till samples collected from within the extent of the eastern domain also reveal the same geochemical characteristics, and these may be examples of northern domain tills deposited in the last ice advance. In addition, a number of northern domain till sites show the influence of the eastern domain compositional pattern. This is probably due to the entrainment of eastern domain till by later southward advancing ice.

The western domain tills appear to be those most likely to reflect local bedrock compositions, not unsurprisingly as total till thicknesses are thinnest in this part of the survey area. An intriguing question concerning the western domain is the role of the Missouri Coteau in marking its eastern limit. Although there is some evidence in the data that northern domain tills were deposited beyond the line of the Coteau, for example southwest of Battleford, and that pebble sized clasts were carried into this region from the east and north, this topographic feature marks fairly well the southwesterly limits of the eastern and northern regional deposition domains. The line of the Coteau follows fairly closely the 600 m bedrock surface contour, and the possibility exists that this posed a sufficient topographic barrier to south and westerly advancing ice that it limited regional deposition of the eastern and northern domain tills.

Within the western domain the Cypress Hills and Wood Mountain, particularly the latter, locally influenced till composition. Quartzite clasts and heavy, including kimberlitic indicator, minerals accumulated by Miocene fluvial processes in the Wood Mountain Formation gravels have been entrained in the surface tills and can now be found in the area surrounding Wood Mountain, particularly to the south. The fact that these clasts and heavy minerals are also found to the north indicates the broader extent of these poorly consolidated Miocene gravels in pre-Pleistocene times, and their destruction and incorporation into glacial sediments during glaciation. The lesser contribution from the Cypress Hills was likely due to their nunatak form.

The characteristic heavy mineral geochemical pattern described earlier along the south side of the South Saskatchewan River, northeast of Saskatoon, could be due to fluvial processes that led to heavy mineral accumulations which were later entrained in the till. The till <63 μm matrix Al_2O_3 data are elevated in some of these same samples, perhaps unexpectedly, and may reflect the presence of corundum. This is confirmed by the fact that a group of 3 of the corundums picked by SRC came from this area. Whether these processes were pre-glacial or inter-glacial, cannot be determined on the basis of the present data.

A speculative chronological model that might assist in diamond exploration is as follows:

1) Initial glaciation from northeast and northerly sources extended across the entire survey area, with the exception of nunataks in the southwest. This was likely repeated several times, as indicated by the multiple tills of the Sutherland Group. However, the limits of subsequent glacial advances may not have extended across the entire survey area. The surface tills of the western domain represent this process and their matrix materials are dominantly locally derived. The coarser gravel fraction contains brown carbonate and Shield-derived clasts transported in excess of 600 km. Locally the nunataks drastically modified ice flow directions (Klassen, 1992, 1994).

2) A major ice advance from the east and northeast that introduced the eastern domain tills that contain a large component of Manitoba-derived Paleozoic carbonates and Cretaceous trace element-rich shales, presumably represented by the Floral Formation. In the eastern and northern domains these tills were very probably deposited on top of earlier stage 1 sediments. The southwestern limit of regional deposition of sediments by this advance seems to be coincident with the present position of the Missouri Coteau, and any extension of flow beyond the line of the Coteau seems to have involved the reworking of older stage 1 tills dissimilar in composition from the eastern domain.

3) A final ice advance from the north and northwest that deposited Battleford Formation sediments with a characteristic Shield provenance or, as a result of dilution due to the incorporation of stage 2 material an enrichment of Shield provenance material, that overrode stage 2 sediments. South of the North Saskatchewan River the geomorphic features indicate that this ice advance continued southeastwards over the stage 2 eastern domain tills. In that domain the ice re-sculpted the earlier easterly derived sediments, or entrained and redeposited them, and only locally appears to have deposited true northern domain glacial sediments with a clear Shield provenance.

The relationship of the compositional data presented and this speculative chronology to the now well established Quaternary stratigraphy is of particular interest, however, this topic is beyond the scope of this report and will be the subject of future work.

Gold Occurrence in Tills

The widespread abundance of gold in tills of southern Saskatchewan raises questions as to its origin. The candidates include: 1) gold occurrences in the Precambrian Shield; 2) unrecognized sources in the Cretaceous rocks of the eastern prairies; 3) paleoplacer sources in Early Cretaceous rocks of the Foothills Ranges [e.g., the McDougal-Segur channel sands (Leckie and Craw, 1995)]; and 4) Miocene and younger gravels and sands. The visible gold and geochemical data indicate that the pre-glacial fluvial sediments bringing gold from the west and southwest were the major source of the gold entrained in the glacial tills in the western domain. The relationship of the patterns in the data to the proto-Saskatchewan River and the Wood Mountain Formation are compelling. Close to the Shield margin, in northern domain tills, the most likely sources are occurrences in Shield host rocks. The Au in the eastern domain is more problematic. The role of rivers flowing in the interglacials cannot be assessed, but must not be ruled out; they may have been particularly important in influencing the Au content of eastern domain tills. None of the Au in eastern domain tills is likely of local origin, but instead was probably brought in from Shield sources to the east, or was entrained from earlier tills where pre-glacial gravels were the most likely source.

IMPLICATIONS FOR DIAMOND EXPLORATION

The link between the discovery of a diamond indicator mineral and its source is the transportation process, or more correctly processes, that brought the indicator mineral to its discovery site. Clearly, for the Quaternary sediments of southern Saskatchewan this is a complex history.

Where indicator minerals are discovered in northern domain Shield derived tills (i.e., dominantly north of the North Saskatchewan River), sources should be sought to the north. However, exploration in this area is made difficult by the thickness of the glacial drift. For example, sources for indicator minerals recovered west and northwest of Prince Albert, have not been identified to the north or northwest, the source of ice during the last glaciation event. This fact, coupled with the abundance of Shield derived clasts and heavy minerals indicates that transport distances are likely long, and source areas may be quite distal (i.e., close to the Shield margin, or even further north). It is interesting to note that the three multiple indicator mineral bearing sites located southwest of Battleford were recovered from till that clearly shows northern domain affinities; and as such may represent the tail of a glacial dispersion train that extends some 200 km to the Shield, indicating that the likely source of the indicator minerals was the Shield, or Phanerozoic sediments close to the Shield margin. However, an alternative hypothesis would be that the indicator minerals were first transported from a source to the east by an earlier glacial event, and then incorporated into younger tills dominantly derived from the north. The intimate juxtaposition of the diamondiferous Sturgeon Lake 02 kimberlite block (35 km NW of Prince Albert), which includes shale breccia, with probably Cretaceous shale blocks, as reported by Scott-Smith (1995), can be interpreted as support for the latter hypothesis of an original easterly source that was south of the subcrop of the Phanerozoic Mannville Formation sandstones adjacent to the Shield margin.

In this context it must be noted that no obvious reflection of the Fort à la Corne (Fig. 1) kimberlite occurrences, and those further north at the War Eagle Property close to Candle Lake, can be seen in the till data collected to the south of the occurrences. It is quite possible that the kimberlites did not undergo erosion during the late southward flowing event that deposited the northern domain tills in the immediate Fort à la Corne area. If the tills that overly bedrock are Sutherland Group, or stage 1, or even Floral Formation, stage 2, the original dispersal trains may never come to surface, as they have been covered by younger Battleford Formation tills. If both Sutherland and Floral tills are present, the later Floral glacial event would simply have moved the indicator minerals further in a generally westerly direction. During the final glacial event these indicator minerals and their generally eastern provenance matrix would have been incorporated into the southward moving domain 3 tills of dominantly Shield provenance. It is worth noting that several of the kimberlitic indicator mineral sites northwest of Prince Albert show a mixed eastern and Shield provenance. If this interpretation is correct, it infers a transport distance, in at least a 2 or 3 stage model, of at least 100 km, and possibly up to 250 km, in a westerly and then southerly direction.

In the eastern domain the real possibility exists that the indicator minerals could have been derived from as far east as Manitoba. The recognition of northern domain till within the general area of the eastern domain is important, for if the indicator minerals are discovered in that material, with its characteristic geochemical and mineralogical composition, the immediate source of the northern domain till is more likely to the north than the east. Again, the relative contribution of earlier tills containing dispersal trains derived from an easterly direction and immediate bedrock sources, as described above, must be considered.

The western domain would perhaps be a simpler "hunting ground" if it was not for the presence of the Miocene Wood Mountain Formation gravels. If earlier fluvial events had concentrated indicator minerals into Oligocene Cypress Hill Formation gravels they would likely not have contributed to the tills due their being perched on the upper levels of the nunataks above ice level. In this domain tills appear to be more locally derived, and therefore a sound knowledge of glacial transportation and ice-flow directions locally would be important in following back dispersal trains to their sources. However, as previously discussed, the presence of extensive fluvial deposits that contain transported indicator minerals complicates the dispersal history. What is particularly intriguing are reports of remarkably fresh-chrome diopsides in the Miocene gravels that might suggest a more local Saskatchewan source than a more distal Montana one, however, as pointed out above, other processes may have led to their presence from more distal sources.

What is clear is that explorationists require good information and sound knowledge of the Quaternary development of the present surface materials of southern Saskatchewan to successfully complete exploration programmes. It is hoped that the present study, and the new data now available from the project will assist in this.

CONCLUSIONS

The PAMD funded southern Saskatchewan kimberlite indicator mineral reconnaissance project has provided the first systematic data on the distribution of kimberlitic and lamproitic indicator minerals, clast lithology, mineralogy and geochemistry for tills, and soil geochemistry of the region. These demonstrate:

1) That indicator minerals are widespread across southern Saskatchewan. Significant, concentrations occur in the Prince Albert area of north-central Saskatchewan and southwestern Saskatchewan; both of these areas were previously known to contain indicator minerals. However, a number of localities outside these two areas have yielded indicator minerals of interesting and encouraging compositions.

2) The till matrix and heavy mineral geochemistry varies systematically and can be related to the bedrock provenance of the tills. These data together with pebble lithology and quantitative heavy mineral abundance data have permitted the surface tills of southern Saskatchewan to be divided into three domains, each with a characteristic compositional signature.

3) The C horizon appears to be a viable mineral exploration sampling medium given that heavy minerals will not be affected by weathering processes any more than those that have modified the underlying tills, and the trace element patterns present in the tills due to provenance appear to be reflected in the C horizon soils.

4) The A horizon geochemical data have proven useful in baseline studies particularly for Cd and Hg, and will be of future use in a variety of environmental and agricultural investigations.

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