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LITHOLOGY, MINERALOGY, AND GEOCHEMISTRY OF GLACIAL SEDIMENTS OVERLYING KIMBERLITE AT SMEATON, SASKATCHEWAN

L.H. Thorleifson and R.G. Garrett

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Cover illustration

GSC borehole geophysical logging truck and the diamond drill used to complete coring at the Smeaton site, 4 September 1992. GSC 2000-001

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Preface

The discovery of a kimberlite occurrence in central Saskatchewan in 1988 significantly increased the level of Canadian diamond exploration activity. It was from this increased level of activity that the exploration industry entered the boom of the 1990s, stimulated by the discovery of kimberlite finds in the Northwest Territories in 1991. As a result of the Saskatchewan discoveries, work related to diamond exploration was included under the Canada–Saskatchewan Partnership Agreement on Mineral Development (1990–1995), a subsidiary agreement under the Canada–Saskatchewan Economic and Regional Development Agreement. The work published in this report is a case study of indicator mineral and geochemical dispersion at a known kimberlite occurrence, and formed part of a multidisciplinary program of research concerning the geology of Canadian kimberlite occurrences. This information, and other outputs of the Canada–Saskatchewan Partnership Agreement, serve as a reference for ongoing mineral exploration activity in Canada.

M.D. Everell
Assistant Deputy Minister
Earth Sciences Sector

Préface

La découverte d'une kimberlite dans le centre de la Saskatchewan en 1988 a suscité beaucoup d'intérêt pour la recherche de diamants au Canada. L'industrie de l'exploration minérale a alors connu un regain d'activité et est entrée dans une véritable période de frénésie au début des années 1990, lorsque l'on a découvert, en 1991, des kimberlites dans les Territoires du Nord-Ouest. C'est à la suite des découvertes faites en Saskatchewan que des travaux reliés à la recherche de diamants ont été entrepris dans le cadre de l'Entente de partenariat Canada–Saskatchewan sur l'exploitation minérale (1990–1995), entente auxiliaire négociée en vertu de l'Entente Canada–Saskatchewan de développement économique et régional. Les données publiées dans le présent rapport constituent une étude de cas de la dispersion de minéraux indicateurs et de la dispersion géochimique à partir d'une intrusion kimberlitique connue. Cette étude s'intégrait à un programme de recherche multidisciplinaire sur la géologie des kimberlites au Canada. Ces données, ainsi que d'autres découlant de l'Entente de partenariat Canada–Saskatchewan, servent de référence pour les travaux d'exploration minérale qui se poursuivent partout au pays.

M.D. Everell
Sous-ministre adjoint
Secteur des sciences de la Terre

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Quaternary glacial sediments over 100 m thick overlie interbedded Cretaceous shale and extrusive kimberlite debris at a site near Smeaton, Saskatchewan. These sediments consist of diamicts interpreted as till, with minor sand, silt, and clay interbeds. The uppermost sediments, 34.6 m thick, contain few kimberlite indicator minerals, but are rich in shield debris, thus resembling, in composition, northerly-derived till that occurs at surface throughout the region between the exposed shield and the North Saskatchewan and Saskatchewan rivers. Underlying sediments, 33.6 m thick, contain numerous kimberlite indicator minerals, and are carbonate rich to very carbonate rich, resembling in composition northeasterly to easterly derived surface till throughout the region south of the Saskatchewan River and east of The Missouri Coteau. The lowermost sediments, 32.2 m thick, contain few kimberlite indicator minerals, but contain both shield and carbonate erratics in intermediate amounts, and are thus of an approximately northeasterly derivation.

Résumé

Près de Smeaton, en Saskatchewan, une séquence de sédiments glaciaires du Quaternaire de plus de 100 m d'épaisseur repose sur une succession de shale du Crétacé dans laquelle sont interstratifiés des fragments de roches kimberlitiques effusives. Ces sédiments glaciaires se composent de diamictes, qui seraient des tills, et d'une moindre quantité d'interstrates de sable, de silt et d'argile. Les sédiments sommitaux, d'une épaisseur de 34,6 m, renferment peu de minéraux indicateurs de kimberlite, mais sont riches en fragments de roches du bouclier. Leur composition s'apparente ainsi à celle du till de surface présent dans toute la région située entre les affleurements du bouclier et les rivières Saskatchewan Nord et Saskatchewan et pour laquelle la source des sédiments est située au nord. Les sédiments sous-jacents, d'une épaisseur de 33,6 m, recèlent de nombreux minéraux indicateurs de kimberlite et leur teneur en carbonates est élevée à très élevée. Cette composition permet d'établir un lien avec le till de surface à source de débris nord-est à est que l'on trouve dans toute la région située au sud de la rivière Saskatchewan et à l'est du coteau Missouri. Les sédiments basaux, d'une épaisseur de 32,2 m, renferment quelques minéraux indicateurs de kimberlite, mais le fait qu'ils contiennent des erratiques de roches du bouclier et de roches carbonatées dans des concentrations intermédiaires indique que leur source est située au nord-est.

SUMMARY

The discovery of kimberlite in central Saskatchewan during 1988 resulted in extensive private sector exploration activity, much of which included sampling and analysis of glacial sediments for kimberlite indicator minerals. The investigation summarized here was designed to support this private sector work by providing a case study regarding the frequency and chemistry of kimberlite indicator minerals in Pleistocene glacial sediments from a kimberlite field. The vertical profile of lithological, mineralogical, and geochemical data can be compared to surface till data, and may be used to interpret transport history of sediments on the basis of their composition. At the study site, located 6.4 km west and 8 km south of the town of Smeaton, Saskatchewan, the 100 m thick Quaternary sequence is underlain by Cretaceous shales interbedded with extrusive kimberlitic debris. Multidisciplinary investigations at the site included collection of seismic data, followed by drilling, which, in addition to the analysis of the

SOMMAIRE

La découverte de kimberlitiques dans le centre de la Saskatchewan en 1988 a incité le secteur privé à entreprendre des travaux d'exploration poussés, qui ont donné lieu en particulier à l'échantillonnage et à l'analyses de sédiments glaciaires afin de déceler toute présence de minéraux indicateurs de kimberlite. Les travaux dont il est ici question visaient à appuyer ceux du secteur privé en produisant une étude de cas sur la fréquence et la composition chimique des minéraux indicateurs de kimberlite dans les sédiments glaciaires du Pléistocène au sein d'un champ de kimberlites. Les données lithologiques, minéralogiques et géochimiques des sédiments recueillis dans une coupe verticale peuvent être comparées à celles des tills de surface, permettant ainsi d'interpréter le transport des sédiments en fonction de la composition des débris. Au site à l'étude, situé à 6,4 km à l'ouest et à 8 km au sud de la ville de Smeaton (Saskatchewan), la séquence du Quaternaire d'une épaisseur de 100 m repose sur une succession de shale du Crétacé dans laquelle sont interstratifiés des fragments de

Pleistocene sequence reported here, facilitated borehole geophysical studies as well as stratigraphic and petrologic analyses of the Cretaceous sequence. Work was initiated in 1991 as a contribution to the Canada–Saskatchewan Partnership Agreement on Mineral Development (1990– 1995), a subsidiary agreement under the Canada–Saskatchewan Economic and Regional Development Agreement.

Diamicts make up over three-quarters of the drilled Quaternary sequence. These relatively unsorted sediments, thought to have been deposited as basal tills, are readily distinguishable at abrupt contacts with interbedded sorted sediments. These sand and gravelly sand beds, silt and/or clay, as well as boulders, make up the remainder of the sediments. Core was split, described in detail, photographed, and sampled. Heavy mineral concentrates, consisting mostly of garnet, amphibole, siderite, and sulphide, were prepared; the fine fraction of till and fine-grained sediments underwent geochemical analysis; the 8–16 mm gravel fraction, consisting mostly of Paleozoic carbonate and Precambrian rocks, was classified with respect to lithology; and weight per cent calcite and dolomite of the <63 µm matrix fraction were determined. The sequence is divisible as informal lithostratigraphic units on the basis of descriptive data as well as pebble lithology and matrix carbonate content, both of which are indicators of the bulk composition and, hence, provenance of the sediment. Two stratified sequences are distinguishable from till-dominated sediments.

Unit 5 till (7.3–34.6 m depth from surface) is characterized by low carbonate, high dolomite/calcite ratio, high SiO_2, Al_2O_3 and Na_2O in the <63 µm fraction, an abundance of shield provenance 8–16 mm clasts and 63–250 µm mineral grains such as amphibole. Unit 4b till (34.6–52.6 m) contains elevated abundances of 8–16 mm carbonate and shale clasts, and exhibits a lower dolomite/calcite ratio relative to unit 5, low SiO_2, Al_2O_3 and Na_2O, high U and low Th to give a high U/Th ratio, high As, Sb, Br, Mo, V, Zn, and Mn, together with low Hf, Zr, Sm, Ce, La, Lu, and Sc levels in the <63 µm fraction. Unit 4a till (52.6–62.0 m) is similar in bulk composition to unit 4b, but shale is lacking, carbonate content is marginally higher, and SiO_2 content is marginally lower. Unit 3 till (62.0–68.2 m) is characterized by the highest yield of 8–16 mm carbonate, a significant component of Shield clasts, extremely high matrix carbonate and Br, low SiO_2, Al_2O_3, and Na_2O levels, and low U, Th, As, Sb, Mo, and Sm levels in the <63 µm fraction. Unit 2 till (68.2–82.3 m) contains a moderate abundance of 8–16 mm carbonate and Shield provenance

roches kimberlitiques effusives. Dans le cadre des études multidisciplinaires menées à cet endroit, on a tout d'abord recueilli des données sismiques avant de réaliser un forage. Ces données, combinées à l'analyse de la séquence du Pléistocène dont il est question ici, ont facilité l'interprétation des levés géophysiques en sondage ainsi que les analyses stratigraphique et pétrologique de la succession du Crétacé. Les travaux, amorcés en 1991, ont été exécutés dans le cadre de l'Entente de partenariat Canada–Saskatchewan sur l'exploitation minérale (1990–1995), entente auxiliaire négociée en vertu de l'Entente Canada–Saskatchewan de développement économique et régional.

Les diamictes constituent plus des trois quarts de la séquence du Quaternaire traversée par le forage. Ces sédiments relativement mal triés, qui ont probablement été déposés sous la forme de tills de fond, tranchent nettement avec les sédiments triés qui y sont interstratifiés et qui montrent des contacts francs. Les sédiments triés, formés de couches de sable et de sable graveleux, de silt ou d'argile, ainsi que de blocs constituent l'autre quart de la séquence. Les carottes recueillies lors du forage ont été fendues, décrites en détail, photographiées et échantillonnées. On a préparé des concentrés de minéraux lourds, principalement composés de grenats, d'amphiboles, de sidérite et de sulfures; on a analysé la composition chimique de la fraction fine du till et des sédiments à grain fin; on a classifié la fraction graveleuse de 8–16 mm, issue principalement de l'érosion de roches carbonatées du Paléozoïque et de roches du Précambrien, en se basant sur la lithologie; et on a déterminé le pourcentage en poids de calcite et de dolomite dans la fraction de moins de 63 µm. On peut diviser la séquence en unités lithostratigraphiques informelles en se fondant sur les données descriptives ainsi que sur la lithologie des cailloux et la teneur en carbonates de la matrice, ces deux derniers éléments étant des indicateurs de la composition globale du dépôt et, de ce fait, de la provenance des sédiments. On distingue deux séquences stratifiées dans les sédiments où domine le till.

L'unité de till 5 (à 7,3–34,6 m de profondeur) est caractérisé par une faible teneur en carbonates, un rapport dolomite/calcite élevé, de fortes teneurs en SiO_2, Al_2O_3 et Na_2O dans la fraction de moins de 63 µm, une abondance de clastes de roches du bouclier dans la fraction de 8–16 mm et une grande quantité de grains de 63–250 µm de certains minéraux comme les amphiboles. L'unité de till 4b (34,6–52,6 m) contient d'abondants clastes de roches carbonatées et de shale dans la fraction de 8–16 mm et affiche un rapport dolomite/calcite inférieur à celui de l'unité 5, des teneurs faibles en SiO_2, Al_2O_3 et Na_2O, une teneur élevée en U et une teneur faible en Th d'où un rapport U/Th élevé, des teneurs élevées en As, Sb, Br, Mo, V, Zn et Mn ainsi que des teneurs faibles en Hf, Zr, Sm, Ce, La, Lu et Sc dans la fraction de moins de 63 µm. L'unité de till 4a (52,6–62,0 m) a, dans l'ensemble, la même composition que l'unité 4b, mais il n'y a pas de shale et, en outre, la teneur en carbonates y est légèrement plus élevée et la teneur en SiO_2 y est légèrement plus basse. L'unité de till 3 (62,0–68,2 m) est celle qui montre la concentration la plus élevée de clastes de roches carbonatés de 8–16 mm. Elle est caractérisée par une proportion importante de clastes de roches du bouclier, une teneur très élevée en carbonates et Br, des teneurs faibles en SiO_2, Al_2O_3, et Na_2O et des teneurs peu élevées en U, Th, As, Sb, Mo et Sm dans la fraction de moins de clasts, which tend to decrease down section. Unit 1 till (87.1–100.4 m) is characterized by relatively low matrix carbonate with a higher dolomite/calcite ratio than observed in units 4, 3 and 2.

Unit 5 is very similar in composition to surface till found throughout the region north of the North Saskatchewan and Saskatchewan rivers, which exhibits an abundance of Shield-derived gravel clasts, amphibole grains, low carbonate, V, Zn, and As content, and high SiO_2, Al_2O_3, Na_2O, U/Th ratio, rare earth and lithophile element levels (Garrett and Thorleifson, 1995). This match between unit 5 and surface till throughout the region implies that the upper till of the region is not missing at Smeaton. The composition of unit 5 is indicative of southward ice flow off the shield. These observations strongly suggest correlation with the Battleford Formation, although the thickness would be highly anomalous relative to the much thinner observations in the Saskatoon area. For unit 4, a provenance from the east or northeast is indicated by abundant carbonate and shale clasts, coupled with a geochemical composition indicative of carbonate and shale bedrock. Unit 3 is characterized by a relative abundance of Paleozoic brown carbonate and Shield provenance pebbles, very high carbonate levels and commensurately low levels of all other trace elements except As, Sb, and Br which are reflected in both the <63 µm fine and <250 µm heavy mineral fractions. Comparison with data presented by Schreiner (1990) suggests that units 3 and 4 correlate with the Floral Formation. The Floral Formation is characterized by elevated carbonate levels, with an abrupt decrease at the contact with adjacent units. Unit 2 seems likely to correlate to the Dundurn till, because there is no downward increase in carbonate content, which would be indicative of a Warman/Dundurn contact being present below sediments likely correlating with the Floral Formation. Warman till, therefore, seems to be absent at the site. The composition of unit 1 indicates a generally northeasterly provenance as evidenced by the presence of carbonate and shield clasts. The low carbonate content of unit 1 is consistent with the observation of Schreiner (1990) in central and Southern Saskatchewan that the lowermost Sutherland Group till, the Mennon, tends to be low in carbonate relative to the other tills. This unit may therefore correlate with the Mennon Formation, based largely on its stratigraphic position underlying the Dundurn till.

Following electron microprobe analysis of 432 mineral grains recovered from the 0.25–2.0 mm fraction of forty-five 25 L till and sand samples, 71 grains were identified as Cr-pyrope, 62 as Mg-ilmenite, 111 as Cr-diopside, and 8 as eclogitic garnet. No Cr-spinels such as chromite were recovered from this fraction. A total of 23 visible gold grains, ranging in size from 25 to 250 µm in long axis dimension were recovered, with never more than two grains in one sample. The tills of the lowermost unit 1 are essentially devoid of

63 µm. L'abondance de clastes (8–16 mm) de roches carbonatées de couleur brune du Paléozoïque et de roches du bouclier dans l'unité de till 2 (68,2–82,3 m) est modérée et tend à diminuer vers le bas de la coupe. L'unité de till 1 (87,1–100,4 m) est caractérisée par une teneur relativement faible en carbonates et un rapport dolomite/calcite plus élevé que dans les unités 4, 3 et 2.

L'unité 5 a une composition très semblable à celle du till de surface que l'on trouve partout dans la région qui s'étend au nord des rivières Saskatchewan Nord et Saskatchewan par son abondance de clastes de roches du bouclier dans la fraction des graviers, une grande quantité de grains d'amphiboles, une faible teneur en carbonates, V, Zn et As, une forte teneur en SiO_2, Al_2O_3 , Na_2O, éléments des terres rares et éléments lithophiles et un rapport U/Th élevé (Garrett et Thorleifson, 1995). Cette correspondance entre l'unité 5 et le till de surface de la région laisse supposer que le till supérieur de la région est présent à Smeaton. La composition de l'unité 5 indique un écoulement glaciaire dirigé vers le sud, en provenance du bouclier. Ces observations font pencher en faveur d'une corrélation avec la Formation de Battleford, même si l'épaisseur de l'unité observée constituerait une importante anomalie par rapport à celle beaucoup plus faible de la Formation de Battleford dans la région de Saskatoon. Dans l'unité 4, l'abondance de clastes de roches carbonatés et de shale, combinée à une composition chimique indiquant un substratum formé de roches carbonatées et de shale, indique une provenance est ou nord-est. L'unité 3 est caractérisée par une abondance relative de cailloux de roches carbonatées de couleur brune du Paléozoïque et de roches du bouclier, des teneurs très élevées en carbonates et des teneurs proportionnellement faibles en éléments traces (à l'exception de As, Sb et Br) tel que révélé par l'analyse de la fraction fine (moins de 63 µm) et celle de la fraction des minéraux lourds (moins de 250 µm). En comparant les données avec celles de Schreiner (1990), il ressort que les unités 3 et 4 peuvent être mises en corrélation avec la Formation de Floral. Celle-ci se distingue par des teneurs élevées en carbonates, lesquelles chutent de façon franche au contact des unités adjacentes. L'unité 2 semble être corrélable avec le till de Dundurn, puisque la teneur en carbonates n'augmente pas vers la base, ce qui indiquerait que le contact entre les tills de Warman et de Dundurn se situe au-dessous des sédiments que l'on met en corrélation avec la Formation de Floral. Le till de Warman semble, par conséquent, absent au site de forage. La présence de clastes de roches carbonatées et de roches du bouclier dans l'unité 1 indique une provenance générale nord-est. La faible teneur en carbonates de l'unité 1 correspond à l'observation faite par Schreiner (1990) dans le centre et le sud de la Saskatchewan selon laquelle le till basal du Groupe de Sutherland, le till de Mennon, serait moins carbonaté que les autres tills. On peut donc établir une corrélation entre cette unité et la Formation de Mennon, en se fondant principalement sur la position stratigraphique de cette unité au-dessous du till de Dundurn.

Une analyse à la microsonde électronique de 432 grains de minéraux prélevés dans la fraction de 0,25–2,0 mm de quarante-cinq échantillons de till et de sable de 25 L a permis de dénombrer 71 grains de pyrope chromifère, 62 grains d'ilménite magnésienne, 111 grains de diopside chromifère et 8 grains de grenat éclogitique. Cette fraction ne contenait pas de spinelle chromifère, telle que la chromite. On a récupéré 23 grains d'or visibles, de taille variant entre 25 et 250 µm dans le sens du grand axe, mais jamais plus de deux grains dans un même échantillon. Les tills de l'unité 1 à la base de la coupe sont essentiellement kimberlite indicator minerals at this site, although there is a significant concentration in the immediately overlying sand. Unit 2 is similarly poor in indicator minerals except for a 1 m section about 27 m above bedrock. Again the sand unit lying on top of unit 2 contains indicator minerals, perhaps reflecting concentration from the underlying tills by fluvial processes. A dispersal train was observed, however, in the tills of units 3 and 4a, about 35 m above bedrock. The concentration of indicator minerals increases upwards through the exotic, high-carbonate unit 3 into the overlying unit 4a, to reach a maximum in the upper 4.4 m immediately below unit 4b. Association with the highest carbonate values suggests transport from the east. In the overlying units 4b and 5, only scattered low numbers of kimberlite indicator minerals are present.

This work has provided new data that demonstrate: 1) that kimberlite indicator minerals at the Smeaton site are concentrated in two compositionally distinct till units, likely correlative with the Floral Formation, 35–48 m above the bedrock surface; 2) that data for pebble lithology, heavy minerals, and heavy mineral geochemistry of the glacial sediments, in addition to results from well-established methods of matrix carbonate content and geochemical analysis, permit enhanced characterization of the till sequence; 3) that carbonate and As contents of the <63 μm fraction of the till matrix could alone permit the recognition of the six different till units identified in the Smeaton section; and 4) that the data from Smeaton, as well as data from surface till reported by Garrett and Thorleifson (1995), indicate extensive patterns of lateral and vertical variability which imply a complex sediment transport history that must be taken into account in the interpretation of mineral exploration data.

dépourvus de minéraux indicateurs de kimberlite au site du forage bien qu'il en existe une concentration significative dans le sable sus-jacent. L'unité 2 est, elle aussi, pauvre en minéraux indicateurs, sauf dans un intervalle de 1 m, à 27 m environ au-dessus du substratum rocheux. Là également, l'unité sableuse qui surmonte l'unité 2 contient des minéraux indicateurs qui ont peut-être été concentrés par le jeu de processus fluviaux à partir des tills sous-jacents. Cependant, on a observé une traînée de dispersion dans les tills des unités 3 et 4a, à environ 35 m au-dessus du substratum rocheux. La concentration des minéraux indicateurs s'accroît vers le haut à travers l'unité 3 qui est riche en fragments de roches de sources variées et de roches carbonatées, jusque dans l'unité 4a sus-jacente. Elle est maximale dans les 4,4 m supérieurs de l'unité, juste au-dessous de l'unité 4b. Une association fondée sur les teneurs les plus élevées en carbonates laisse croire à une source située à l'est. Dans les unités 4b et 5 sus-jacentes, les minéraux indicateurs de kimberlite sont disséminés et peu abondants.

Des nouvelles données acquises dans le cadre de ces travaux ont permis de mettre en évidence les points suivants : 1) les minéraux indicateurs de kimberlite au site de Smeaton sont concentrés dans deux unités de till de composition distincte situées entre 35 et 48 m au-dessus du substratum rocheux et qui peuvent vraisemblablement être mises en corrélation avec la Formation de Floral; 2) les données sur la lithologie des cailloux, les minéraux lourds et la composition chimique des minéraux lourds que l'on trouve dans les sédiments glaciaires, conjuguées aux données obtenues par les méthodes bien établies d'analyse de la teneur en carbonates et de la composition chimique de la matrice, facilitent la caractérisation de la séquence de till; 3) les teneurs en carbonates et en As de la fraction de moins de 63 μm de la matrice des tills pourraient à elles seules permettre d'identifier les six unités de till dans la coupe de Smeaton; et 4) les données recueillies au site de Smeaton, ainsi que les données sur les tills de surface présentées par Garrett et Thorleifson (1995), révèlent une variabilité importante, tant latéralement que verticalement, et, par conséquent, un transport complexe des sédiments dont il faut tenir compte lorsqu'on interprète les données destinées à l'exploration minérale.

INTRODUCTION

In 1988, the discovery of kimberlite in central Saskatchewan was announced (Lehnert-Thiel et al., 1992). Resulting exploration was accompanied by the initiation of government surveys designed to define relevant aspects of regional geology, to provide reference data, and to demonstrate kimberlite indicator methods developed by Canadian commercial laboratories. The investigation summarized here was part of a multidisciplinary effort and was designed as: 1) a case study regarding the frequency and chemistry of kimberlite indicator minerals in Pleistocene glacial sediments from a kimberlite field; and 2) a vertical profile of lithological, mineralogical, and geochemical data that could be compared to surface till data obtained throughout southern Saskatchewan by Garrett and Thorleifson (1995). A major objective was to interpret transport history of sediments on the basis of their composition, a crucial factor in interpretation of indicator mineral data. Work was initiated in 1991 as a contribution to the Canada–Saskatchewan Partnership Agreement on Mineral Development (1990–1995), a subsidiary agreement under the Canada–Saskatchewan Economic and Regional Development Agreement.

A study site near the town of Smeaton, Saskatchewan (Fig. 1) was chosen with the co-operation of Uranerz Exploration and Mining Limited and Cameco Corporation, who at the time held the only known in situ kimberlite occurrence in Saskatchewan. A tentatively defined composite kimberlite body that was road accessible, large, and which held some promise of including both intrusive and extrusive kimberlite phases was selected. Plans for sampling at multiple sites were abandoned due to the presence, throughout the area, of glacial sediments exceeding 100 m in thickness.

The Quaternary sequence at the site is underlain by Upper Albian (Lower Cretaceous) fine-grained clastic sedimentary rocks of the Westgate Member, Ashville Formation (McNeil and Caldwell, 1981; Mossop and Shetsen, 1994), which are interbedded with extrusive kimberlitic debris dated at about 100 Ma (Kjarsgaard, 1995; Leckie et al., 1997). Separating the glacial sediments and the uppermost occurrence of kimberlitic material is a 15 m sequence of shale. Below these shales, and in outcrop to the north, are Lower Cretaceous Manville Group sandstone and shale. Paleozoic carbonate rocks, which underlie the Cretaceous sequence at depth, outcrop125 km to the northeast. Precambrian igneous and metamorphic rocks of the Canadian Shield underlie the carbonates and are exposed 175 km to the northeast.

The multidisciplinary effort at Smeaton began with the collection of seismic data (Richardson et al., 1995). This was followed by the drilling reported here, which, in addition to analysis of the Pleistocene sequence, facilitated borehole geophysical studies (Richardson et al., 1995) as well as a stratigraphic and petrological investigation of the sequence of interbedded Cretaceous sedimentary rocks and extrusive kimberlitic debris that occurs at the site (Kjarsgaard, 1995; Leckie et al., 1997).

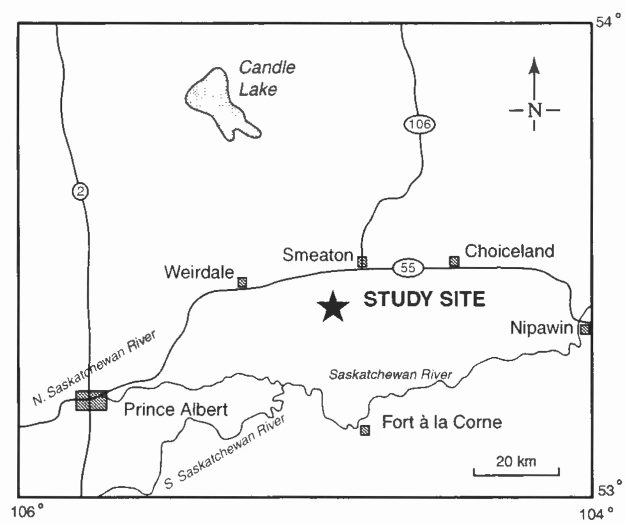

Figure 1. *Location of the cored site.*

PREVIOUS RESEARCH

Johnston and Wickenden (1931) concluded that at least three drift sheets are present in south-central Saskatchewan. The uppermost till, after its recognition by Craig (1959), was described and named the Battleford Formation (Fig. 2) by Christiansen (1968a). This unit commonly rests on a striated boulder pavement, and ranges in thickness from discontinuous cover between Saskatoon and Regina (Christiansen, 1972), to 45 m at some sites near Saskatoon (Christiansen, 1968b). Christiansen (1968b) subdivided till and associated sorted sediments in the Saskatoon area into the sandier, more carbonate-rich Saskatoon Group, consisting of the Battleford Formation and the underlying, relatively compact (Sauer and Christiansen, 1991) Floral Formation, and the older Sutherland Group. The three till units of the Sutherland Group (Christiansen, 1983) were named the Warman, Dundurn, and Mennon by Christiansen (1992). Stratified sediments of Quaternary and Tertiary age that overlie bedrock and underlie the oldest till were named the Empress Formation by Whitaker and Christiansen (1972).

Christiansen (1992) cited periods of subaerial exposure as the cause of zones showing evidence of oxidation at the top of each till. These zones were described as commonly having abrupt upper limits and gradational lower limits. Radiocarbon ages for carbonaceous silt and wood from below Battleford till range from 18 to 38 ka (Christiansen, 1968a, 1992; Fenton, 1984). Westgate et al. (1977) dated tephra from below the Battleford Formation at 0.6–0.7 Ma. Till underlying the tephra physically resembles Floral till, although the great age of the ash casts doubt on this correlation. SkwaraWoolf (1981) reported paleontological data from an 8 m thick sand overlain only by striated boulders and

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

Figure 2. *Quaternary stratigraphy of the Saskatoon area (Christiansen, 1992) with mineralogical and geochemical characterization of the tills (Schreiner, 1990). Relative concentration levels are indicated as very low (--), low (-), moderate (•), high (+), very high (++), and insufficient data (?).*

reworked till at the Riddell site, near Saskatoon. This reworked fossil assemblage includes extinct taxa of late Rancholabrean affinity, although other indicator taxa are no earlier than Sangamonian. A radiocarbon date of 15.4 ka was considered incompatible with components of the assemblage, despite evidence for reworking and mixing. It was argued that this surface sand correlates with a sand unit that had elsewhere been intersected during drilling of the Floral Formation, and, hence, that this till should be subdivided into Illinoian and early Wisconsinan strata.

Schreiner (1990) described Battleford till as sandy and calcareous, upper Floral till as silty and calcareous, lower Floral till as silty and highly calcareous, Warman till as clayey to silty and slightly calcareous, Dundurn till as sandy and calcareous, and Mennon till as clayey and slightly calcareous. Schreiner (1990) demonstrated that the concentration of V and Zn contrasted between till units (Fig. 2), whereas Ni, Cu, Pb, and Co, as well as numerous other elements analyzed in the early phase of his work, showed little or no variation throughout the sediment sequence. The Warman Formation is most distinctive, standing out as being low in carbonate and high in V and Zn. Schreiner (1990) postulated that the distinctive composition of this is unit is due to debris derived 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, although the Battleford Formation is characterized by lower carbonate, V and Zn levels than the Floral Formation. Limited dolomite and calcite data indicate that upper Floral and Battleford tills are relatively richer in dolomite than the underlying sediments.

The landscape under which the Battleford is the uppermost till has been sculpted with abundant ice-flow features indicating generally southward ice flow (Prest et al., 1968). Christiansen (1968a) reported a striation orientation of 020° for the boulder pavement at the lower contact of this unit. Schreiner (1990) proposed generally southward ice-flow for all tills except the Dundurn, for which westward ice flow was inferred, although the possibility of westward ice-flow was mentioned for the Floral Formation. McMartin et al. (1996) indicate that late-glacial generally southward striations on the shield, 200 km northeast of the Smeaton area, overprint a well-recorded earlier episode of westward ice flow.

Simpson et al. (1990), in a report on the geology of the Prince Albert area stimulated by diamond-related activity, correlated an 80 m sequence 40 km west of Smeaton with the Saskatoon Group and the underlying 35 m to the Sutherland Group. They noted that the Sutherland Group is harder and more difficult to penetrate by drilling than the Saskatoon Group, and contains shale fragments.

Garrett and Thorleifson (1995) reported analyses of till collected at 1–2 m depth at 390 sites located across southern Saskatchewan, south of the Precambrian shield. This survey demonstrated that surface till west of The Missouri Coteau, as well as the area north of the North Saskatchewan and Saskatchewan rivers, is relatively low in carbonate, with values around 10% in the less than 63 μm fraction. Values of 25% are typical of the area east of The Coteau and south of the Saskatchewan River. Below the Manitoba Escarpment, and extending slightly into Saskatchewan, is an area where till matrix carbonate values of 50% are typical. Surface till in southeastern Saskatchewan contains abundant carbonate pebbles attributable to sources in Manitoba, and elevated values for geochemical variables apparently associated with shale of the Manitoba Escarpment. North of the North Saskatchewan and Saskatchewan rivers, surface till is enriched in shield-derived components such as granite pebbles, amphibole, and soda (Na_2O), whereas As concentrations in the matrix are consistently lower than those to the south.

LOCATION

The cored site is located 6.4 km (4 miles) west and 8 km (5 miles) south of the town of Smeaton. The upper 96.3 m of the Quaternary sequence was cored at 585W/001S on the property grid. This location corresponds to UTM coordinates 505770 m east and 5917550 m north in UTM zone 13, or latitude 53° 24′ 32″ N, longitude 104° 54′ 47″ W. The site is on a section line between sections 17 and 20, township 51, range 20 west of the second meridian, 585 m west of the road allowance. A second attempt to complete coring was made at a site 4.5 m to the east of the first site. Quaternary sediments from 96.3 m to 100.4 m, and the underlying Cretaceous sequence to 242 m, were then cored at a third site located another 9 m to the east. All three sites were located on the east–west seismic line discussed by Richardson et al. (1995).

FIELD METHODS

The upper 96.3 m of the Quaternary sequence was cored using a rotasonic drill operated by Midwest Drilling of Winnipeg. Despite being slower and more expensive than rotary methods that recover cuttings, this drilling method was chosen due to its ability to recover continuous, intact 8 cm core from all materials, thus enabling detailed sedimentological and stratigraphic analysis. The nature of the rotasonic drilling method was discussed by Thorleifson and Kristjansson (1993).

Drilling commenced on 5 August 1992, and coring was completed to 96.3 m on 8 August, but breakage of casing halted progress. Attempts to recover the lost casing were unsuccessful, so steel casing 14 cm in diameter, extending from 82.3 to 96.9 m depth, was left in the hole. Drilling was restarted on 9 August, 4.5 m to the east. After advancing without coring to 96.3 m, an attempt to case to this depth was again unsuccessful due to breakage. Once more, recovery was unsuccessful, and casing was abandoned in the hole from 67.0 to 88.4 m. Rotasonic drilling operations were terminated on 10 August.

Plans to core the underlying Cretaceous sequence using diamond-drilling equipment adapted to the rotasonic drill were abandoned. Instead, plans were made to complete coring of the Quaternary sequence and to core the Cretaceous sequence using a diamond drill equipped with a tungsten carbide bit.

Diamond drilling commenced on 25 August, at a site 9 m east of the second hole. After advancing without coring, drill water was treated with additives designed to maximize recovery of glacial sediments. Coring was initiated on 28 August, and excellent HQ core was recovered from Quaternary sediments between 96.3 and 100.4 m. HQ coring continued into the Cretaceous sequence to a depth of 119.5 m. A switch to NQ coring was made at this point, and continuous coring was completed to 223 m on 31 August.

Plans to install 3.5″ (87.5 mm) plastic pipe down to the HQ/NQ step at the top of Cretaceous strata were cancelled due to the inability to advance HW casing beyond 77.4 m. The drill, therefore, was left on site so that borehole geophysical tools could be lowered down the drill rods to obtain electric logs from the open hole in the Cretaceous sequence. On 4 September, an attempt to obtain these electrical logs was unsuccessful due to blockage at 140 m (Richardson et al., 1995). The blockage stimulated a plan to case the entire hole.

On 14 September, the blockage was cleared, coring was extended to 242 m, and plastic pipe was successfully installed to 242 m despite limited clearance. Schedule 80 PVC pipe with an outside diameter of 60 mm (2 3/8″) and an inside diameter of 48 mm (1.9″) was advanced down the 76.2 mm (3″) inside diameter of the HQ drill rods (N casing) to 119.5 m, and down the 69.9 mm (2 3/4″) open NQ hole to 242 m. Drilling operations on the site were completed on 16 September 1992.

Borehole geophysical data were then obtained using a portable EM-39 logger. Data were obtained for gamma ray, magnetic susceptibility, and inductive conductivity to a depth of 185.7 m, with the exception of the heavier gamma-ray tool which penetrated viscous fluids to 191.2 m. These and other data obtained later from the cased hole were discussed by Richardson et al. (1995). Core from the Cretaceous sequence was discussed by Kjarsgaard (1995) and by Leckie et al. (1997).

At the Saskatchewan Research Council in Saskatoon, between 31 August and 10 September, core recovered from the Quaternary sequence was split using hand tools, described in detail, and photographed. Homogeneous sediments or graded sequences exceeding 0.1 m in thickness were distinguished as units, and observations regarding texture and sedimentary structures were recorded. Colour of the moist sediment was described using a Munsell colour chart. A 15 cm half-core from each metre of core was archived in sealed plastic bags. In the case of till and sand, nearly all of the remaining material from each increment of about 2 m of core was collected, broken up and homogenized, and divided into a 2 kg split for matrix carbonate and fine fraction geochemistry, and a 25 L split for recovery of heavy minerals and the gravel fraction. A total of 40 till samples and five sand samples were collected. An additional 19 samples weighing 2 kg each were collected from fine grained sediments and thin till beds. Three samples were taken from unlithified clay in the upper 12 m of the Cretaceous sequence.

LABORATORY METHODS

Sample preparation

At the Saskatchewan Research Council, the mean total moist weight of the 25 L till and sand samples was found to be 25 kg. The 2 kg till samples, which had been stored in sealed pails, were weighed before and after being air dried at less than 40°C. The resulting moisture content determinations averaged 9%, hence the mean air-dry weight of the large samples was 23 kg. The 25 L samples were disaggregated in a cement mixer with the aid of a sodium hexametaphosphate (calgon) solution (Fig. 3). The disaggregated sediment was screened at 10 mesh to remove the greater than 2 mm fraction, which was washed, dried, and screened at 4, 8, and 16 mm, weighed and then retained. The samples contained an average of 2 kg of gravel (>2 mm). The -10 mesh (<2 mm) material was passed over a shaker table twice to obtain a large heavy mineral preconcentrate.

At Overburden Drilling Management Ltd. of Nepean, Ontario, heavy mineral separations were completed using methylene iodide diluted with acetone to a specific gravity of 3.2. The table concentrates were screened at 0.5 mm. All greater than 0.5 mm material was submitted directly to heavy liquid separation. Some of the less than 0.5 mm fractions were re-tabled to reduce their mass prior to heavy liquid separation. Ferromagnetic minerals were removed from the greater than 0.5 mm and less than 0.5 mm fractions using a hand magnet. The less than 0.5 mm nonferromagnetic concentrates were then sieved at 63 and 250 μm.

The 2 kg subsamples from till as well as Quaternary and Cretaceous fine-grained sediments were air dried at less than 40°C, gently disaggregated to avoid crushing rock and mineral grains, and screened using a 2 mm stainless steel sieve. The oversize fraction was discarded, and sufficient of the fine fraction was screened using a 63 μm stainless steel sieve to yield approximately 50 g of material that was stored for analysis. No chemical analyses were attempted on the fine fraction, if present, of the sorted sand units.

Gravel fraction lithology

The 8–16 mm gravel fraction was classified with respect to lithology into nine classes: brown carbonate and associated chert, intrusive and high-grade metamorphic rocks, low-grade metasedimentary and metavolcanic rocks, quartzitic sandstone, quartzite, shale, ironstone, grey carbonate and associated chert, and unmetamorphosed volcanic rocks. Each class was weighed, weight per cent was calculated, and yield in grams per kilogram of less than 16 mm air-dry till or sand, as well as weight per cent, were calculated.

Matrix carbonate content

Weight per cent calcite and dolomite in the less than 63 μm fraction of till and silt-clay samples were determined using the Chittick gasometric apparatus (Dreimanis, 1962) in the Terrain Sciences Division laboratories at the Geological Survey of Canada (GSC), Ottawa. In order to determine the

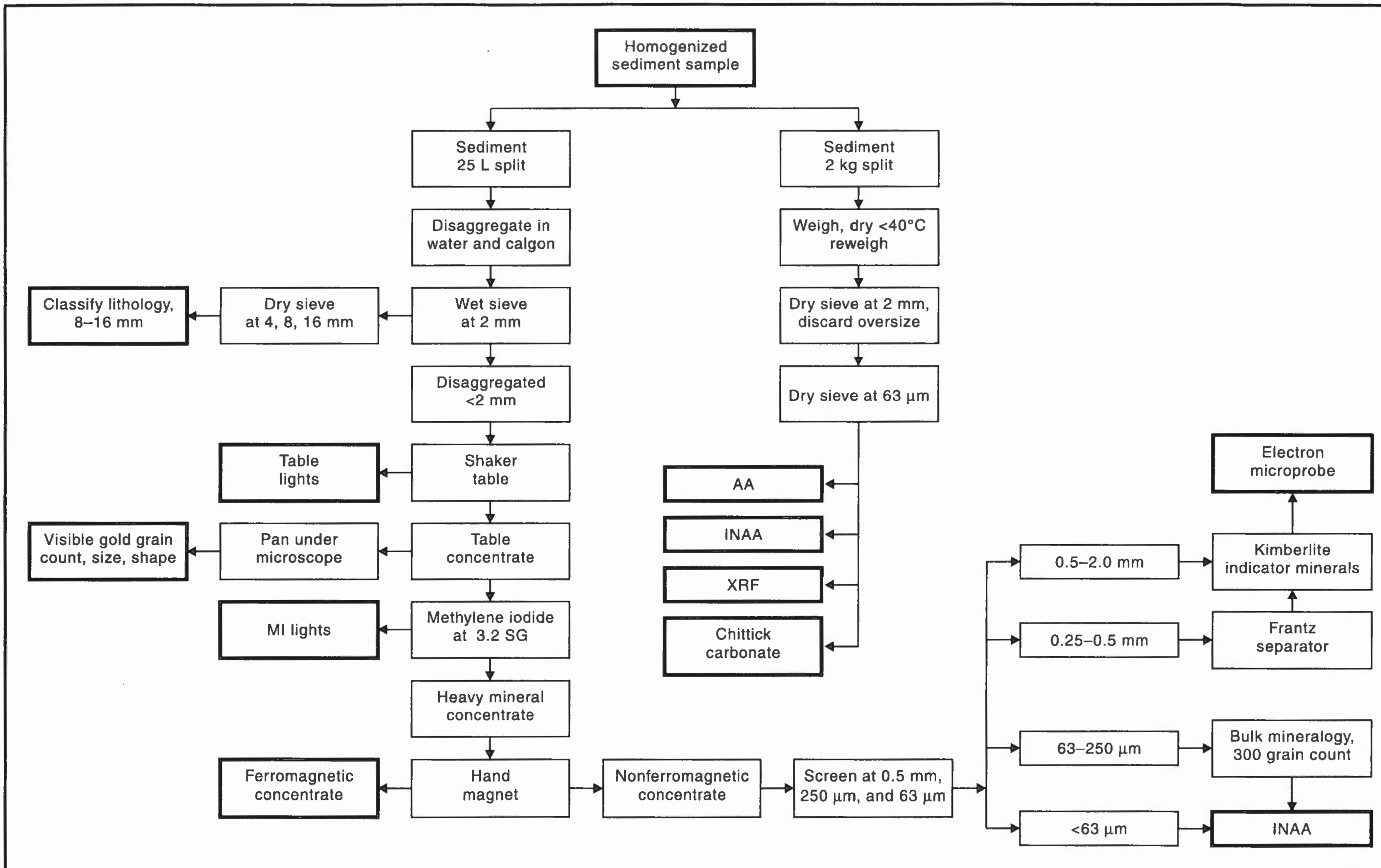

Figure 3. *Sample processing and analysis.*

correlation between GSC Chittick analyses of the less than 63 µm fraction and analysis by chemical methods on the less than 2 mm fraction, the standard method at Saskatchewan Research Council, a test set of 169 surface and subsurface till samples from across the Prairie region was analyzed by both methods. Comparison of the results (Fig. 4) indicates that the GSC analyses tend to be about 15% higher than the equivalent Saskatchewan Research Council determinations, presumably due to a tendency for carbonate to reside in the silt rather than the sand fraction.

Mineralogy

The table concentrates were panned by Overburden Drilling Management Ltd. prior to heavy liquid separation in order to recover visible gold grains, which were measured and classified with respect to size and morphology prior to being returned to the concentrate.

The 63–250 µm fraction of the nonferromagnetic concentrates was submitted to Consorminex Inc. of Gatineau, Quebec, for estimation of bulk mineralogy based on visual identification of 300 grains, mounted in araldite, using a stereoscopic microscope equipped for occasional use of crossed polarized light. Data are reported as milligrams per kilogram (mg/kg) of air-dry less than 2 mm till or sand, with data for grain counts converted to estimated mass using specific gravity values for pure minerals, as well as count per cent.

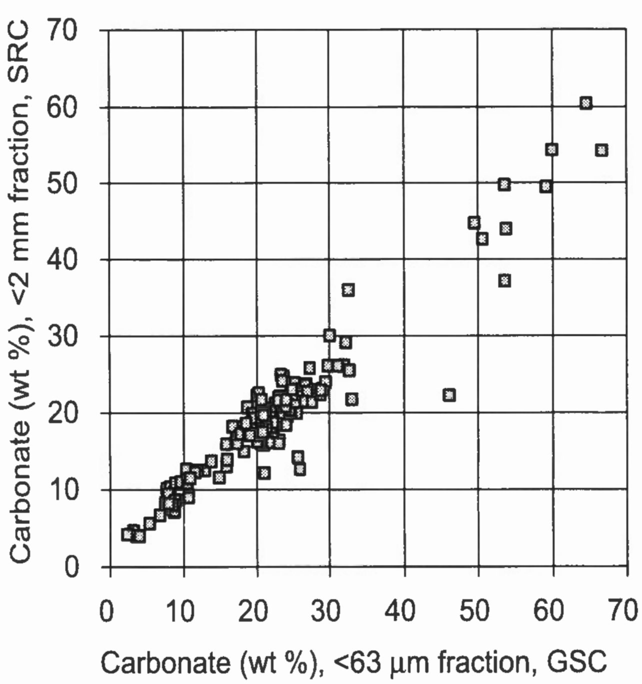

Figure 4. Comparison of carbonate analytical methods; Geological Survey of Canada carbonate analyses of the less than 63 µm fraction and Saskatchewan Research Council analyses of the less than 2 mm fraction for 169 till samples from across the Prairie region

The greater than 0.25 mm heavy mineral concentrates were returned to the Saskatchewan Research Council and were examined under a stereoscopic microscope for potential kimberlite indicator minerals, including garnet, pyroxene, and oxide. An average of 15 minutes was spent examining each 0.5–2.0 mm nonferromagnetic concentrate. An average of three potential kimberlitic indicator mineral grains from this fraction were selected for analysis from each till sample, and an average of four grains were selected from each sand sample. The 0.25–0.50 mm nonferromagnetic 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 moderately paramagnetic fraction, which is rich in almandine garnet, was visually scanned under a microscope for Mg-ilmenite and Cr-spinel. A visual scan of the weakly paramagnetic to nonmagnetic fraction for indicator garnet and pyroxene required an average of 20 minutes per sample. Following further selection at Consorminex, an average of nine grains per till sample and thirteen grains from each sand sample were selected for analysis. Minerals were mounted in 25 mm cylindrical epoxy mounts, with grains arranged in rows within nine cells per mount. Grains from the 0.5–2.0 mm fraction were arranged in five rows of six grains per cell, to yield a total of 270 grains per mount. Grains from the 0.25–0.5 mm fraction were placed in eight rows of ten in each cell, resulting in 720 grains per mount. The mounts were polished using diamond paste. Maps were used to record the sample number and identification number of each of the 432 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 s were used for Na_2O, K_2O, CaO, total Fe as FeO, MgO, Al_2O_3, MnO, and SiO_2, and 40 s for TiO_2 and Cr_2O_3. Calibration was confirmed at the beginning and end of each batch. Background determinations were made on every 50th grain. The analyses were completed in an automated run driven by a set of x-y-z coordinates for one point per grain. Points were selected to avoid inclusions, fractures, and pits. At the end of the batch, every 40th grain was reanalyzed at a 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, so determining which were kimberlite indicators (Gurney and Zweistra, 1995). The data are considered clearly adequate for the recognition of Cr-pyrope, Mg-ilmenite, and Cr-spinel, adequate for the selection of Cr-diopside; and marginally adequate for definition of eclogitic titanian almandine garnet (>0.2% TiO_2). Garnets were classified using the Dawson and Stephens (1975, 1976), Gurney (1984), and Gurney and Moore (1993) classifications. Diopsides with greater than 0.50% Cr_2O_3 (Deer et al., 1982; Fipke, 1989) were regarded as Cr-diopside. The Mg-ilmenite in every case contained well in excess of 6% MgO. The classification procedures employed are detailed by Thorleifson et al. (1994).

All G9, G10, and G11 (Dawson and Stephens, 1975, 1976) Cr-pyrope grains were subsequently 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 Cr-pyrope using the equation presented by Griffin et al. (1989).

Eclogitic garnet, and those with values just below the selection criteria, also were reanalyzed by electron microprobe at reduced detection limits. The electron microprobe routine described above was used 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 garnet.

Geochemistry

X-ray fluorescence analyses of the less than 63 µm fraction of till and silt-clay for major and some minor elements were completed by X-ray Assay Laboratories, Don Mills, Ontario. Instrumental Neutron Activation Analysis for a suite of 34 elements was completed by Becquerel Laboratories, Inc., Mississauga, Ontario, for the less than 63 µm fraction of till and silt-clay samples, and the less than 63 µm and 63–250 µm nonferromagnetic heavy mineral concentrates. CanTech Laboratories, Ltd., Calgary, Alberta, analyzed the less than 63 µm fraction of till and silt-clay samples for a suite of trace elements as well as Fe and Mn, using Atomic Absorption Spectrophotometry following total decomposition of a 1 g sample by a fuming HF-$HClO_4$-HNO_3 mixture.

In order to estimate the accuracy and precision of the analyses, sample preparation duplicates, GSC internal till control samples, and CANMET/GSC international reference materials were added to the batch prior to analysis. The samples were then randomized and relabelled at GSC Ottawa, in order to destroy any relationship between the order of analysis and the stratigraphic location of the samples.

DESCRIPTION OF THE SEDIMENTS

Diamicts, which are relatively unsorted sediments generally thought in this case to have been deposited as till, and which are readily distinguishable at abrupt contacts with interbedded sorted sediments, make up 77.4% of the drilled Quaternary sequence (Fig. 5). Sand and gravelly sand beds comprise 15.9% of the material, 6.2% consists of silt and/or clay, and 0.5% consists of two cobbles and/or boulders which exceed core diameter.

Till beds average 1.5 m in thickness and include two anomalously thick beds, 13.2 m and 9.4 m thick, which could not be visually subdivided. Sand beds range from 0.1 to 1.6 m and average 0.4 m in thickness. Silt and clay beds range from 0.1 to 1.0 m and average 0.4 m in thickness.

Till throughout the sequence typically consists of massive, hard, calcareous silt diamict which ranges from sandy to clayey (Fig. 6). Stratified diamicts which include numerous sand laminae occur high in the sequence, making up almost 20% of the interval between 3.4 and 22.1 m. The massive diamicts are consistently dark grey to very dark grey, with slightly brownish colours (e.g. Munsell 10YR 3/1) being typical in the sandy silt diamicts above 34 m depth, and more olive colours (e.g. 5Y 3/1) being dominant in the sandy to clayey silt diamicts present below this depth. Rusty staining, usually along joints and sand laminae, was observed at 7.6–12.8 m, at 27.7 m, at 39.9–41.1 m, at 54 m, at 70.1–71.4 m, at 72.5–73.5 m, at 75.2–77 m, and at 80 m. Joints are filled with crystals visually identified as selenite from 89.5 to 89.9 m, and at 99.8 m. A 0.4 m thick granite boulder was cored at 34.2 m, and a brown Paleozoic carbonate clast, 0.1 m thick, was cored at 61.9 m depth.

Sand strata are commonly silty and range from very fine to coarse in texture. Silt and clay, aside from a few thin strata, are present from 82.3 to 87.1 m (Fig. 6E) as a laminated, calcareous sequence with numerous sand laminae and disseminated organic material. Laminae in this sequence range from 1 to 6 mm thick, and rhythmic intervals include couplets ranging from 4 to 6 mm in thickness. Black clay at 100.4 m (Fig. 6F) was judged to be pre-Quaternary on the basis of very dark colour and lack of carbonate.

In the 8–16 mm fraction, brown carbonate clasts and minor associated chert (Fig. 7) make up 53%, by weight, of all pebbles in the cored sediment. Intrusive and high-grade metamorphic rocks derived from the Precambrian shield, mostly granite, make up the next most prominent class, at 38% of all pebbles. Low-grade metasedimentary and metavolcanic rocks, also derived from the shield, contribute a further 8% of this size fraction. Quartz sandstone, quartzite, shale, ironstone, grey carbonate, and unmetamorphosed volcanic rocks, in order of descending abundance, make up less than 1% each. Although observed elsewhere in the region, no locally derived sandstone or coal was observed at the Smeaton site. This classification scheme is compatible with that of Shetsen (1984), Shaw and Kellerhals (1982) as well as Metz (1968), although Metz (1968) separated chert as a distinct class.

The total yield of 8–16 mm pebbles in till ranged from less than 1 to 93 g/kg of air-dry less than 16 mm fraction. Expression of these values as pebble yield, rather than percentage, results in values in which the levels for one variable are less likely to be affected by fluctuations in another, although the values are correlated to total gravel content.

The abundance of brown carbonate clasts ranges from 0–72 g/kg. There are two types of sediment in the sequence with respect to carbonate abundance. In sediments above 34.6 m and below 82.3 m, yield is nearly constant at 0–5 g/kg (Fig. 7, 8), but percentage ranges widely from 10% to about 50% (Fig. 9). Distinctly different sediment, from 34.6 to 82.3 m, contains a relatively constant proportion of brown carbonate in the 8–16 mm pebbles, 60–80%, but yield ranges widely from 10 to 72 g/kg. Among the carbonate-rich sediments, there is a strong positive relationship between carbonate yield and shield pebble yield, whereas no relationship is present in the low-carbonate till. This implies that the gravel fraction of the carbonate-rich till is well mixed and from a relatively constant source, whereas the low-carbonate till was derived from multiple sources in which carbonate-to-shield ratio varied widely.

Throughout the sediment sequence, shield pebbles are present at about 5–20 g/kg (Fig. 8). Striking changes occur, however, in percentage values. Sediments from surface to 34.6 m contain 8–16 mm pebble fractions consisting of 70–90% shield pebbles (Fig. 9). From 34.6 to 82.3 m, values range from 20–35%, and values of 40–60% were obtained from 87.1 to 100.4 m (Fig. 9).

Quartz sandstone pebbles, possibly derived from the Athabasca sandstone of northern Saskatchewan, are scattered throughout the sequence, although the highest values, at 0.7 g/kg, occur between 11.3 and 18.3 m. Quartzite pebble abundance is less informative, with a mean elevated by one anomalous value at 46 m.

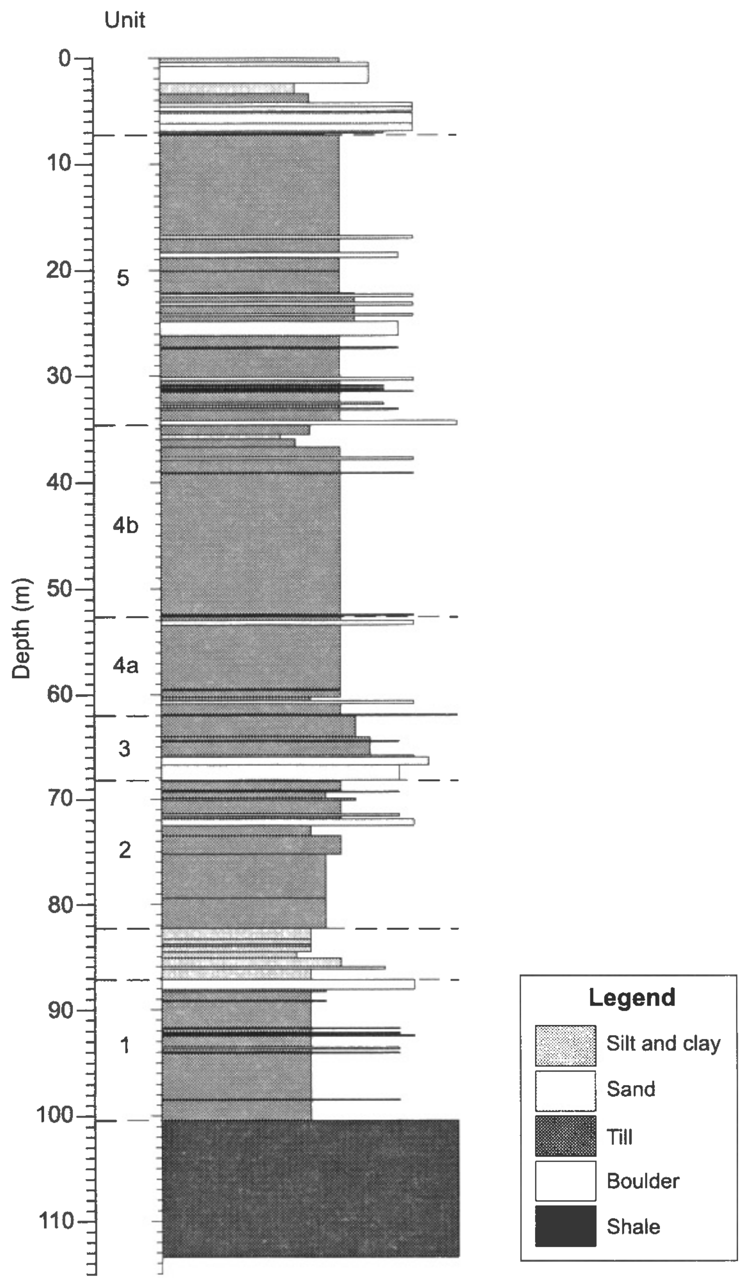

Figure 5. Lithology of the cored sediments. Width varies with texture.

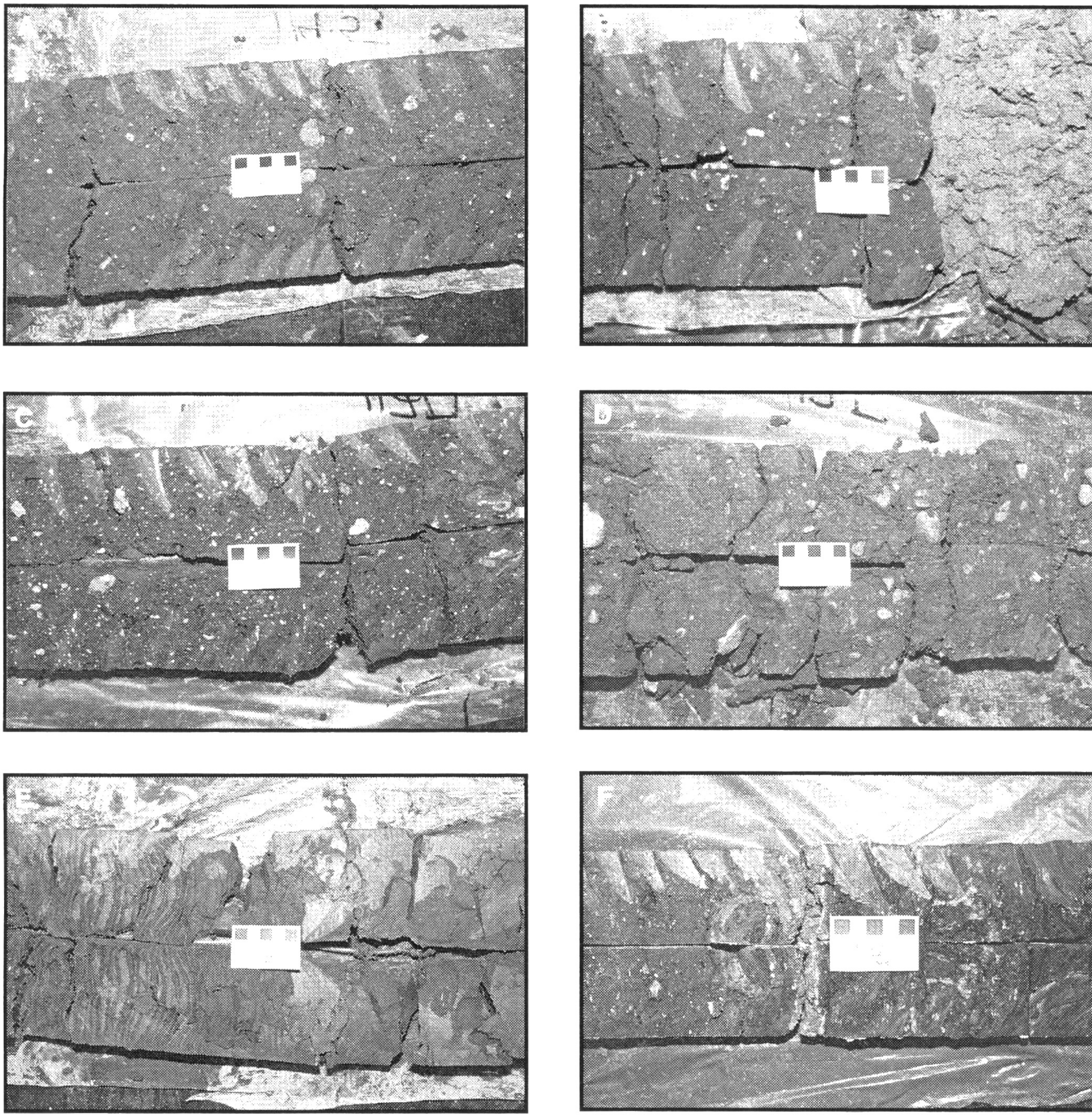

Figure 6. *Photographs of cored sediments.* ***A****) split rotasonic core from thick massive diamict rich in Precambrian debris (unit 5; 14.3 m depth; GSC 1996-086L);* ***B****) split rotasonic core from thin massive diamict interbedded with sand (unit 5; 27.1 m depth GSC 1996-086K);* ***C****) split rotasonic core from thick massive diamict rich in Paleozoic debris (unit 4; 47.3 m depth; GSC 1996-086J;* ***D****) split rotasonic core from thin massive diamict very rich in Paleozoic debris (unit 3; 63.5 m depth; GSC 1996-086I);* ***E****) split rotasonic core from laminated silt and clay (84.0 m depth, GSC 1996-086H);* ***F****) split diamond drill core from the contact between massive diamict (unit 1) and Cretaceous, noncalcareous black soft shale (100.4 m depth; GSC 1996-086G). Scale increments are 1 cm. Knife marks are apparent along the edges of the opened core.*

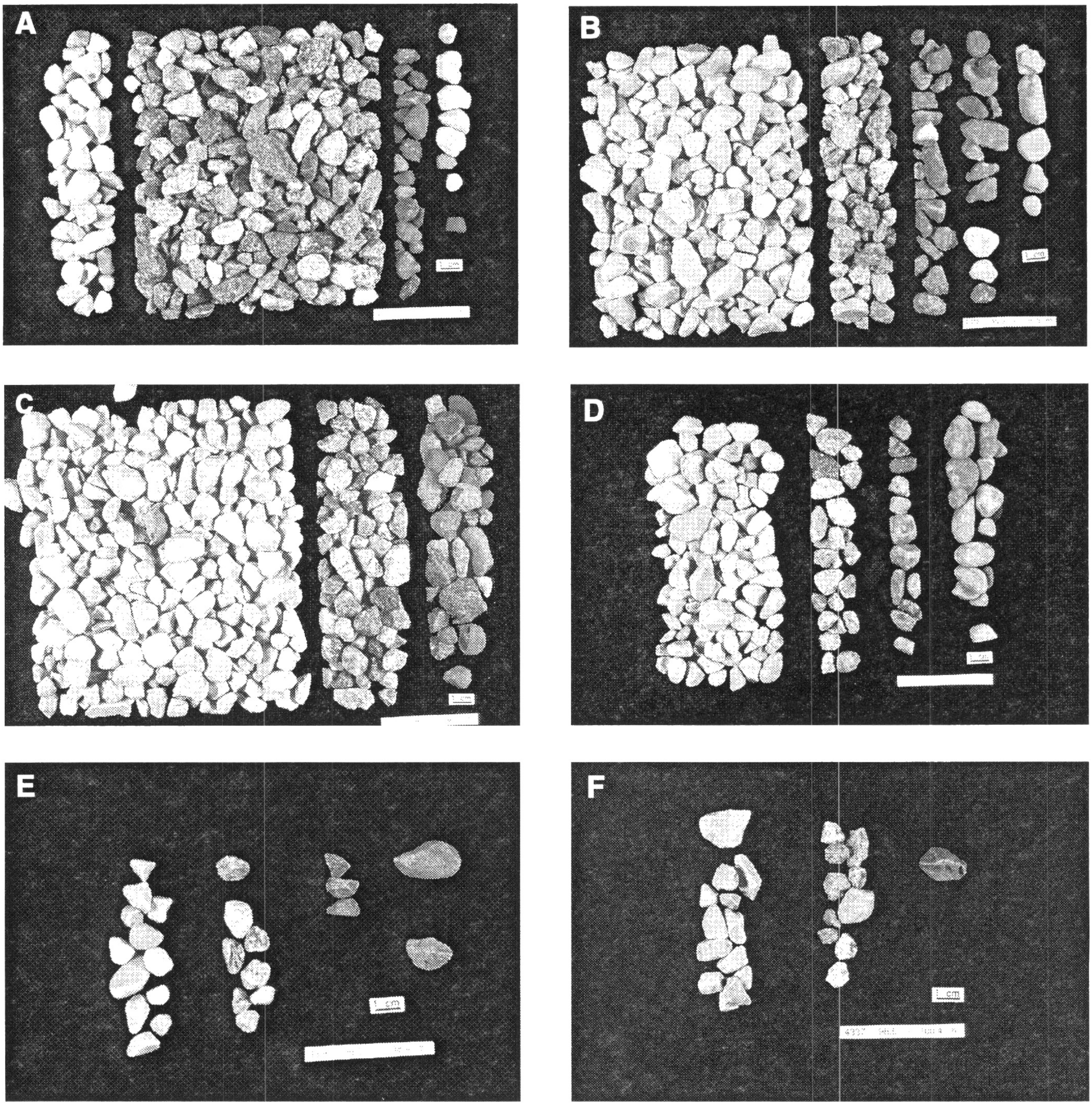

Figure 7. *Photographs of pebble fractions (8–16 mm) from 25 L till samples. In each case, pebbles are arranged from Paleozoic carbonate rocks on the left, intrusive and high-grade metamorphic rocks next to the right, and low-grade metasedimentary and metavolcanic rocks next to right. These groups are followed on the right by other types, including quartz sandstone (A, B, D), shale (B, D), quartzite (B), and ironstone (A, E).* ***A****) unit 5, 17.0–18.3 m, GSC 1996-086F;* ***B****) unit 4, 45.0–46.5 m, GSC 1996-086E;* ***C****) unit 3, 64.0–65.8 m, GSC 1996-086D;* ***D****) unit 2, 72.5–73.5 m, GSC 1996-086C;* ***E****) unit 1, 96.3–98.4 m, GSC 1996-086A;* ***F****) unit 1, 98.5–100.4 m, GSC 1996-086B. Scale card indicates 1 cm.*

Yields for shale are low, in part due to the low bulk density of this rock. The data show a clearly defined stratigraphic pattern (Fig. 8), however, with values from 0.1 to 0.7 g/kg being produced by light grey clasts, identical to the rock that caps the Manitoba Escarpment, from 36.7 to 55.0 m. Grey shale is also present at 72.5–73.5 m. Soft black shale was seen in the core, however, at 35.9–37.9 m, at 44 m, at 58.6 m, and at 88.1–89.1 m. This soft shale would have been readily disaggregated during sample processing and, hence, was not recovered in the gravel fraction.

Ironstone is present, at 0.15–0.3 g/kg, from 91.5 to 98.4 m. A few grey carbonate and unmetamorphosed volcanic clasts also were encountered in the sequence. These unmetamorphosed volcanic clasts, in most cases, are attributable to sources in the District of Keewatin, 1000 km to the north.

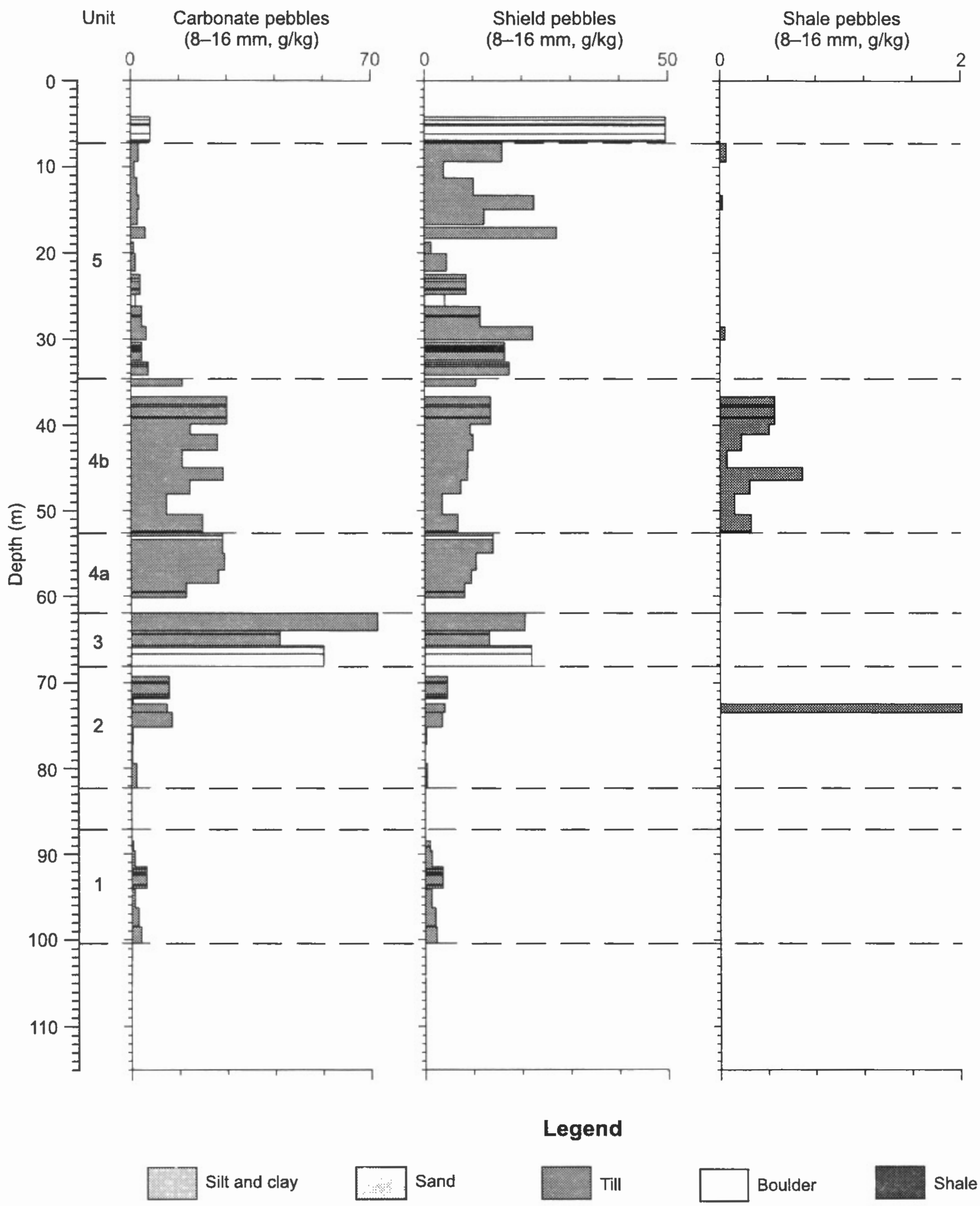

Figure 8. Carbonate, shield-derived rocks, and shale in the pebble fraction (yield) in the 8–16 mm fraction of till and sand. Values are expressed as grams per kilogram of air-dry less than 16 mm till or sand.

Carbonate in the less than 63 μm fraction of till from the Smeaton site ranges from 10 to 50% (Fig. 10), and averages 25%, as indicated by the Chittick method. Calcite ranges from 2 to 15% and averages 7%, while dolomite ranges from 5–35% and averages 17%. The highest matrix carbonate values correlate with elevated carbonate pebble frequency (Fig. 10), although changes in matrix carbonate content in some cases do not correlate with discernible changes in pebble lithology. Dolomite is more abundant, relative to calcite, in the upper sequence, however, in the lowermost till it rises again (Fig. 10). Till containing less than 5 g/kg carbonate pebbles contains 10–20% carbonate in the matrix, till with 10–30 g/kg carbonate pebbles contains 30–40% carbonate in the matrix, while till with greater than 40 g/kg carbonate pebbles contains 45–50% carbonate in the matrix.

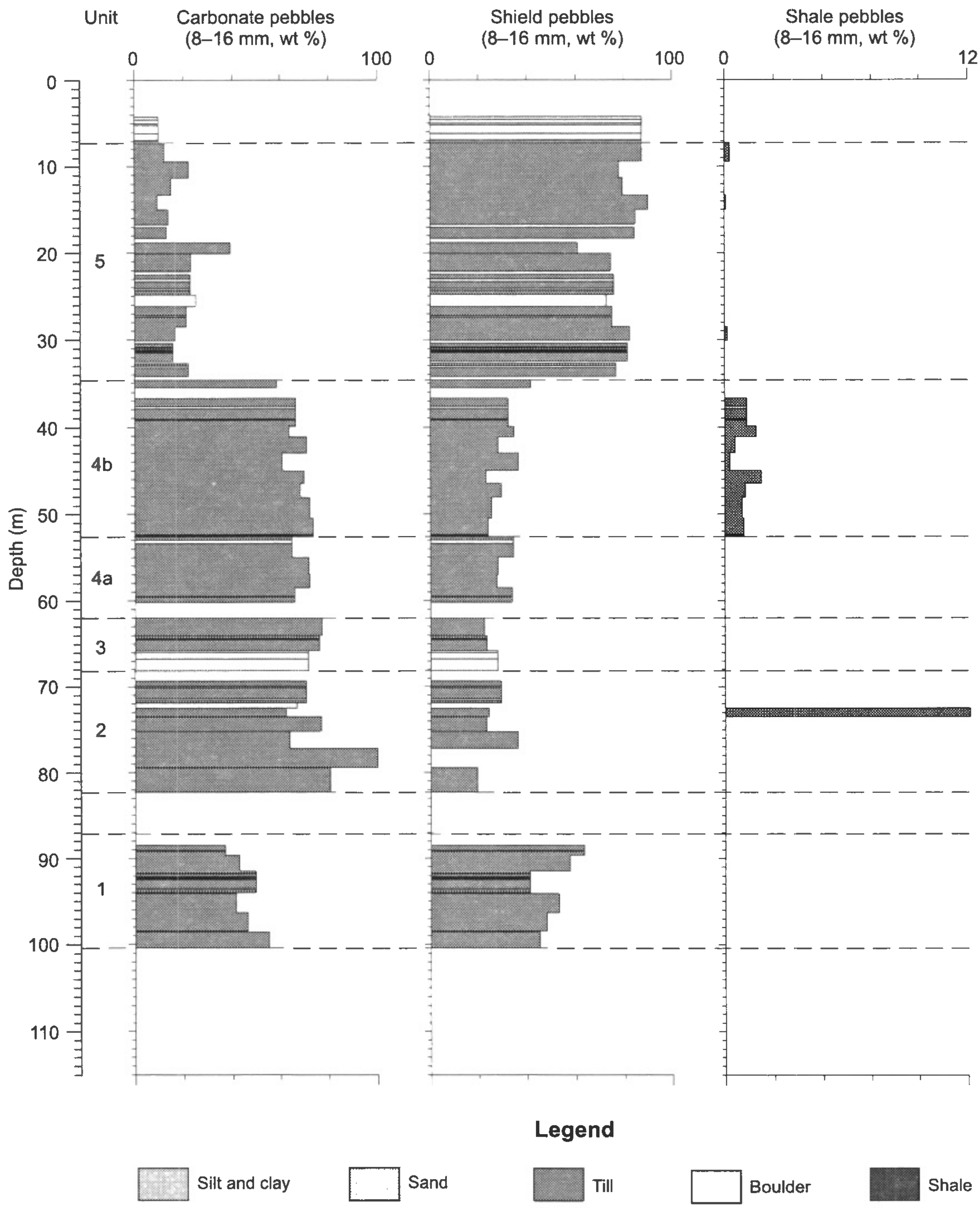

Figure 9. Carbonate, shield-derived rocks, and shale in the pebble fraction (weight per cent) in the 8–16 mm fraction of till and sand.

Unit descriptions

The sediments are divisible into informally designated lithostratigraphic units on the basis of descriptive data as well as pebble lithology and matrix carbonate content, both of which are indicators of the bulk composition and hence provenance of the sediment. Two stratified sequences are distinguishable from till-dominated sediments. In order to facilitate discussion of their composition, the till-dominated sediments have been subdivided as follows.

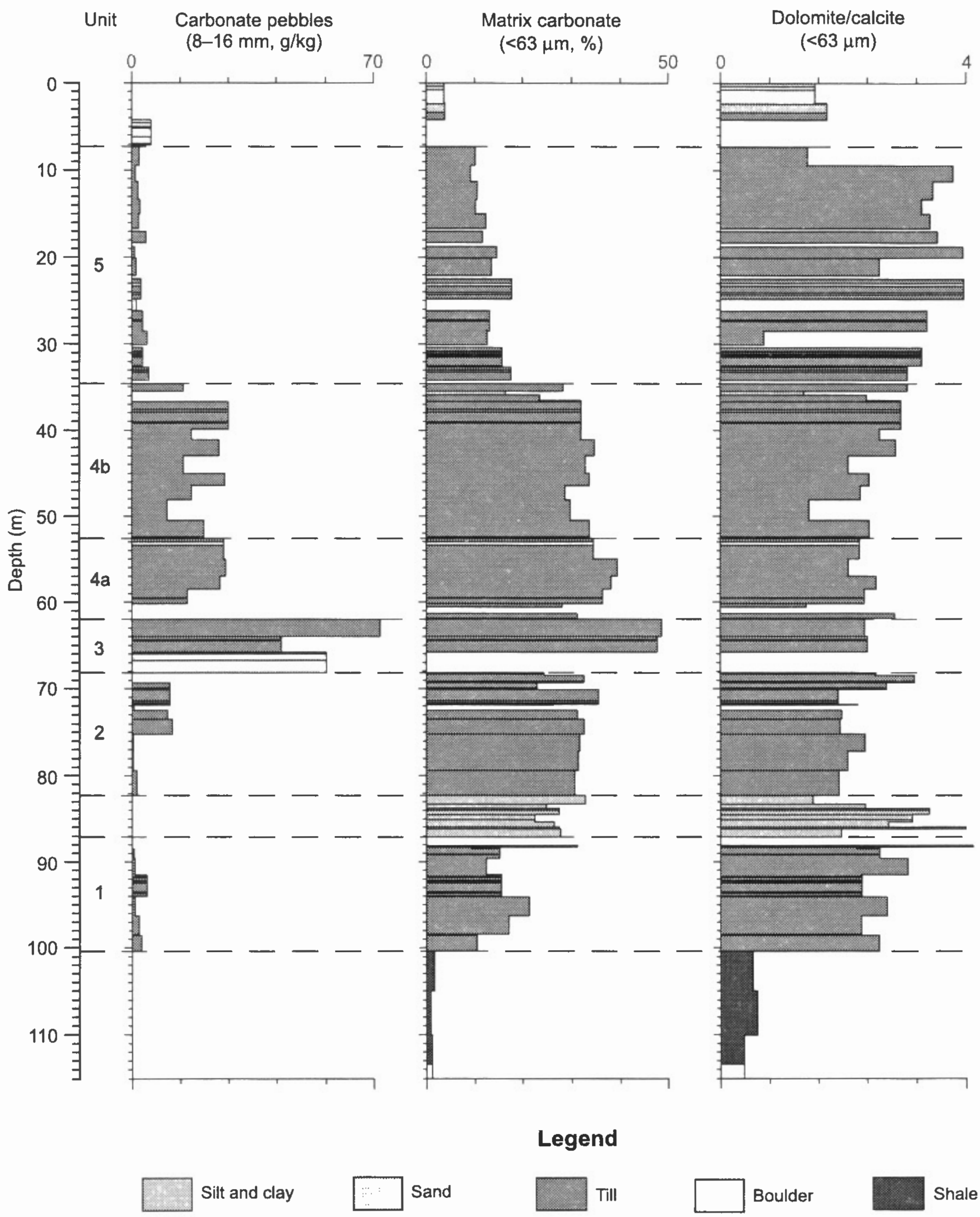

Figure 10. *Comparison of downhole carbonate values; pebble yield, matrix carbonate concentration, and dolomite/calcite ratio in the matrix.*

Surficial stratified sediments

The uppermost sediments, from surface to 7.3 m depth, consist of sand, and laminated silt and clay. At surface is a 2.4 m thick silty fine sand. Laminated silt and clay occurs from 2.4 to 4.2 m. Gravelly sand, in which pebbles are predominantly shield derived, extends from 4.2 to 7.3 m.

Drift unit 5

From 7.3 m to 34.6 m is a sequence of sandy silt diamict interbedded with sand. These sediments are readily distinguishable from underlying sediments on the basis of relatively low matrix and pebble carbonate, and relatively high dolomite content. The sediments consist of an anomalously thick, massive diamict which caps a sequence of interbedded sand and diamict. It is possible that the granite clast at 34.6 m is part of a boulder pavement, which rests at the lower contact of this distinct sequence.

Drift unit 4

An abrupt increase to moderate carbonate values at 34.6 m is sustained to 62.0 m. This sequence is divisible, at a sand bed, at 53.4 m into an upper unit 4b and a lower unit 4a. The upper unit is characterized by the presence of shale clasts, whereas the lower unit is slightly richer in matrix carbonate. Like unit 5, these sediments consist of interbedded sandy silt diamict and sand, as well as including an anomalously thick diamict unit high in the sequence, as well as is a cobble or boulder at the lower limit, where a compositional change occurs.

Drift unit 3

An interval from 62.0 to 68.2 m is characterized by very high carbonate content with gravel clast abundances exceeding 40 g/kg and matrix carbonate values of nearly 50%. These sediments consist of 3.8 m of sandy diamict containing abundant gravel, overlying 2.4 m of gravelly sand containing wood fragments.

Drift unit 2

An abrupt decrease in the abundance of carbonate pebbles (Fig. 10) and a return to matrix carbonate values similar to unit 4 occurs in interbedded silt diamict and sand which extends from 68.2 to 82.3 m. Rusty discoloration of joints is apparent in this unit.

Stratified sediments

Stratified sediments ranging from laminated clay to sand occur from 82.3 m to 87.1 m.

Drift unit 1

The lowermost interval, from 87.1 m to 100.4 m, is a sequence of diamict with a few thin sand units. This sequence has low matrix and pebble carbonate values, and includes selenite vein fillings.

BULK MINERALOGY OF CONCENTRATES

The yield of ferromagnetic minerals, almost entirely magnetite, was determined on the basis of total weight recovered. These data are presented as milligrams of less than 2 mm ferromagnetic concentrate per kilogram of air-dry less than 2 mm till or sand (Fig. 11). Values for ferromagnetic yield tend to decrease downhole.

The most abundant mineral in the 63–250 μm nonferromagnetic heavy mineral concentrates is garnet. Almandine garnet, which predominates, makes up 20–50% of the concentrates by count, with yields averaging 1400 mg/kg and ranging from less than 200 to nearly 4000 mg/kg (Fig. 11, 12). Garnet yield, as well as ferromagnetic yield, is markedly lower below 75.2 m (Fig. 11), in the lower part of unit 2 as well as unit 1.

Amphibole, siderite, (Fig. 12) and sulphide minerals (Fig. 13) with yields on average one-third that of garnet, are the next most abundant minerals in this fraction. The greatest yield of amphibole grains is in unit 5 (Fig. 11, 12), which probably reflects the high concentration of shield debris in this unit. Unaltered sulphide minerals, which imply lack of oxidation, are present in every sample, with two exceptions at 30.4–32.5 m and 79.4–82.3 m (Fig. 13). These intervals occur just above the compositional breaks which mark the lower limits of units 5 and 2.

Next in abundance are hematite, goethite (Fig. 13), and a group of black opaque minerals. The last group consists largely of ilmenite, but likely also contains chromite, black rutile, and black hematite. Traces of magnetite may also be present in the latter fraction due to imperfect separation. The upper sequence, containing an elevated abundance of amphibole, also contains higher abundances of red and specular hematite. There also are occurrences of enhanced hematite yield between 45 and 75.2 m. Also present in the concentrates, in order of decreasing abundance, are epidote, clinopyroxene, barite, orthopyroxene, zircon, leucoxene, sphene, rutile, staurolite, kyanite, and monazite.

Several multimineral abundance increases are associated with specific till or sand intervals in the section. In the sand layers intersected at 24.8–26.2 m and 87.1–88.1 m, abundances of barite, epidote, and ilmenite, as well as ferromagnetic minerals, garnet, sphene, ilmenite, sulphide, and siderite are elevated. In till sections at 18.8–20.1 m there is an 2- to 3-fold increase in ferromagnetic minerals; between 45.0

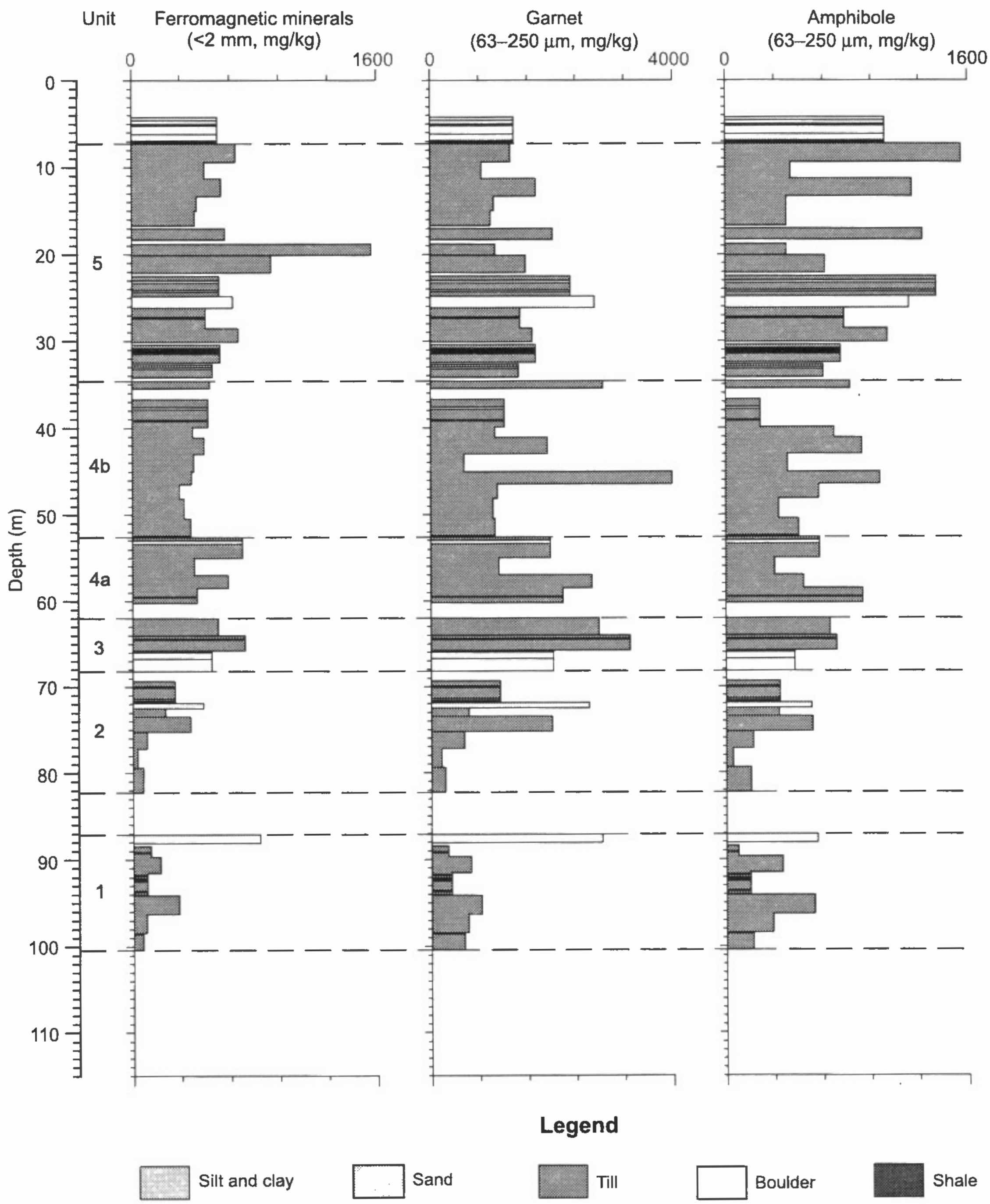

Figure 11. *Ferromagnetic minerals, garnet and amphibole (yield) in the less than 2 mm fraction; numerator is less than 2 mm grains for ferromagnetic minerals, and 63–250 μm grains only for garnet and amphibole; denominator is air-dry less than 2 mm till or sand.*

and 46.5 m there are similar increases in garnet, amphiboles, sulphide, and siderite; between 58.5 and 60.2 m the abundance of ortho- and clinopyroxenes is greater; and between 64.0 and 65.8 m ferromagnetic minerals, garnet, orthopyroxenes, ilmenite, amphiboles, hematite, sulphide, and siderite all occur with increased abundance. These increases in abundance may be due to glaciofluvial processes in the cases of sands.

KIMBERLITE INDICATOR MINERALS

Following electron microprobe analysis of 432 mineral grains recovered from the 0.25–2.0 mm fraction of forty-five 25 L till and sand samples, 71 grains were identified as Cr-pyrope, 62 as Mg-ilmenite, 111 as Cr-diopside, and 8 as eclogitic garnet. No Cr-spinels such as chromite were recovered from this fraction.

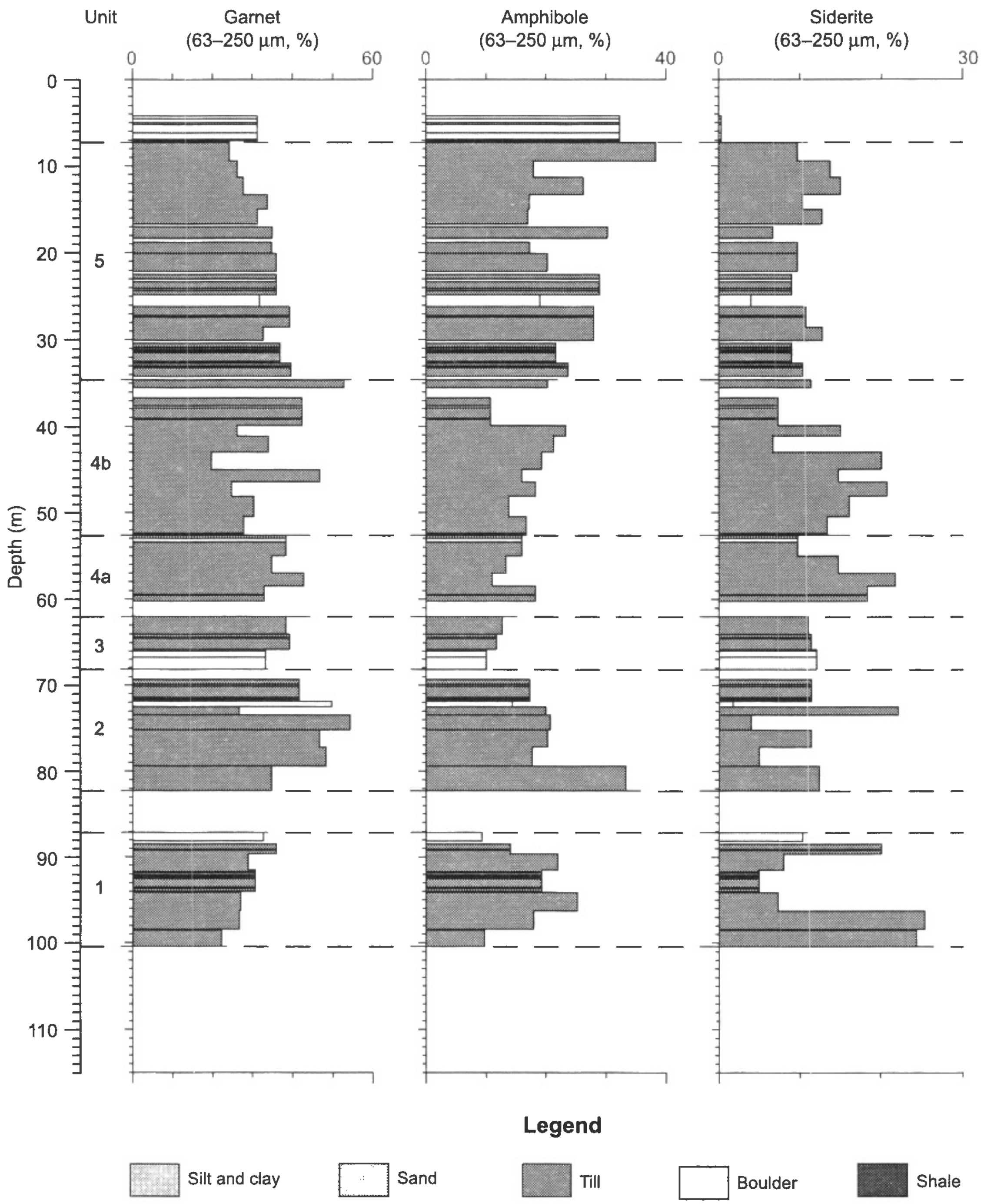

Figure 12. Garnet, amphibole, and siderite (count per cent) in the 63–250 µm, nonferromagnetic, greater than 3.2 specific gravity fraction.

The 71 Cr-pyrope grains were selected from analyses of 167 garnets (Fig. 14) on the basis of compositions with greater than 13% MgO and greater than 0.5% Cr_2O_3. Other Cr-bearing, but nonmagnesian, garnet was present as 3 Cr-grossularite garnets, as well as a pyrope containing 18% MgO and 0.19% Cr_2O_3. The Cr-pyrope garnets are divisible at 0.3% TiO_2 into nontitanian and titanian groups (Fig. 15). The nontitanian Cr-pyrope garnets include one strongly subcalcic and two marginally subcalcic harzburgitic G10 (Dawson and Stephens, 1975, 1976) garnets (Fig. 16). The remaining 29 nontitanian Cr-pyrope garnets classify as lherzolitic G9 garnet. No high-CaO, wehrlitic, G7 compositions are present. The titanian Cr-pyrope garnets may be separated at 4% Cr_2O_3 into a low-chrome G1/G2 cluster and a

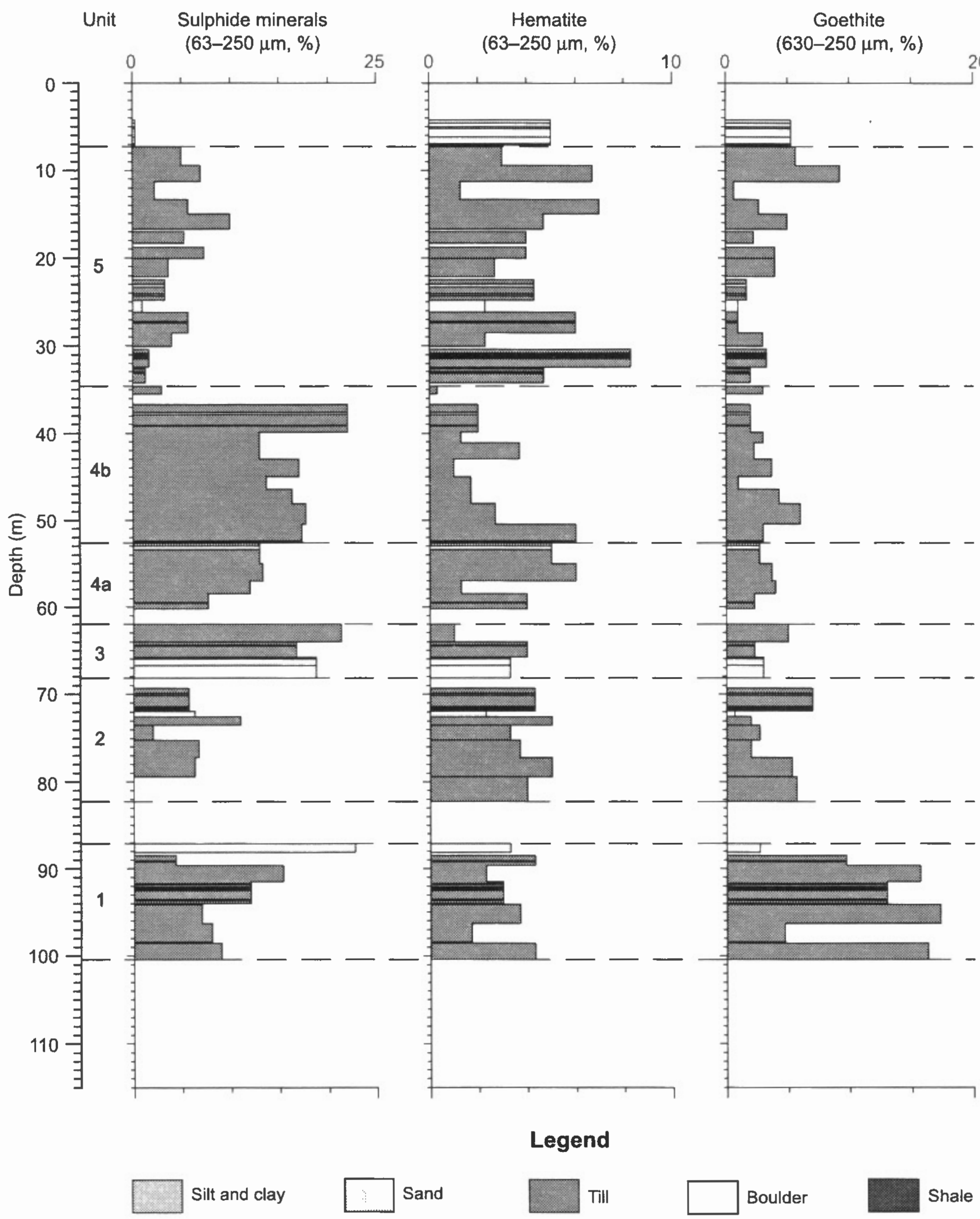

Figure 13. Sulphides, hematite, and goethite (count per cent) in the 63–250 µm, nonferromagnetic, greater than 3.2 specific gravity fraction.

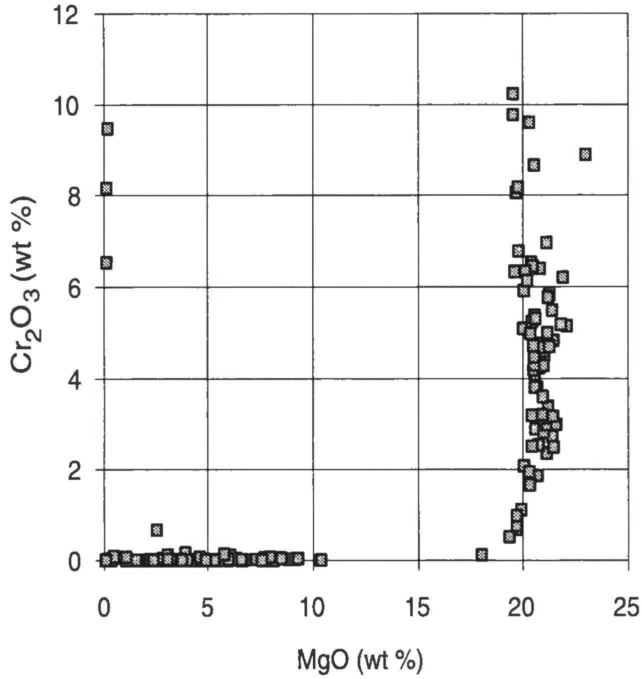

Figure 14. *Electron microprobe data for garnet, MgO versus Cr_2O_3, n = 167; Cr-pyropes are those with greater than 13% MgO and greater than 0.5% Cr_2O_3.*

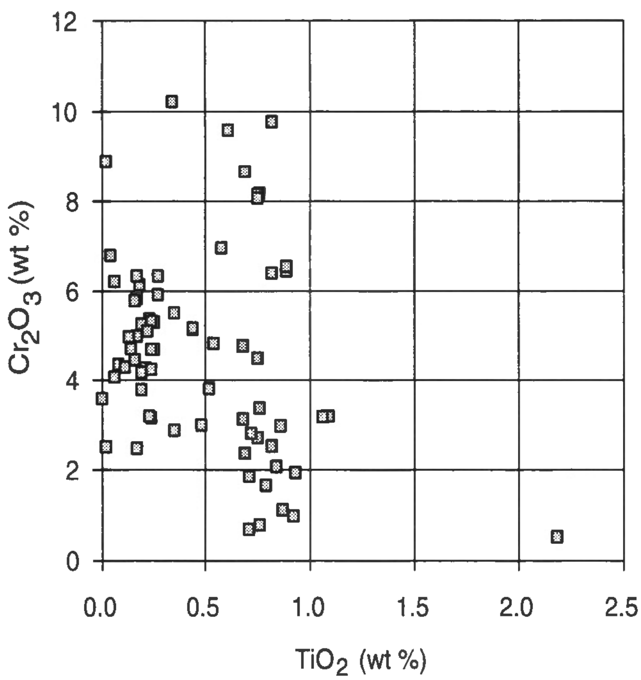

Figure 15. *Electron microprobe data for Cr-pyrope, TiO_2 versus Cr_2O_3, n = 71; nontitanian Cr-pyrope (G7, G9, G10) are those with less than 0.3% TiO_2. Among the titanian Cr-pyropes, high-chrome titanian Cr-pyrope (>4% Cr_2O_3; G11) may be distinguished from low-chrome titanian Cr-pyrope (G1, <0.9% TiO_2; G2, >0.9% TiO_2).*

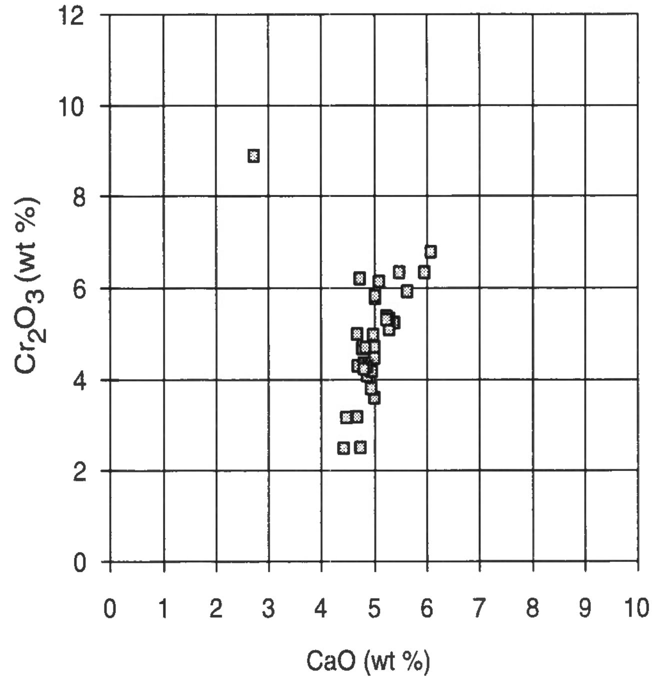

Figure 16. *Electron microprobe data for nontitanian Cr-pyrope, CaO versus Cr_2O_3, n = 32; two subcalcic, harzburgitic, G10 grains are present, one of which stands out from a typical cluster of lherzolitic G9 compositions. Calcic, wehrlitic G7 compositions are absent.*

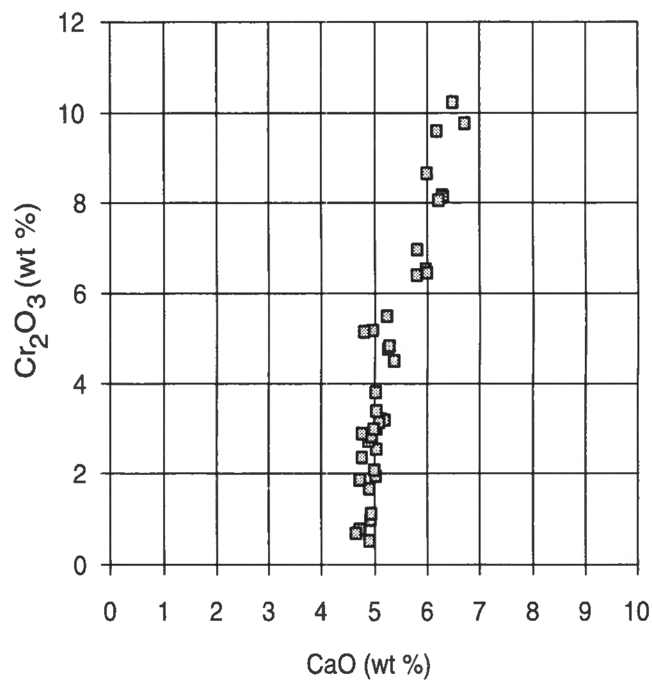

Figure 17. *Electron microprobe data for titanian Cr-pyrope, CaO versus Cr_2O_3, n = 39.*

high-chrome G11 cluster (Fig. 17). Among the low-chrome titanian Cr-pyrope garnets, 6 grains exceed 0.9% TiO_2 and were classified as G2. The titanian Cr-pyrope compositions span a greater Cr_2O_3 range and a lesser CaO range than nontitanian Cr-pyrope (Fig. 16, 17).

The Cr-pyropes are most abundant in units 3 and 4a, from 53.4 m and 68.2 m, (Fig. 18). Below this interval, Cr-pyrope is rare except in a 1 m sand layer from 87.1 to 88.1 m. The harzburgitic G10 subcalcic Cr-pyropes were recovered from adjacent sampled sections of till from 52.6 to 57 m.

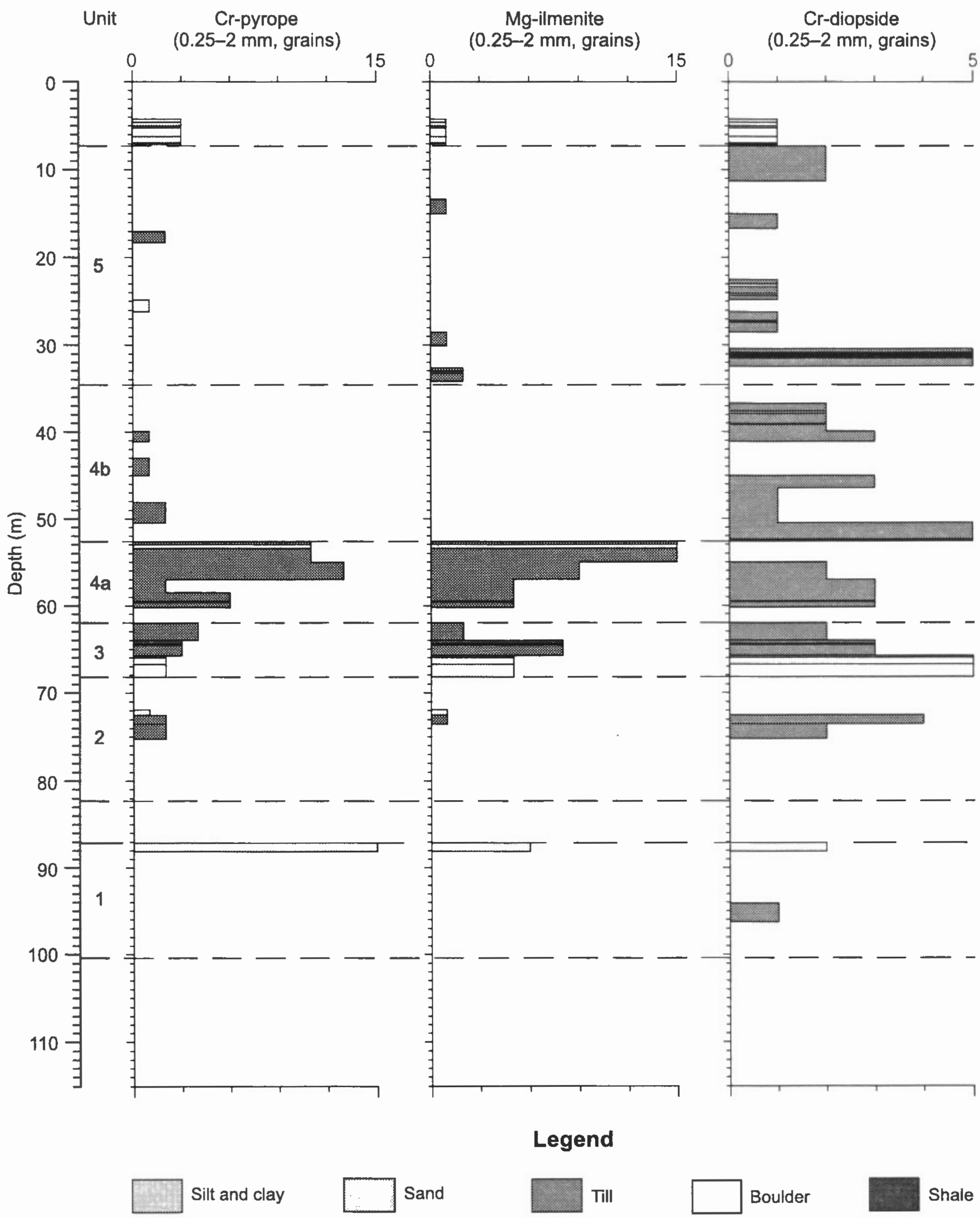

Figure 18. Cr-pyrope, Mg-ilmenite, and Cr-diopside frequency, number of grains per till or sand sample.

A total of 43 G9, G10, and G11 Cr-pyropes were analyzed by proton microprobe. The G1 and G2 titanian, low-chrome Cr-pyrope garnets were not analyzed. The Ni determinations 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. The G11 garnets contain the highest Ni levels and hence imply the highest temperatures (T_{Ni}; Table 1). Among the nontitanian Cr-pyropes, nine or 28% are in the diamond stability field (950 to 1250°C or 32–75 ppm Ni), and 23 or 72% are below this range (<950°C or <32 ppm Ni). Of the grains in the Griffin diamond window (32–75 ppm Ni), eight or 89% contain less than 50 ppm Zr, a positive sign regarding diamond grade (Griffin and Ryan, 1993, 1995). All three G10 garnets yielded Zr concentrations less than 50 ppm and two are in the Griffin diamond window.

Among 93 analyzed ilmenites, a clear break between magnesian (>6% MgO) and nonmagnesian compositions is present (Fig. 19). The Mg-ilmenites include numerous high-chrome values (Fig. 20), indicative of a reduced

Table 1. Electron and proton microprobe data for G9, G10, and G11 garnets.

Field ID	Lab ID	Grain ID	Sediment type	Depth (m)	Mineral ID	CaO (wt %)	Cr_2O_3 (wt %)	TiO_2 (wt %)	Ni (ppm)	T_{Ni} (°C)	Zr (ppm)
5196	610001	6071	sand	5.7	G9	5.62	5.91	0.27	24	874	17
4303	510026	6043	till	17.7	G11	6.73	9.77	0.82	86	1312	88
5197	610028	4247	sand	24.5	G11	5.80	6.39	0.82	90	1334	70
4313	510031	6046	till	40.5	G9	4.74	2.51	0.02	16	781	18
4318	510061	6069	till	49.3	G9	4.80	4.35	0.08	24	874	8
4320	510032	6047	till	53.8	G9	4.47	3.16	0.24	26	894	28
4320	510032	6049	till	53.8	G9	4.68	3.19	0.23	11	708	24
4320	510032	6050	till	53.8	G9	5.29	5.09	0.22	30	932	16
4320	510032	6051	till	53.8	G9	5.28	5.32	0.24	18	806	27
4320	510032	6052	till	53.8	G9	5.24	5.37	0.23	22	852	23
4320	510032	6053	till	53.8	G9	5.24	5.30	0.25	19	818	21
4320	510032	6054	till	53.8	G10	4.73	6.20	0.06	44	1047	47
4320	510032	6055	till	53.8	G9	5.96	6.33	0.27	38	1000	32
4320	510032	6056	till	53.8	G9	4.98	4.97	0.13	21	841	37
4321	510048	4244	till	56.0	G11	6.23	8.06	0.75	67	1201	64
4321	510048	6063	till	56.0	G11	6.29	8.17	0.76	66	1195	67
4321	510048	6064	till	56.0	G9	6.08	6.78	0.04	28	913	9
4321	510048	6065	till	56.0	G11	6.32	8.14	0.75	62	1170	66
4321	510048	6066	till	56.0	G9	5.47	6.33	0.17	22	852	19
4321	510048	6067	till	56.0	G9	4.95	4.17	0.19	28	913	20
4321	510048	6068	till	56.0	G10	2.72	8.89	0.02	52	1104	33
4322	510052	7616	till	57.8	G9	4.94	3.79	0.19	25	884	28
4323	510044	6059	till	59.4	G11	6.50	10.22	0.34	94	1355	53
4323	510044	6061	till	59.4	G9	5.01	4.70	0.14	23	863	19
4323	510044	6062	till	59.4	G9	4.42	2.49	0.17	22	852	15
4324	510023	6038	till	63.0	G9	4.83	4.69	0.25	40	1016	42
4324	510023	6039	till	63.0	G11.	5.98	6.53	0.89	92	1344	119
4324	510023	6040	till	63.0	G9	4.78	4.68	0.24	41	1024	53
4324	510023	6041	till	63.0	G11	6.00	6.44	0.89	94	1355	122
4325	510071	4245	till	64.9	G9	5.02	5.77	0.16	29	923	33
4325	510071	4246	till	64.9	G9	5.02	5.82	0.17	36	984	27
5199	610026	6077	sand	72.2	G9	5.37	5.24	0.19	41	1024	28
5200	610042	6080	sand	87.6	G9	5.01	3.59	0.00	24	874	3
5200	610042	6082	sand	87.6	G11	6.20	9.59	0.61	83	1295	78
5200	610042	6084	sand	87.6	G9	4.87	4.08	0.06	6	609	58
5200	610042	6085	sand	87.6	G11	6.01	8.66	0.69	83	1295	85
5200	610042	6086	sand	87.6	G11	5.81	6.96	0.58	82	1289	65
5200	610042	6088	sand	87.6	G9	4.81	4.23	0.24	37	992	24
5200	610042	6089	sand	87.6	G9	4.69	4.29	0.11	22	852	18
5200	610042	6090	sand	87.6	G9	5.10	6.13	0.18	28	913	52
5200	610042	6091	sand	87.6	G9	4.87	4.27	0.21	36	984	22
5200	610042	6092	sand	87.6	G10	4.68	4.99	0.17	27	904	27
5200	610042	6093	sand	87.6	G9	5.00	4.46	0.16	15	768	30

likelihood of diamond resorption (McCallum and Vos, 1993). The similar distribution of Mg-ilmenite and Cr-pyrope garnet (Fig. 18) implies a similar source.

The 111 analyzed clinopyroxenes, all of which were visually an anomalous green, includes 59 grains that exceed 0.5% Cr_2O_3 (Fig. 21). Data for these clinopyroxenes indicate that Cr_2O_3 values span the arbitrary minimum of 0.5% Cr_2O_3, that numerous anomalously low CaO values are present, and that some anomalously high Cr_2O_3 values are present. Among these Cr-clinopyroxenes, one grain with a high-Na content was classified as a Cr-omphacite (Fig. 22), and three grains with greater than 0.5% Cr_2O_3 and greater than 6.1% total Fe

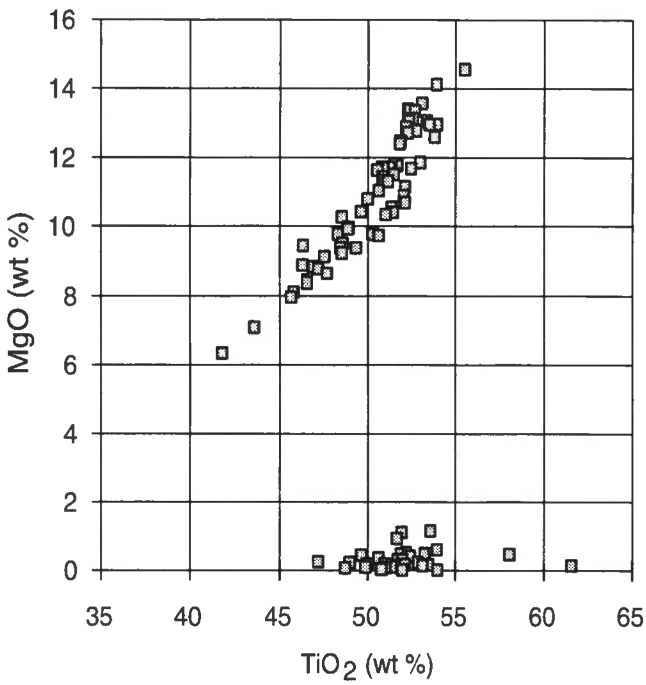

Figure 19. Electron microprobe data for ilmenite, TiO_2 versus MgO, n = 93; Mg-ilmenite are those with greater than 6% MgO.

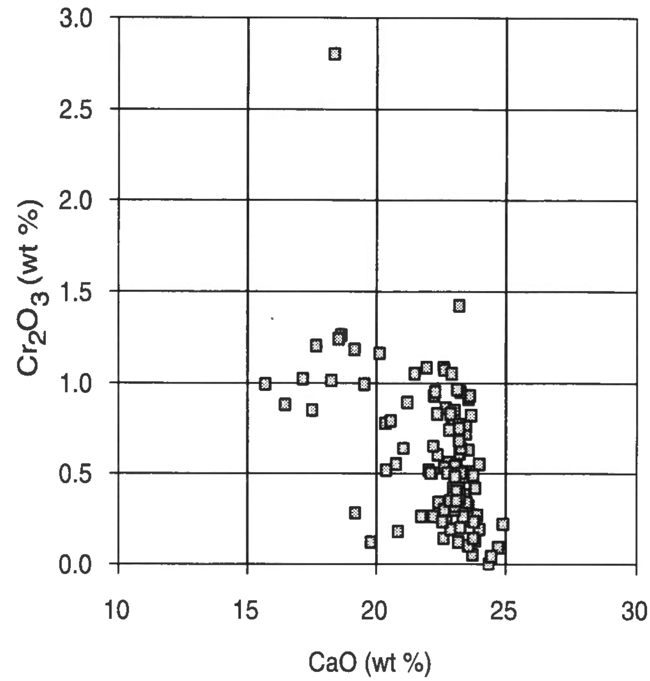

Figure 21. Electron microprobe data for clinopyroxene, CaO versus Cr_2O_3, n = 111.

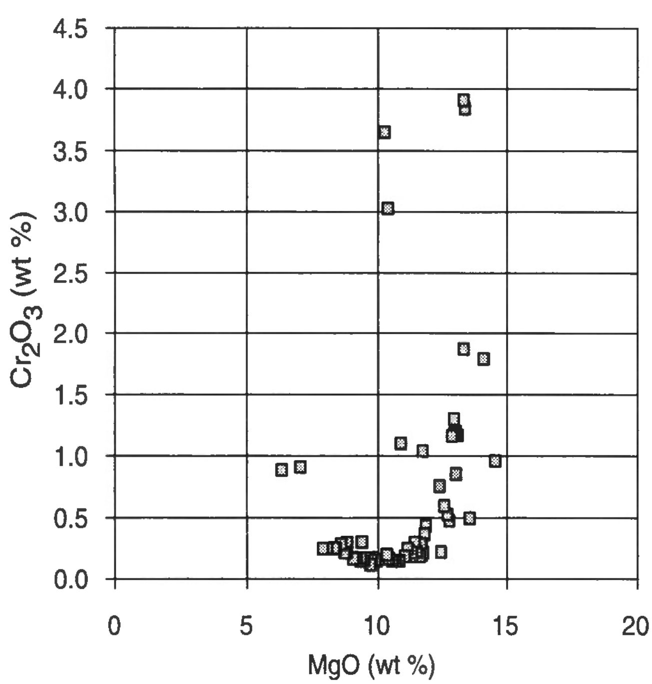

Figure 20. Electron microprobe data for Mg-ilmenite, MgO versus Cr_2O_3, n = 62.

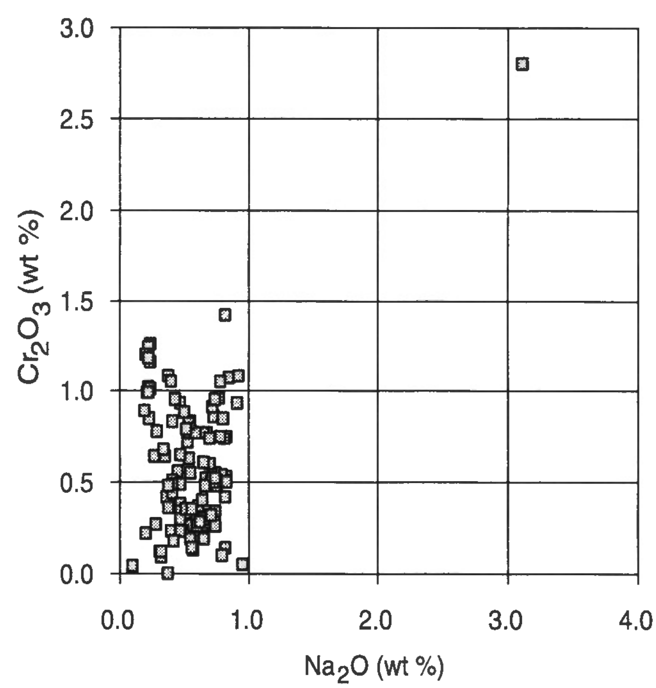

Figure 22. Electron microprobe data for clinopyroxene, Na_2O versus Cr_2O_3, n = 111.

as FeO (Deer et al., 1982) were classified as Cr-Fe-clinopyroxenes (Fig. 23). The Cr-diopsides show a pattern of occurrence that is far more dispersed than is the case for Cr-pyrope and Mg-ilmenite (Fig. 18), although there is little Cr-diopside present below 68.2 m.

Among the low-Na, low-Fe Cr-diopsides, 42 contain less than 1% Cr_2O_3, and 13 greater than 1% Cr_2O_3. Those with greater than 1% Cr_2O_3 are scattered throughout the entire sediment sequence. The highest count, three grains in one sample, occurs immediately above the interval that contains numerous Cr-pyrope and Mg-ilmenite grains. It appears, therefore, that most of the Cr-diopsides, regardless of Cr_2O_3 content, are derived from a source that is different from the source of the Cr-pyrope and Mg-ilmenite grains, and that the Cr-diopside source is relatively lacking in Cr-pyrope and Mg-ilmenite.

A total of eight garnets exceed the minimum values for definition as eclogitic garnet (>4% MgO, >2% CaO, and >0.2% TiO_2), all of which classified as G3 (Table 2). All of these grains, after reanalysis, were found to contain low Na_2O levels ranging from 0.01 to 0.07%. Hence, no diamond-inclusion compositions (>0.07% Na_2O; Gurney and Moore, 1993) were present. There is no clear association between the eclogitic garnet and other indicator minerals.

Five olivine grains, all from the 0.5–2.0 mm fraction, were recovered between 52.6 and 73.5 m, in association with the interval of numerous kimberlite indicator minerals.

Table 2. Eclogitic garnets recovered from glacial sediments.

Field ID	Lab ID	Grain ID	Sediment type	Depth (m)	Mineral ID	Na_2O (wt %)	K_2O (wt %)	CaO (wt %)	FeO (wt %)	MgO (wt %)	Al_2O_3 (wt %)	MnO	TiO_2	Cr_2O_3	SiO
5196	610001	7656	sand	5.7	G3	0.01	0.01	7.1	23.2	8.4	20.7	0.55	0.22	0.02	39.1
4315	510004	7483	till	44.0	G3	0.03	0.00	10.7	21.9	6.6	20.8	0.41	0.20	0.00	38.6
4317	510033	7573	till	47.3	G3	0.03	0.00	6.4	22.6	9.2	21.3	0.46	0.24	0.07	39.1
4320	510032	4075	till	53.8	G3	0.07	0.01	5.9	11.7	18.0	21.2	0.48	0.54	0.19	41.6
5200	610042	7801	sand	87.6	G3	0.03	0.00	7.3	23.6	8.1	21.0	0.61	0.25	0.00	39.4
4333	510034	7578	till	90.6	G3	0.01	0.00	6.5	23.1	9.3	21.1	0.62	0.21	0.06	39.5
4333	510034	7579	till	90.6	G3	0.02	0.00	7.5	23.6	8.0	20.9	0.52	0.23	0.03	39.7
4333	510034	7581	till	90.6	G3	0.02	0.01	6.5	22.9	9.2	21.2	0.66	0.21	0.06	39.7

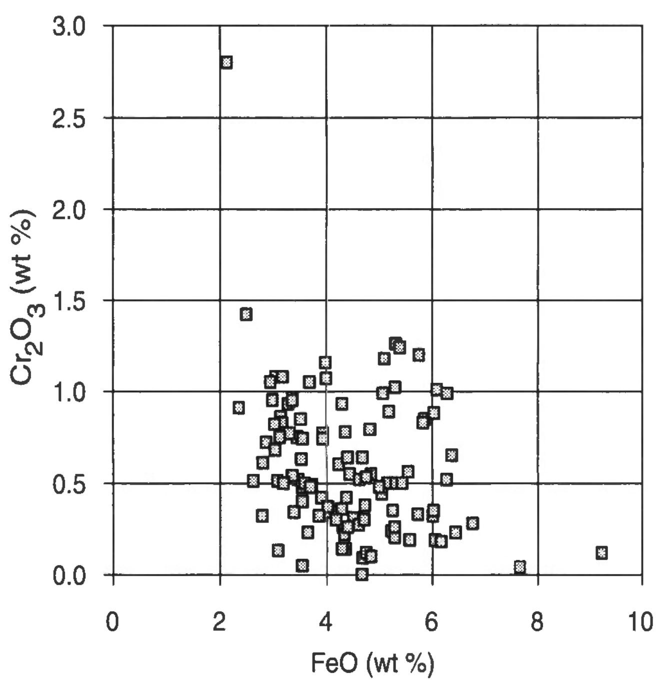

Figure 23. Electron microprobe data for clinopyroxene, FeO versus Cr_2O_3, n = 111.

The elevated frequency of kimberlite indicator minerals between 52.6 and 57 m does not show strong correlation with the bulk mineralogy of the 63–250 μm nonferromagnetic concentrates. With prior knowledge of the indicator mineral occurrences, slightly enhanced abundances of ferromagnetic minerals, garnet, barite, amphibole, epidote, hematite, ilmenite, and zircon can be recognized in this interval.

VISIBLE GOLD

A total of 23 visible gold grains, ranging in size from 25 to 250 μm in long axis dimension were recovered. These grains occur throughout almost the entire section, with never more that two grains in one sample. There were no intersections where samples containing two grains were adjacent to each other, and there seems to be no pattern to the occurrences. The only consistent feature is an interval with no observed gold grains from 71.9 to 88.1 m that consists of tills overlying silt and clay.

GEOCHEMISTRY

Quaternary sediments of the Prairie region are largely derived from Phanerozoic shale, carbonate, and sandstone, as well as from the Precambrian shield. Sediments derived from carbonate source rocks would contain elevated carbonate, low silica (SiO_2), and low alumina (Al_2O_3) concentrations, whilst tills derived to a greater degree from shield rocks and sandstone would contain more SiO_2, and tills derived from shale would be expected to be higher in Al_2O_3.

Till units 5, 4, and 3 contain progressively lower SiO_2 and Al_2O_3 levels that are compensated for by increasing carbonate levels (Fig. 24). Below this, unit 2 is somewhat similar to unit 4 but exhibits increased Al_2O_3 levels. In unit 1, carbonate levels fall while SiO_2 and Al_2O_3 levels rise. These data primarily imply a shifting balance between carbonate and siliceous shield debris. The only indication of a shift in favour of locally derived argillaceous debris at the expense of the exotic calcareous/siliceous assemblage is a slight shift in favour of Al_2O_3 in unit 1.

Elevated Na_2O levels in unit 5 (Fig. 25) likely are due to feldspars in shield debris. Unit 5 is highest in Na_2O, whilst units 4 and 3 are low, and units 1 and 2 intermediate. The Na_2O/carbonate and Al_2O_3/carbonate ratios fall precipitously from high values in the surface sand, silt, and clay, to lower levels at the top of the uppermost tills, and then continue to fall at a slower rate over the next 20 m. Unit 1 tills exhibit higher ratios, particularly Al_2O_3/carbonate, indicating a relative paucity of carbonate.

Lime (CaO) and magnesia (MgO) levels follow very closely those exhibited by carbonate and permit the recognition of the same 5 units. Elevated total iron (as Fe_2O_3) permits units 5 and 1 to be differentiated from units 4 to 2, but does not permit further differentiation. Finally, the potash (K_2O) content of unit 5 is greater than that of the tills lower in the section.

Unit 5 contains relatively low levels of As, Br (Fig. 26), and Sb. Molybdenum exhibits considerable variability (Fig. 26), but is present at intermediate levels in unit 5. Unit 4b is characterized by elevated levels of As, Br, Mo (Fig. 26), and Sb, whereas unit 4a exhibits lower levels of these elements. The carbonate-rich unit 3 is notable for its elevated Br, while As and Sb are at low levels similar to unit 4a, as well as low Mo and Rb levels. Levels of As, Mo, and Sb are low in unit 2, whereas Br levels are less depressed. In the lowermost tills of unit 1 As, Sb, Ba, and Cr increase, whereas Br levels fall, relative to unit 2.

Units 5 and 4b show an antipathetic pattern for U, Th, and U/Th (Fig. 27); unit 5 being low in U and high in Th, whereas unit 4b is vice versa. This makes the U/Th ratio a clear indicator of the contact between these two units. Unit 4a is characterized by sharply lower U levels than unit 4b, but similar Th levels, causing a shift in U/Th ratio. The high carbonate unit 3 exhibits the lowest levels of U and Th in the section. Below this, unit 2 exhibits similar U levels as unit 4a, but higher Th levels, leading to subtly lower U/Th ratios. Finally, U levels in unit 1 increase significantly, and Th levels less so, to generate a small increase in the value of the U/Th ratio.

Hafnium and Sm values (Fig. 28) are elevated in unit 5, reflecting derivation from the shield, or from sandstone containing shield-derived detritus, as already indicated by Na_2O (Fig. 25). Unit 5 also contains increased levels for Zr, Ce, La, Lu, and Sc. The Hf data show little variability through units 4 to 2, but increase significantly in unit 1. The Sm and Ba data are somewhat similar, except that there is a marked minimum coincident with the high carbonate unit 3 tills. The Cs data (Fig. 28) show little variability through units 5 and 4, but show a minimum in unit 3 and thereafter increasing levels in units 2 and 1 to the base of the section where the highest Cs levels are found.

Schreiner (1990) reported greatest stratigraphic contrast across southern Saskatchewan in data for carbonate, V, and Zn in till. At Smeaton, V and Zn generally vary sympathetically (Fig. 29), although V is less variable within units. Unit 5 is characterized by lower Zn, V, and Mn levels than unit 4; the unit 4b–4a break is marked by a drop in Zn, V, Fe, and Mn levels. Unit 3 exhibits the lowest levels of Zn, V, Cu, Ni, and Co. Units 2 and 1 exhibit increasing levels of Zn and V, with unit 1 also exhibiting higher levels of Cu, Mn, Fe, and Pb.

Gold levels in the less than 63 μm fraction of the Quaternary sediments range from less than 2 to 10 ppb. Levels equal to or above 5 ppb occur at three intervals close to the bases of units 5 (28.5–30.1 m) and 2 (79.4–82.3 m) tills, and midway up unit 1 (89.6–91.5 m). None of these intersections shows any unusual response in any of the 63–250 μm mineralogical estimations.

Results for Instrumental Neutron Activation Analysis of the less than 63 μm and 63–250 μm nonferromagnetic heavy mineral concentrates were combined into a composite less than 250 μm value because the two size fractions demonstrated very similar patterns. Only a few elements, i.e. As, Sb, Ba, Br, Ce, La, Sm, Ta, Tb, Th, U, and Yb reveal any systematic patterns of distribution through the section (Fig. 30). The

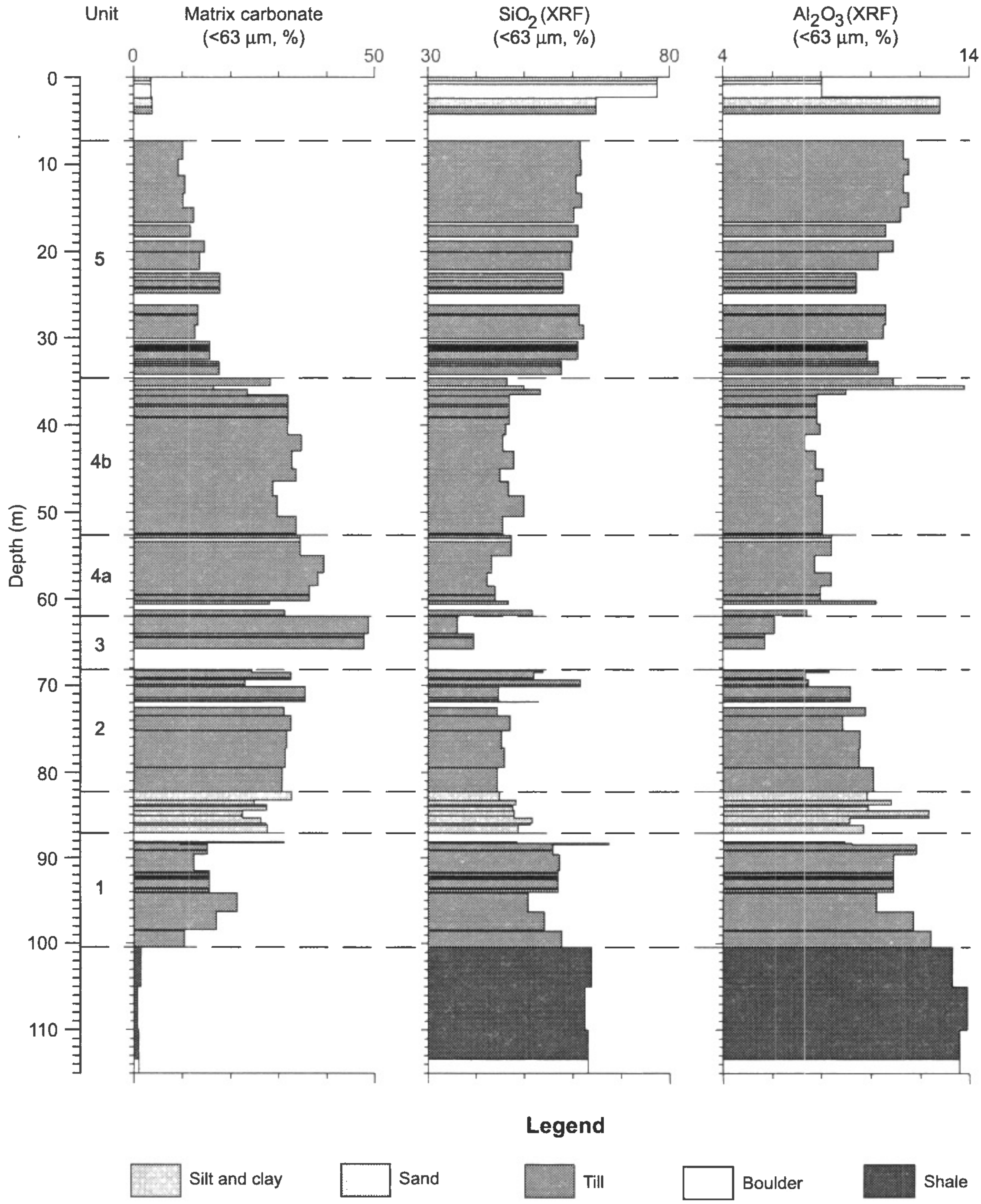

Figure 24. *Matrix carbonate content, SiO_2, and Al_2O_3 in the less than 63 μm fraction.*

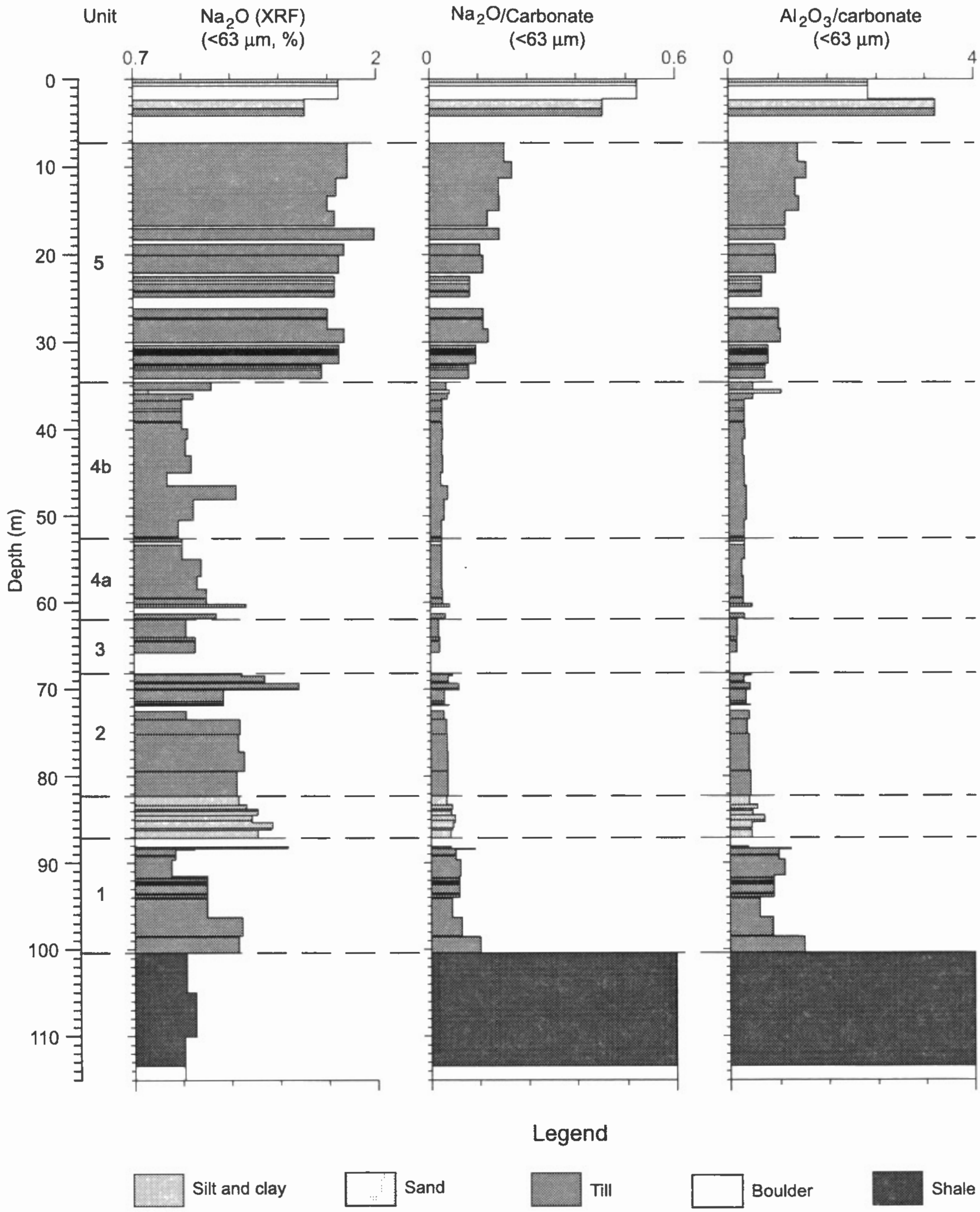

Figure 25. *The Na_2O content, Na_2O/carbonate ratio, and Al_2O_3/carbonate ratio in the less than 63 μm fraction.*

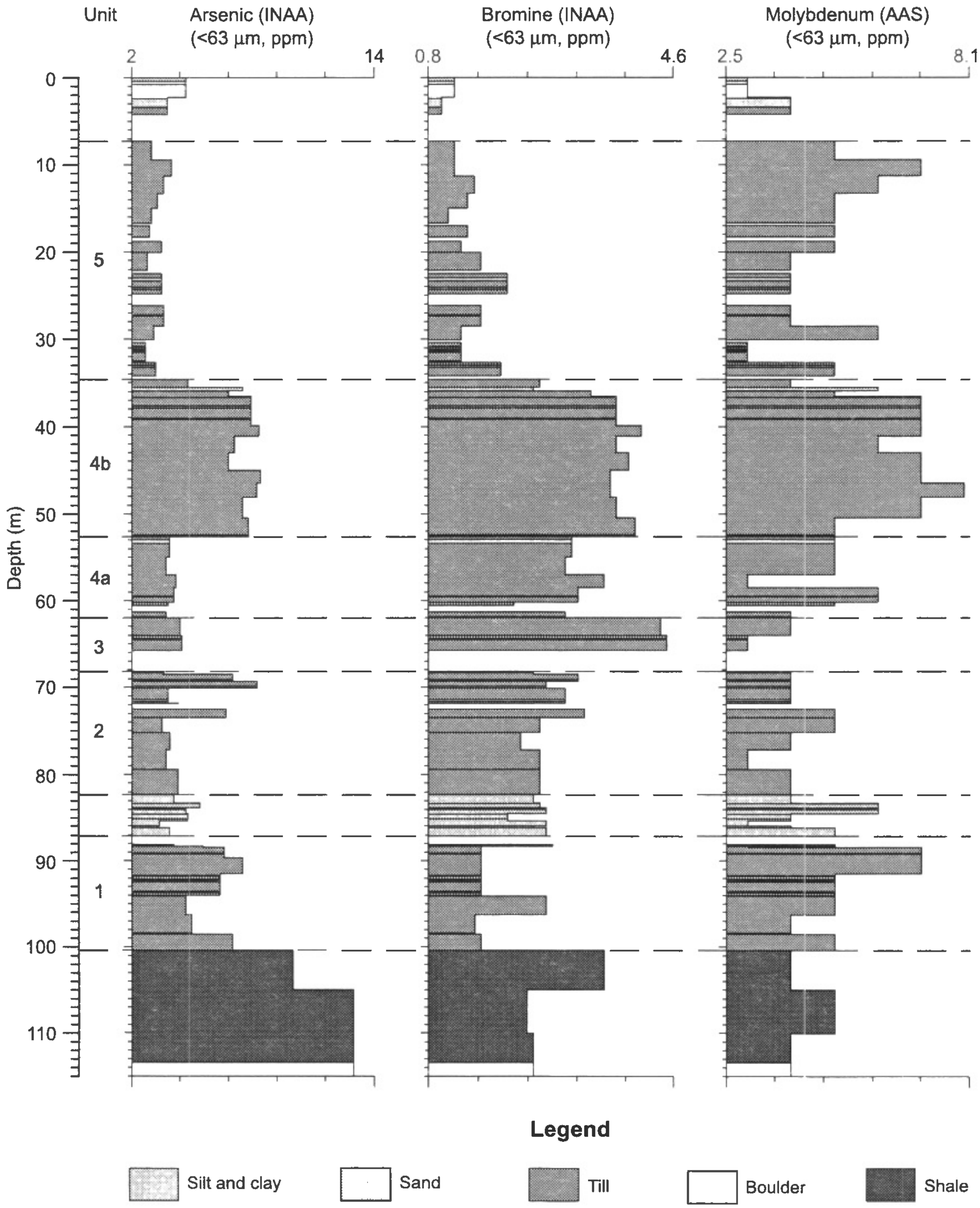

Figure 26. *Arsenic, bromine, and molybdenum in the less than 63 µm fraction.*

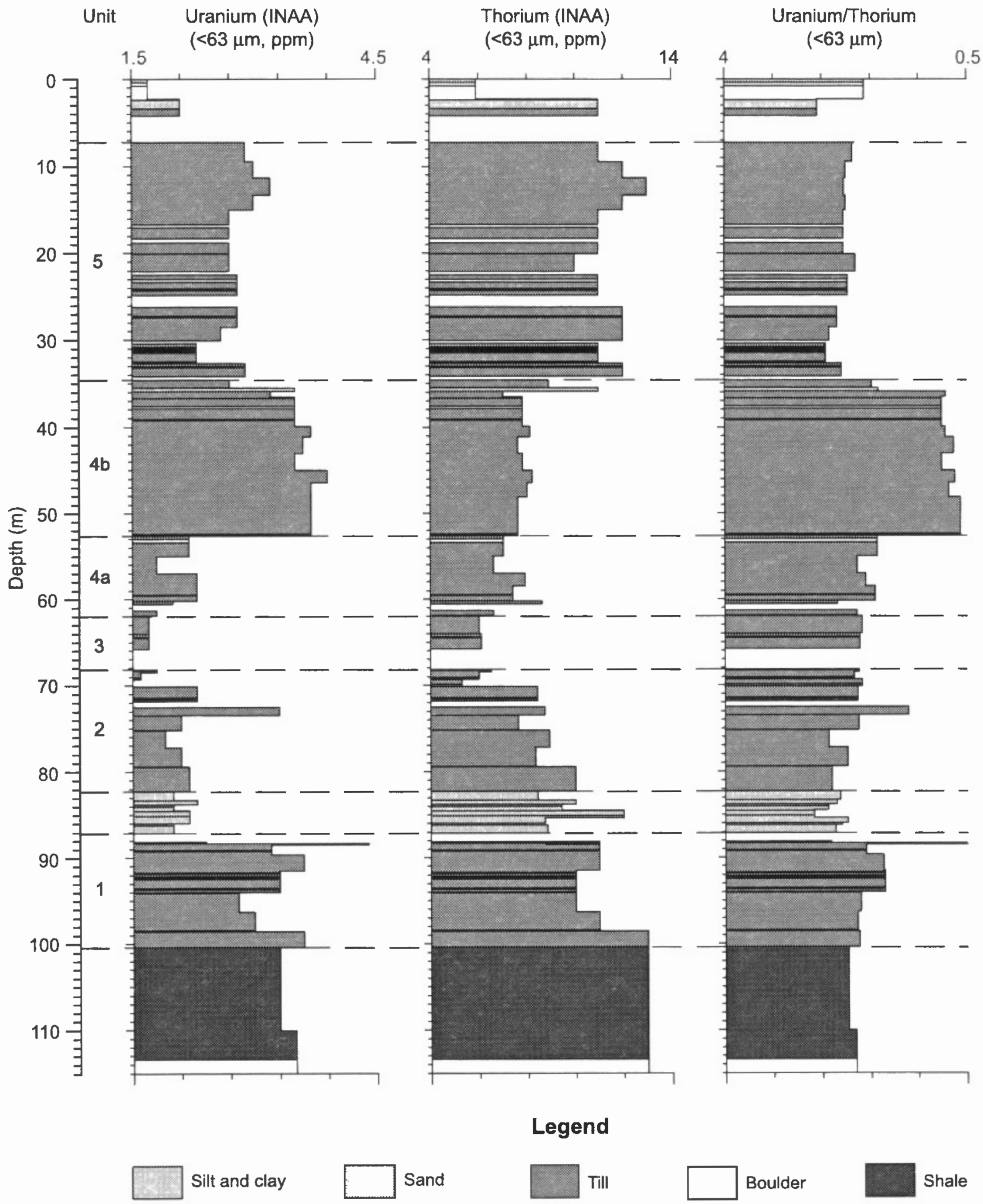

Figure 27. Uranium, thorium, and uranium/thorium ratio in the less than 63 µm fraction.

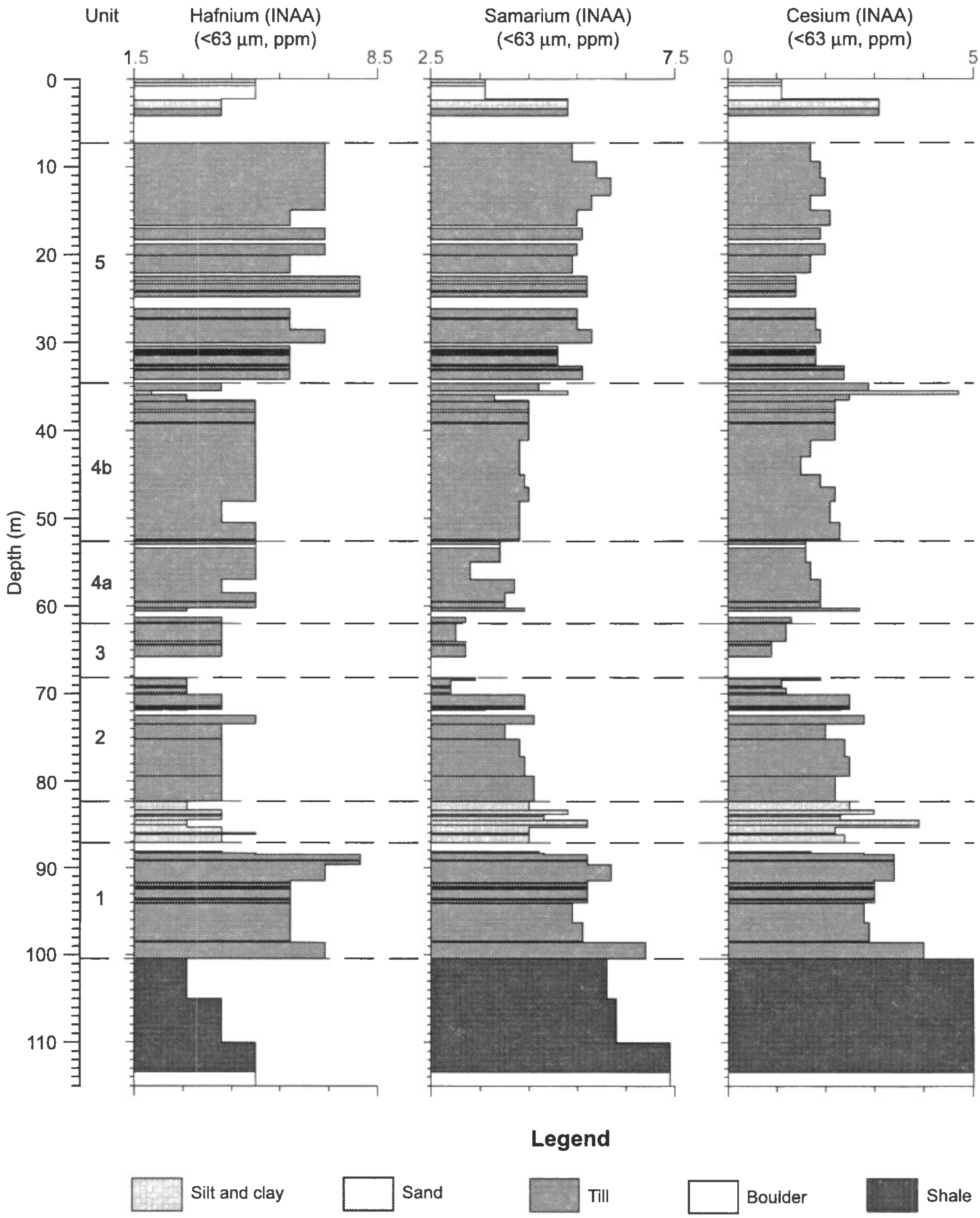

Figure 28. *Hafnium, samarium, and cesium in the less than 63 µm fraction.*

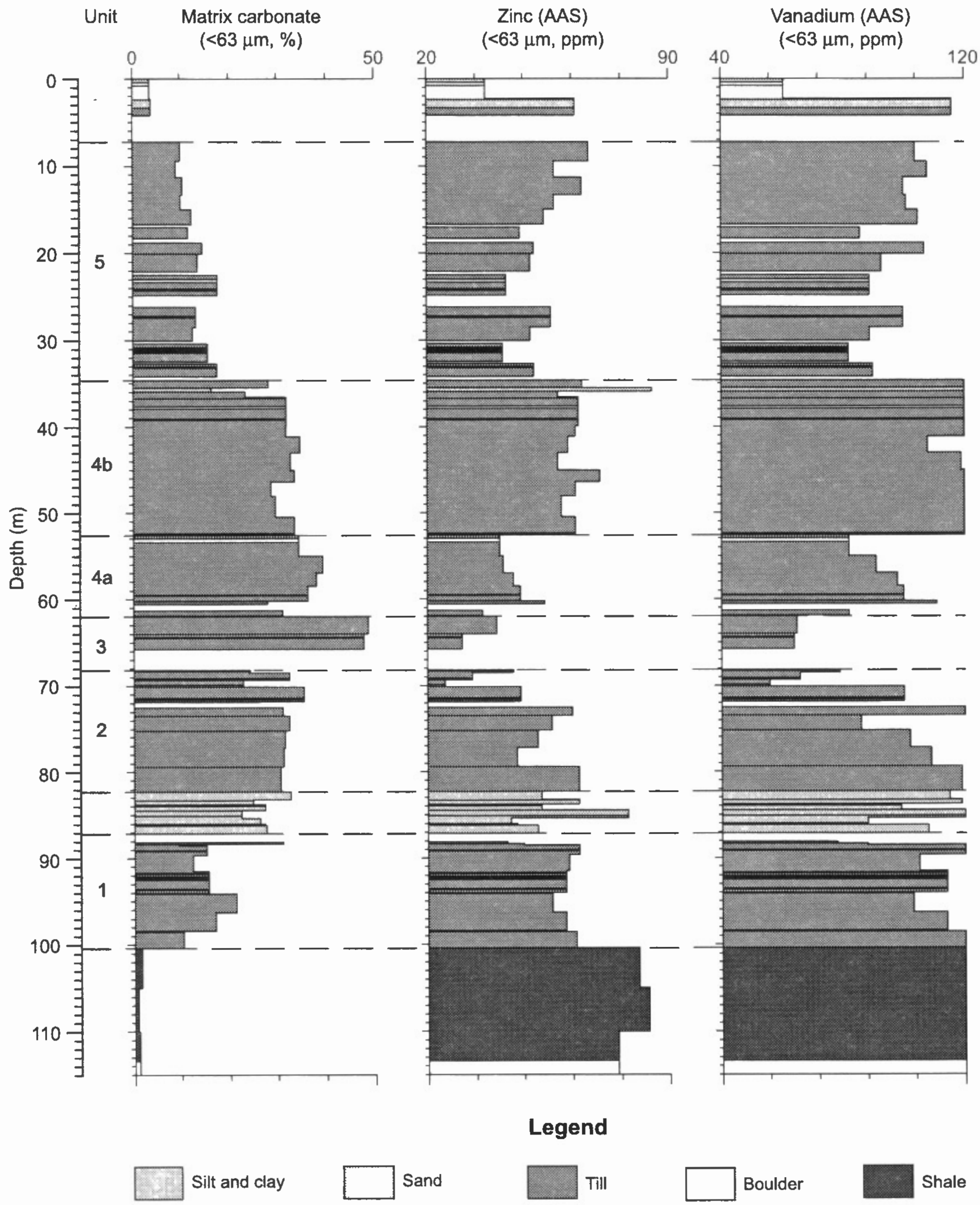

Figure 29. *Carbonate, zinc, and vanadium in the less than 63 µm fraction.*

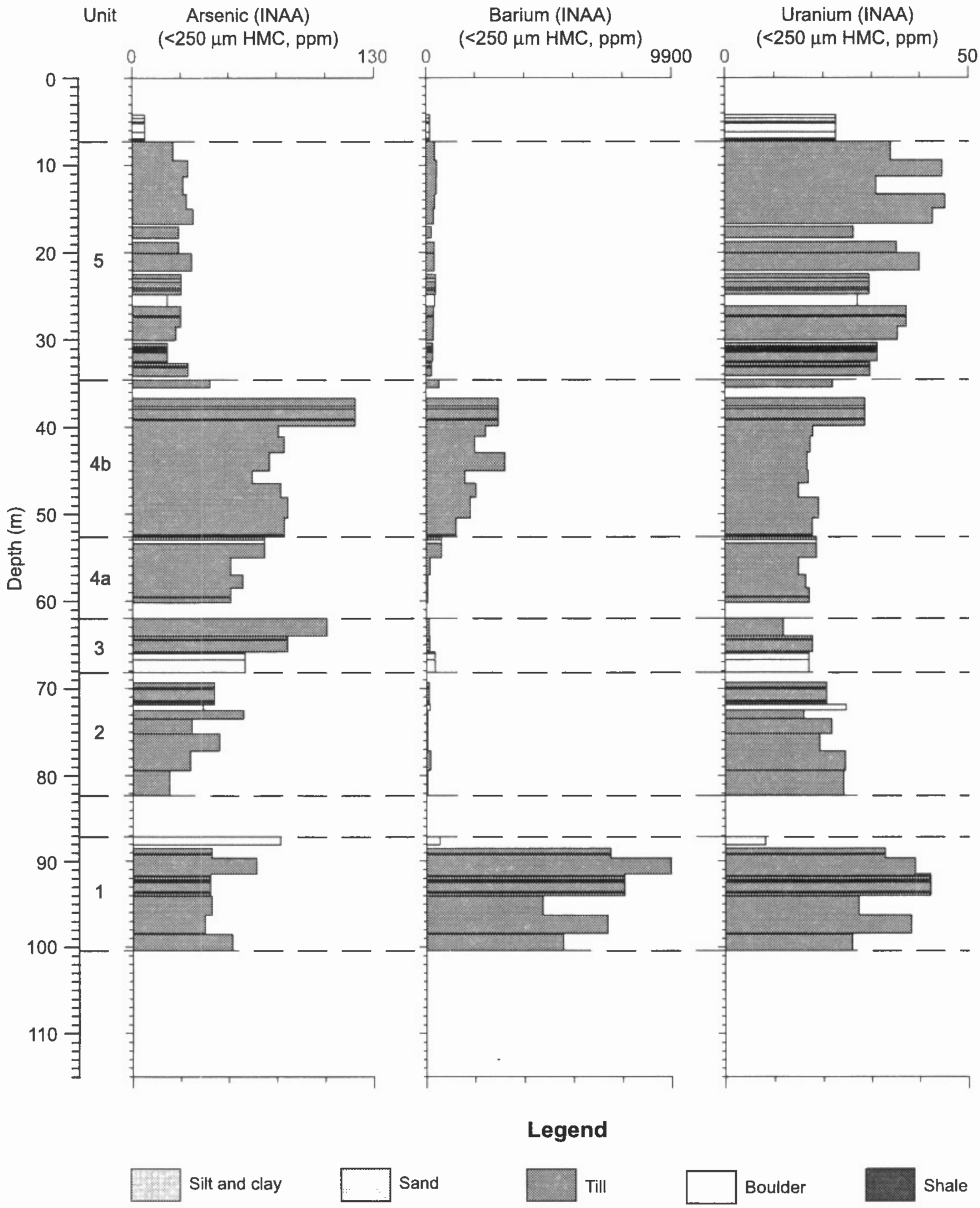

Figure 30. *Arsenic, barium, and uranium in heavy mineral concentrates (<250 µm nonferromagnetic, >3.2 specific gravity).*

rare-earth and lithophile elements (Ce to U above) permit units 5 and 1 to be distinguished from the intervening units 2 to 4 by their higher levels of these elements. Notable exceptions are As, Sb, Ba, and Br which exhibit low levels in unit 5, high levels in unit 4b, decreasing values in unit 4a and higher again in unit 1. Interestingly, levels of As and Sb also exhibit high levels in unit 3 and intermediate levels in unit 2.

BOREHOLE GEOPHYSICAL DATA

Borehole geophysical data for the Quaternary sequence (Fig. 31) show reduced values for gamma-ray count in units 4a and 3. Despite major changes in U and Th concentrations between units 5 and 4, total gamma count does not change notably, presumably due to compensation for increasing U by decreasing Th, or due to variability in the role of K. Spectral

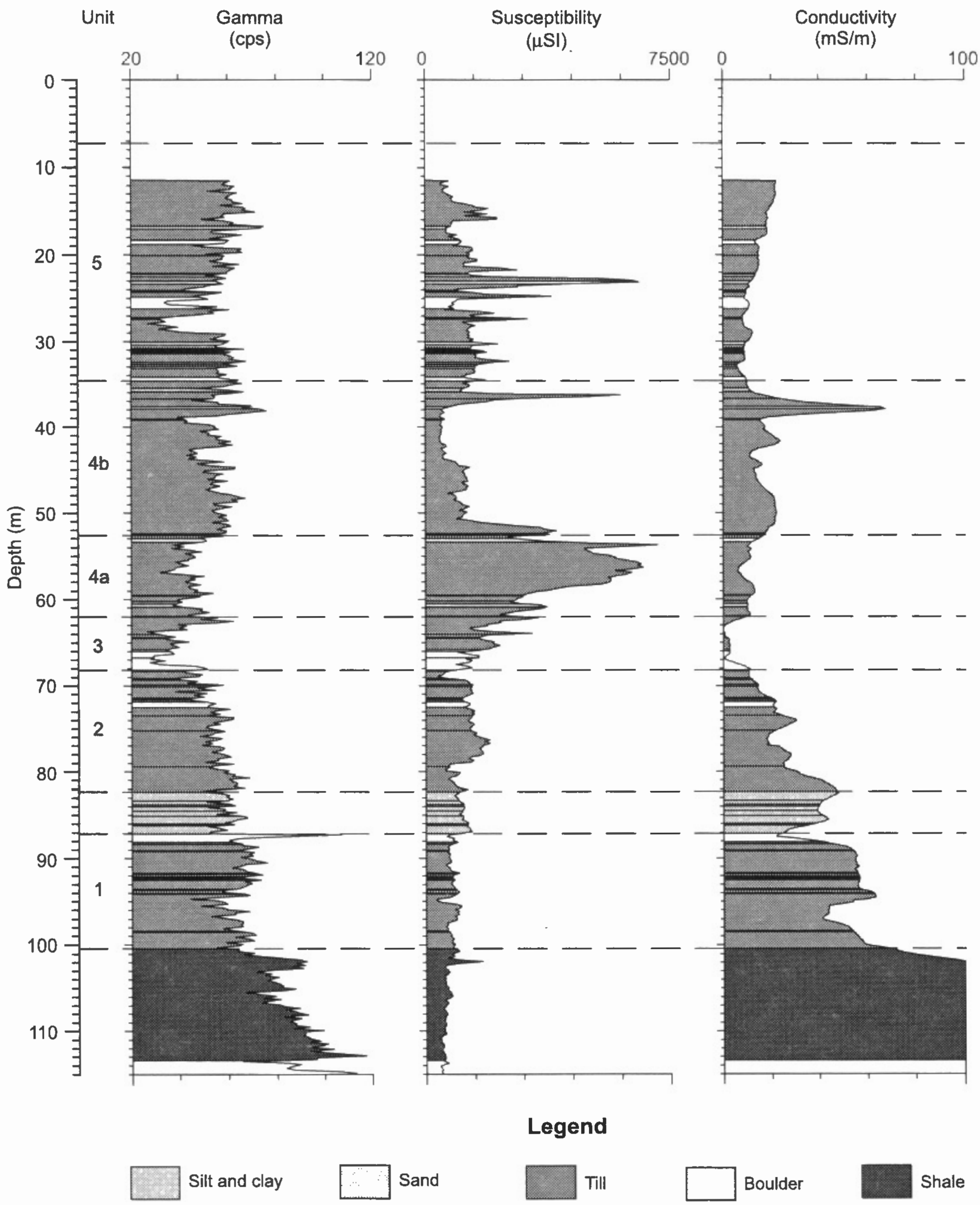

Figure 31. Borehole geophysical data; natural gamma, magnetic susceptibility, and conductivity.

gamma-ray data were not collected due to limited casing diameter. Unit 1, characterized by increased U and Th levels, can be discerned by a subtle increase in total gamma counts. The spike in the log coincident with the sand layer at 87.1–88.1 m may be associated to a heavy mineral concentration noted in the 63–250 μm mineralogical data.

The magnetic susceptibility log exhibits one broad and two narrow peaks. The broad peak (52–60 m) happens to correspond to the greatest accumulation of kimberlitic indicator minerals in the section. The plot of less than 2 mm ferromagnetic minerals (Fig. 11) does not correlate well with the magnetic susceptibility log, although there seems to be some correlation to Mg-ilmenite (Fig. 18). A susceptibility peak at 23 m correlates to ferromagnetic mineral yield (Fig. 11), but another peak at 37 m does not correspond with any particular measured compositional parameter. This may reflect sampling limitations in that the geophysical probe responds to sediment around the hole, whereas the samples collected for compositional study are much smaller in volume.

The conductivity of the sediments is lowest in the carbonate-rich unit 3, and then rises to a uniformly high conductivity in the lowermost unit 1 till. This corresponds to an increase in Al_2O_3 content, and therefore possibly clays, in the lower part of the section. However, increases in Al_2O_3 content in the upper parts of the hole are not reflected in coincident increases in conductivity, perhaps reflecting the presence of Al_2O_3 in comminuted feldspars rather than clay minerals.

SUMMARY OF COMPOSITIONAL DATA

The Quaternary sequence at the Smeaton drill site consists almost entirely of till. Compositional data allow these strata to be grouped on the basis of abrupt changes in bulk composition, as illustrated by pebble lithology and matrix carbonate content. Other compositional variables that vary between units are summarized as follows:

Unit 5 till (7.3–34.6 m) is characterized by low carbonate, a high dolomite/calcite ratio, high SiO_2, Al_2O_3, and Na_2O in the less than 63 μm fraction, an abundance of shield provenance 8–16 mm clasts and 63–250 μm mineral grains such as amphibole. The less than 63 μm fraction exhibits low U and high Th combining to give a low U/Th ratio; it also exhibits low As, Sb, Br, V, Zn, and Mn; together with high Hf, Zr, Sm, Ce, La, Lu, and Sc levels; whereas the less than 250 μm heavy mineral concentrates are characterized by elevated levels of Ce, La, Sm, Ta, Tb, Th, U, and Yb. A granite boulder rests at the lower contact of this compositionally distinct sequence.

Unit 4b till (34.6–52.6 m) contains elevated abundances of 8–16 mm carbonate and shale clasts, and exhibits a lower dolomite/calcite ratio relative to unit 5, it also exhibits low SiO_2, Al_2O_3, and Na_2O contents, together with high U and low Th to give a high U/Th ratio, levels of As, Sb, Br, Mo, V, Zn, and Mn are high, whereas levels of Hf, Zr, Sm, Ce, La, Lu, Sc are low in the less than 63 μm fraction. The less than 250 μm fraction of the heavy mineral concentrate is characterized by high levels of As, Sb, Ba, and Br, whereas levels of the rare-earth and lithophile elements are low compared to the overlying unit 5. Unit 4a till (52.6–62.0 m) is similar in bulk composition to unit 4b, but shale is lacking, matrix carbonate content is marginally higher, and SiO_2 content is marginally lower. These sediments exhibit ever lower U, As, Br, Mo, Zn, V, Fe, and Mn levels in the less than 63 mm fraction. Levels of As, Sb, Ba, and Br in the less than 250 μm heavy mineral fraction decrease downsection from the upper contact with unit 4b.

Unit 3 till (62.0–68.2 m) is characterized by the highest yield of 8–16 mm carbonate, a significant component of shield clasts, extremely high matrix carbonate and Br, with low SiO_2, Al_2O_3, and Na_2O levels, as well as low U, Th, As, Sb, Mo, and Sm levels in the less than 63 μm fraction. Levels of As and Sb in the less than 250 μm heavy mineral concentrate are characteristically high, similar to unit 4b.

Unit 2 till (68.2–82.3 m) contains a moderate abundance of 8–6 mm Paleozoic brown carbonate and shield provenance clasts, which tend to decrease down section. The SiO_2 levels in the less than 63 μm fraction are similar to unit 4, but Al_2O_3 and Na_2O levels are higher. In general, matrix carbonate, dolomite/calcite ratio, and SiO_2 levels decrease with depth, while Na_2O and Al_2O_3 levels increase. Levels of U are generally low, and combine with higher Th to give higher U/Th levels than units 4 and 3. Levels of As, Sb, Mo, and Hf are low, but Zn, V, Hf, Zr, Sm, and Cs increase downward following Al_2O_3 and Na_2O.

Unit 1 till (87.1–100.4 m) is characterized by relatively low carbonate with a higher dolomite/calcite ratio than observed in units 4, 3 and 2. The SiO_2 and Al_2O_3 levels in the less than 63 μm fraction are similar to unit 5 and higher than the intervening units, while Na_2O levels are similar to units 4 and 3 and lower than unit 2. Levels of U, Th, Ba, As, Sb, Pb, Fe, Cr, V, Ni, Mo, Ta, Hf, Zr, Sm, La, Ce, Rb, and Cs are higher than in unit 2, whereas Zn, and Cu exhibit similar levels, and Br content is lower. The less than 250 μm heavy mineral concentrate is characteristically high in As, Sb, Br, Ce, La, Sm, Ta, Tb, Th, U, and Yb, and particularly high in Ba.

DISCUSSION

Unit 5 is very similar in composition to surface till found throughout the region north of the North Saskatchewan and Saskatchewan rivers. This area was referred to as the northern zone described by Garrett and Thorleifson (1995). The uppermost till in this area exhibits an abundance of shield-derived gravel clasts, amphibole grains, but low carbonate, V, Zn, and As content, together with high SiO_2, Al_2O_3, Na_2O, U/Th ratio, rare-earth and lithophile element levels. This match between unit 5 and surface till throughout the region implies that the upper till of the region is not missing at Smeaton. The composition of unit 5 is indicative of southward ice flow off the shield. These observations strongly suggest correlation to the Battleford Formation, although the thickness would be highly anomalous relative to the much thinner observations in the Saskatoon area. The presence of Paleozoic carbonate clasts, derived from the east, in these tills indicates that the southward Battleford ice flow incorporated material from earlier glacial events, although it is possible that limestone and dolomite rocks outcrop to the north as outliers on the

Precambrian Shield basement. The low carbonate but high dolomite/calcite ratio, V, and Zn were features identified by Schreiner (1990) as being characteristic of Battleford till. If it is judged to be inconceivable that Battleford till could be this thick, one might contemplate that the Battleford till is present, less than the thickness of unit 5, but compositionally indistinguishable from underlying units. Another alternative, however unlikely, is that Battleford till is missing from this region where surface till is enriched in shield debris.

For unit 4, a provenance from the east or northeast is indicated by abundant carbonate and shale clasts, coupled with a geochemical composition indicative of carbonate and shale bedrock. Changes in composition from unit 4b to 4a, such as reduced levels of U, As, Br, Mo, Zn, V, Fe, and Mn, coincides with the disappearance of shale clasts and abrupt increase in kimberlite indicator mineral frequency. The abrupt change in trace element geochemistry from unit 4a to 4b cannot readily be explained by the progressive stripping mechanism discussed by Schreiner (1990), which accounts well for regional trends in till composition. Progressive exposure of debris sources would imply that trace-element-poor shale had been stripped from a trace-element-rich unit. According to Schreiner (1990, his Fig. 20) the Niobrara and Morden shale units have the highest Zn and V concentrations in the Cretaceous sequence. The alternative, unroofing of these units by removal of Pierre Shale produced the shift from unit 4a to unit 4b is disallowed by the occurrence of siliceous shale clasts very likely derived from Pierre shale only in unit 4b. A mosaic of sources and varying ice-flow directions may account for the change.

Unit 3 is characterized by a relative abundance of Paleozoic brown carbonate and shield provenance pebbles; very high carbonate levels; and commensurately low levels of all other trace elements except As, Sb, and Br which are reflected in both the less than 63 μm fine and less than 250 μm heavy mineral fractions. This unit exhibits a mixed Precambrian and Phanerozoic provenance derived from the east. The high Br may indicate that the erosive phase of this till unit was incorporating material from the Prairie Evaporite in the area of Lake Winnipegosis (Thorleifson and Garrett, 1993).

Comparison with data presented by Schreiner (1990) suggests that units 3 and 4 correlate with the Floral Formation, with the Floral Formation upper contact at an abrupt increase, relative to overlying sediments, and the Floral Formation lower contact at an abrupt decline in carbonate content, relative to the underlying sediment. Because Schreiner (1990) described the contrast between the upper Floral Formation and the lower Floral Formation as a change from a weakly calcareous matrix to a strongly calcareous matrix, it seems likely that unit 3 represents the lower Floral Formation. If unit 5 is judged to be too thick to be Battleford till, one is left to speculate that units 3 to 5 all correlate with the Floral Formation. Deposition of these more calcareous sediments may be associated with the old westward striations reported by McMartin et al. (1996).

Unit 2 seems likely to correlate with the Dundurn till, because there is no downward increase in carbonate, which is indicative of a Warman–Dundurn contact, below sediments likely correlating with the Floral Formation. Like units 3 and 4, unit 2 has a mixed provenance, with carbonate and shield debris indicating a source to the northeast. Relative to other easterly provenance tills, unit 2 is poorer in As and U, but richer in Na_2O and Al_2O_3, perhaps indicating a greater influence from younger shale. Hence, the Warman till seems to be missing at this site.

The composition of unit 1 indicates a generally northeasterly provenance as evidenced by the presence of carbonate and shield clasts. The high Ba content of the heavy mineral fraction implies an abundance of barite or witherite. The former is considered more likely, and this, combined with the recorded presence of selenite in the tills, is indicative of a high sulphate environment. The selenite is authigenic, and the barite could be similarly formed or have been derived from sandstone where it may be present as interstitial cement. Manville Group and Swan River Formation sandstone may have provided a significant contribution to the unit 1 tills. The low carbonate content of unit 1 is consistent with the observation of Schreiner (1990) in central and Southern Saskatchewan that the lowermost Sutherland Group till, the Mennon, tends to be low in carbonate relative to the other tills. This unit may therefore correlate with the Mennon Formation, largely on the basis of its stratigraphic position underlying Dundurn till. The geochemistry of unit 1 till is distinct from the underlying shale, and is best exemplified by the low carbonate and dolomite/calcite ratio, the high SiO_2, Al_2O_3, As, Cs, Th, and Na_2O/carbonate and Al_2O_3/carbonate ratios. This confirms that the lowermost till was not derived from the immediately underlying Cretaceous sediments, but from different units including older sandstone in an up-ice direction.

The glacial sequence at Smeaton was deposited by net sedimentation associated with a series of events known from regional investigations of Sutherland tills, the Floral till, and Battleford till. Sutherland Group tills, deposited by early phases of glaciation in which low-carbonate sediments were transported largely from Cretaceous shale and sandstone (Schreiner, 1990), are not commonly detectable at surface, and it seems unlikely that Sutherland tills at Smeaton have any association with outcropping till. In the case of units 3 to 5, however, these sediments seem likely to be associated with Floral and Battleford events, and correlations to surface till are apparent. Units 3 and 4 resemble the high-carbonate surface till east of The Coteau and south of the Saskatchewan River (eastern zone), whereas unit 5 resembles till north of the North Saskatchewan and Saskatchewan rivers (northern zone).

This leads to a model in which units 3 and 4 are correlated with Floral till, and surface till in the eastern zone has a composition produced by transportation of Floral Formation. Westward transportation of Floral Formation in this scenario produced a thick (Fenton et al., 1994) cover of calcareous till extending to The Coteau, but in the western zone, thin Floral Formation sediments were mixed with locally derived debris. The shift to the southward ice flow of Battleford time is well displayed by geomorphic features throughout southern Saskatchewan (Prest et al., 1968). Unit 5 is homogeneous and similar in composition to surface till throughout the northern zone, suggesting correlation of this thick, largely shield-derived sequence to Battleford till. The observation that surface till throughout the eastern zone compositionally resembles Floral till at Smeaton and Saskatoon suggests that Battleford till south of the Saskatchewan River consists of thin, locally reworked Floral Formation.

These observations imply a similar transport model for both Floral and Battleford formations. Each event produced a thick and extensive deposit, which abruptly gives way down-ice to thinner, discontinuous deposits. This pattern resembles till plumes in northern Ontario (Thorleifson and Kristjansson, 1993), where ice streams emanating from the sedimentary terrane of the Hudson Bay Lowland transported thick, exotic till deposits that abruptly shift to thin and discontinuous at limits well back from the associated ice margin. Thorleifson and Kristjansson (1993) called for subglacial deformation transport to explain this process of sedimentation.

The ratio of Precambrian to carbonate gravel clasts in till across the Prairie region (Fig. 32), calculated from data described by Garrett and Thorleifson (1993, 1996), changes abruptly along a line extending southwest from the western limit of Paleozoic carbonate outcrop. Areas down-ice-flow from carbonate outcrop would be relatively enriched in carbonate pebbles and related debris, so southwestward transport is indicated. The upward shift from carbonate-rich unit 4 to shield-debris-rich unit 5 at the Smeaton site represents a shift from the lithology typical of areas southeast of this line to that typical of areas to the northwest. Hence the shift from unit 4 to unit 5 may be regarded as a counter-clockwise change in ice flow that caused this line to shift from north of the Smeaton site to south of the site.

The presence of wood fragments in sand between units 2 and 3 could be regarded as evidence suggestive of deglaciation, supporting correlation of this level to the boundary between Saskatoon Group and Sutherland Group sediments. The 5.4 m sequence of silts, clays and minor sands underlying unit 2 contains organic debris, again suggestive of deglaciation. Presence of unaltered sulphide throughout most of the sequence, however, is not supportive of deglaciation having occurred, given that sulphide would be expected to have been destroyed in aerated soils.

IMPLICATIONS FOR DIAMOND EXPLORATION

One might expect the dispersal train of kimberlite indicator minerals from the Fort à la Corne camp to be reflected in the lowermost till unit. However, this is not the case. The tills of the lowermost unit 1 are essentially devoid of kimberlite indicator minerals at this site (Fig. 18), although there is a significant concentration in the immediately overlying sand. Unit 2 is similarly poor in indicator minerals except for a 1 m section about 27 m above bedrock. Again the sand unit lying on top of unit 2 contains indicator minerals, perhaps reflecting concentration from the underlying tills by fluvial processes. A dispersal train was observed, however, in the tills of units 3 and 4a, about 35 m above bedrock. The concentration of indicator minerals increases upwards through the exotic, high-carbonate unit 3 into the overlying unit 4a, to reach a maximum in the upper 4.4 m immediately below unit 4b. Association with the highest carbonate values suggests transport from the east. In the overlying units 4b and 5, only scattered low numbers of kimberlite indicator minerals are present.

Potential explanations of the dispersal train observed in the Smeaton section, 35–48 m above bedrock, are 1) direct erosion from kimberlite on a bedrock high or from an erratic block, up-ice to the east; 2) reworking of older, indicator-mineral-rich till to the east; or 3) the indicator minerals were derived from a distant source to the east.

Garrett and Thorleifson (1995, 1996, 1999) concluded that the surface indicator mineral expression of the Fort à la Corne camp was to be found some 100 km to the west of the source, indicating a significant episode of westward sediment transport, prior to southward reworking in the Battleford till.

The present study exemplifies the complexity of the glacial stratigraphy of areas in Saskatchewan covered by deep drift. An adequate interpretation of the data from the section at Smeaton would require information from several additional drill-hole sections, and a working knowledge of the underlying bedrock topography of the area, in order to understand the glacial stratigraphy and the areal extent and provenance of the identified till units.

One line of future research that might prove useful is a further investigation of the use of magnetic susceptibility logging. The broad peak encountered from 52–60 m corresponds to the greatest accumulation of kimberlite indicator minerals in the section. If the response is a general feature, it would present the possibility of logging holes through the drift to contribute to mapping the extent and shape of the dispersal train on the basis of its magnetic susceptibility.

CONCLUSIONS

Work at Smeaton has provided new data that supplement published carbonate and geochemical data presented by Schreiner (1990). These new data demonstrate

1) Kimberlite indicator minerals at the Smeaton site are concentrated in two compositionally distinct till units, which likely correlate with the Floral Formation, 35–48 m above the bedrock surface. Due to limited knowledge of the bedrock surface topography, it cannot be ascertained whether this anomaly originated in the Fort à la Corne camp, or further to the east.

2) Data for pebble lithology, heavy minerals, and heavy mineral geochemistry of the glacial sediments, in addition to results from well established methods of matrix carbonate content and geochemical analysis, permit enhanced characterization of the till sequence.

3) Carbonate and arsenic contents of the less than 63 µm fraction of the till matrix could alone permit the recognition of the six different till units identified in the Smeaton section. However, a broader data set for pebble lithology, carbonate content, major elements (SiO_2, Al_2O_3, and Na_2O), and trace elements (As, U, and Th) offers additional insights into the definition of till units and determination of their provenance.

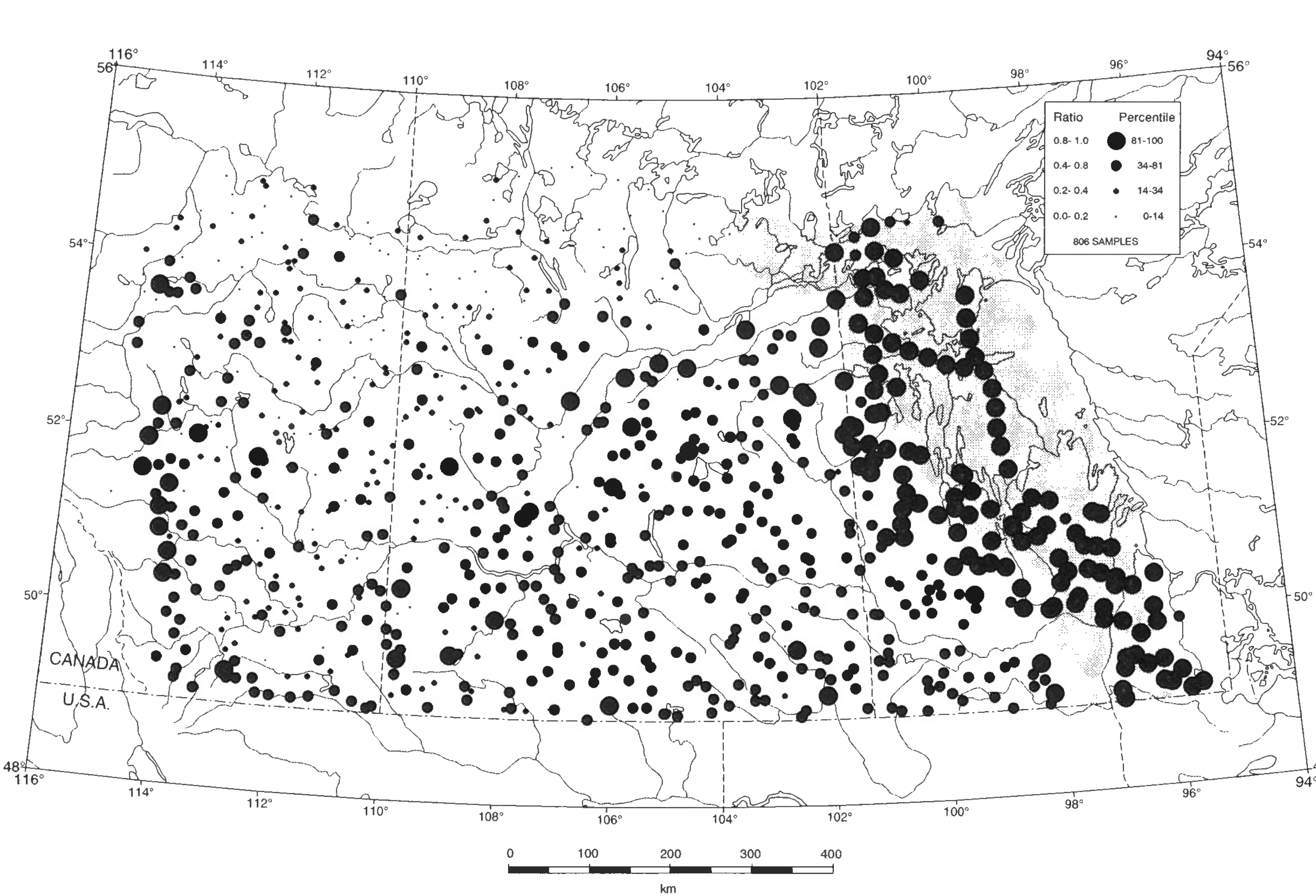

Figure 32. *Regional pebble lithology; ratio of Paleozoic brown carbonate to Precambrian shield-derived intrusive and metamorphic rocks in the 8–16 mm pebble fraction of till samples in the Prairie region (Garrett and Thorleifson, 1995; Thorleifson and Garrett, 1997; unpublished data collected by the authors in Manitoba), calculated as brown carbonate/(shield+brown carbonate). Shaded area indicates the outcrop of Ordovician, Silurian, and Devonian strata (Wheeler et al., 1996), considered the source of nearly all brown carbonate pebbles east of Calgary.*

4) Data from Smeaton, as well as data from surface till reported by Garrett and Thorleifson (1995), indicate extensive patterns of lateral and vertical variability which imply a complex sediment transport history that must be taken into account in the interpretation of mineral exploration data. For example, the carbonate-rich till found at surface in southeastern Saskatchewan seems to be present at Smeaton below a thick mantle of till that matches the composition of surface till throughout the area north of the North Saskatchewan and Saskatchewan rivers.

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