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Geology of the Sturgeon Lake 01 Kimberlite Block, Saskatchewan

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Abstract—The Sturgeon Lake 01 body was the first kimberlite discovered in Saskatchewan. It was found by heavy mineral sampling and shown to be diamondiferous, but not economic. The body is a glacially transported megablock of crater-facies volcaniclastic kimberlite that is at least 200 m by 125 m by 40 m in size. The block, which is 98 Ma in age, occurs within 100 m of glacial sediments that overlie Cretaceous bedrock shale. Marine shale of a similar age occurs adjacent to the kimberlite and appears to represent a separate glacial block(s) at least 110 m by 90 m by 16 m in size. The kimberlite is typical of Group 1, containing two generations of olivine, macrocrysts of ilmenite, garnet, spinel and mica together with groundmass mica, spinel, perovskite, apatite, carbonate and serpentine. Texturally, the kimberlites are subaerial pyroclastic airfall lapilli tuffs and coarse ash composed mainly of juvenile lapilli and single grains of olivine. The juvenile lapilli have amoeboid shapes and are vesicular; a feature which is similar to the kimberlites at Sturgeon Lake 02 and Fort à la Corne, but unusual compared to other kimberlites worldwide. This suggests that the Sturgeon Lake 01 kimberlites formed by different emplacement processes to most documented kimberlites; probably by Hawaiian- and Strombolian-style eruptions infilling maar-like craters with no associated diatreme as proposed for the Fort à la Corne province. **Copyright ©1996 Canadian Institute of Mining, Metallurgy and Petroleum.**

Introduction

The Sturgeon Lake 01 body in Saskatchewan was the first kimberlite found in the Prairies of central Canada. It is located 35 km northwest of Prince Albert on the north shore of Sturgeon Lake at 106°07'W, 53°24'N (Fig. 1). It was discovered by Monopros Limited in 1987, following heavy mineral sampling in the area. This paper presents a summary of the exploration work undertaken by Monopros, together with a geological summary of the kimberlite. Published information for this kimberlite is relatively limited (GSC Open File, 1989; Dunn, 1993; Katsube et al., 1992; Gent, 1992; Nixon et al., 1993). In 1989, a second kimberlite was discovered about 8 km northwest of this body (Fig. 1; Scott Smith, 1995); there are many similarities in the geology of the two kimberlites. The only other documented kimberlites in Saskatchewan occur at Fort à la Corne, 60 km east of Prince Albert. This province includes a large number of kimberlites (possibly over 70) which range in size up to 74 ha. (Lehnert-Thiel et al., 1992; Scott Smith et al., 1994); some of these are diamondiferous and contain crater-facies kimberlite.

Geological Setting

The Sturgeon Lake 01 kimberlite occurs near the northeastern edge of the Phanerozoic sedimentary rocks of the Northern Interior Platform, which overlies Archaean basement. The stratigraphy of the area is described by Simpson et al. (1990). Bedrock units include Palaeozoic sediments disconformably overlain by sandstone, siltstone and shale of the Cretaceous Mannville and Lower Colorado Groups, and the overlying Lea Park Formation (Table 1). These units

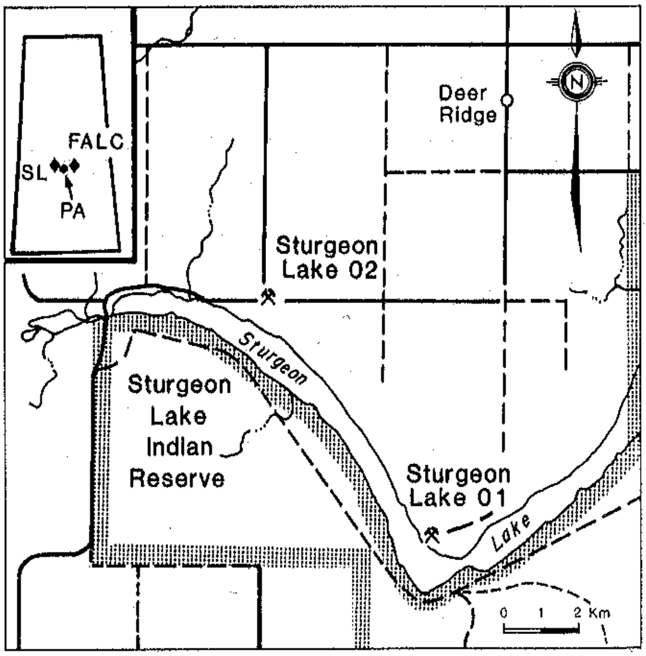

Fig. 1. Location of the Sturgeon Lake 01 and 02 kimberlites. Inset shows location of Sturgeon Lake (SL), Prince Albert (PA), and Fort à la Corne (FALC) within Saskatchewan. The Sturgeon Lake 01 kimberlite is 35 km northwest of Prince Albert.

Table 1. Stratigraphic column for the Sturgeon Lake-Prince Albert region (from Simpson et al., 1990)

Quaternary		Saskatoon Group	Surficial Stratified Drift Battleford Formation Floral Formation
		Sutherland Group	
		Empress Group	
Cretaceous	Late	Lea Park Formation and Upper Colorado Group	
		Ashville Formation — Lower Colorado Group	
	Early	Swan River Formation — Mannville Group	
Palaeozoic		(Undifferentiated)	

have a combined thickness of about 200 m to over 450 m. In the area around Sturgeon Lake, the uppermost bedrock unit consists of late Cretaceous shales and siltstones of the Lea Park Formation and Upper Colorado Group (Christiansen, 1973).

Glacial deposits overlying bedrock vary in thickness from 75 m to more than 200 m and are mainly till, with lesser stratified gravels, sands, silts and clays. This sequence records several glacial advances and retreats, indicating periodic erosion and deposition in the area. The glacial deposits have been divided into three groups (Table 1). The lower, Late Tertiary-to-Quaternary, Empress Group comprises two units of stratified gravels and finer sediments between the bedrock surface and the lowest till (6 m to 55 m thick, probably 30 m in this area (Whittaker and Christiansen, 1972). The overlying Sutherland Group (0 m to 130 m thick) consists of three till units and associated inter- and intra-glacial sediments. All sediments above the Sutherland Group are assigned to the Saskatoon Group, which includes at least three till units and associated non-glacial sediments. Recorded thicknesses in the Sturgeon Lake — Prince Albert area range from 26 m to 157 m. The Saskatoon Group is divided into two glacial units, the Floral and Battleford Formations, and an upper surficial stratified drift, which consists of post-glacial sediments. Gravels on the north side of Sturgeon Lake were deposited as a glaciofluvial terrace by meltwater flowing west through the Sturgeon Channel to Glacial Lake, Saskatchewan.

The Sturgeon Lake 01 kimberlite outcrops at an elevation of about 470 m above sea level, whereas the bedrock surface elevation 800 m to the south is only 347 m. Glacial thrusting of bedrock over till is known in the area; for example at Red Deer Hill, a prominent topographic high about 42 km SSE of Sturgeon Lake 01 (16 km SSW of Prince Albert). Here, a 106 m thick block of Cretaceous shale (Lea Park Formation and Upper Colorado Group), as well as overlying Empress Group, Sutherland Group and Floral Formation glacial sediments have been thrust over till of the Floral Formation (Simpson et al., 1990; Christiansen and Sauer, 1993). The basal shear plane occurs at about 400 m above sea level. The lateral movement of this thrust block may have been about 10 km. Simpson et al. (1990) have recorded similar features elsewhere in the province.

Exploration

Limited heavy mineral sampling in 1986 confirmed an earlier isolated positive result for kimberlite indicator minerals. Systematic till sampling was carried out in 1987, when 20-litre samples of -20 mm till were collected at 2 km to 3 km intervals along all roads in the area. Some of these samples contained significant numbers of indicator minerals. All gravel pits in the vicinity were then examined, and kimberlite clasts were found in a pit about 10 km southeast of the eventual discovery. Geological traversing was concentrated up-ice from this locality. The kimberlite was found outcropping in a gravel pit on the north shore of a prominent bend of Sturgeon Lake (Fig. 2), some 25 km up-ice from the initial positive sample. Subsequent investigation has shown that the indicator minerals are dispersed in glaciofluvial sands and gravels blanketing a well-incised meltwater channel. Indicator minerals are found along the full length of the channel as far as the discovery site (the Penitentiary Pit) of the first diamond to be discovered in Saskatchewan in 1948.

Mapping on north-south traverse lines spaced at 25 m showed that the kimberlite outcrops along the river escarpment, where it was exposed by glacial meltwater erosion, and also sporadically within the southern part of the gravel pit (Fig. 2). Trenching and a preliminary ground magnetic survey showed that the kimberlite did not extend northward. This was confirmed later by a detailed ground magnetic survey. The kimberlite produces an almost symmetrical anomaly with a central high of about 1200 nT, extending 190 m east-west by 110 m north-south (Fig. 2). It is flanked by magnetic lows of lesser amplitude.

This kimberlite did not produce any anomaly on the 1971 Geological Survey of Canada aeromagnetic map (1.14 km line spacing and 300 m ground clearance). However, it can be detected in a more recent survey flown at 120 m line spacing and 120 m terrain clearance. A dramatic decrease in magnetic field with height suggests that the kimberlite is rootless (Gent, 1992).

Trenching (Fig. 2) was carried out to provide additional geological control and material for bulk sampling. A total of 188 m^3 of excavated kimberlite was processed and yielded three macro-diamonds (0.183, 0.074 and 0.011 carats). Seven 12 cm holes were drilled with a rotary rig in 1988 (SL-1 to 7), and a further three holes (SL-8 to 10) in 1989 (Fig. 2). Drill chips from these holes provided samples for micro-diamond analysis. Some micro-diamonds were recovered but, in keeping with the bulk sampling results, the predicted macro-grade was low. The diamond potential of the Sturgeon Lake 01 kimberlite was also estimated as being very low (<1 carat per 100 tonnes) based on the geochemistry of the indicator minerals in heavy mineral concentrates prepared from kimberlite samples (GSC Open File, 1989).

Thirty samples of organic-rich A horizon soil were collected at 10 cm depth from three parallel lines over the southern portion of the kimberlite, and on lines trending northwest and northeast on either side of the gravel pit (Fig. 3). The samples were dried, sieved to -80 mesh, and analyzed by standard ICP methods at Chemex Labs Inc., Sparks, Nevada, U.S.A. The results for Ni are shown in Fig-

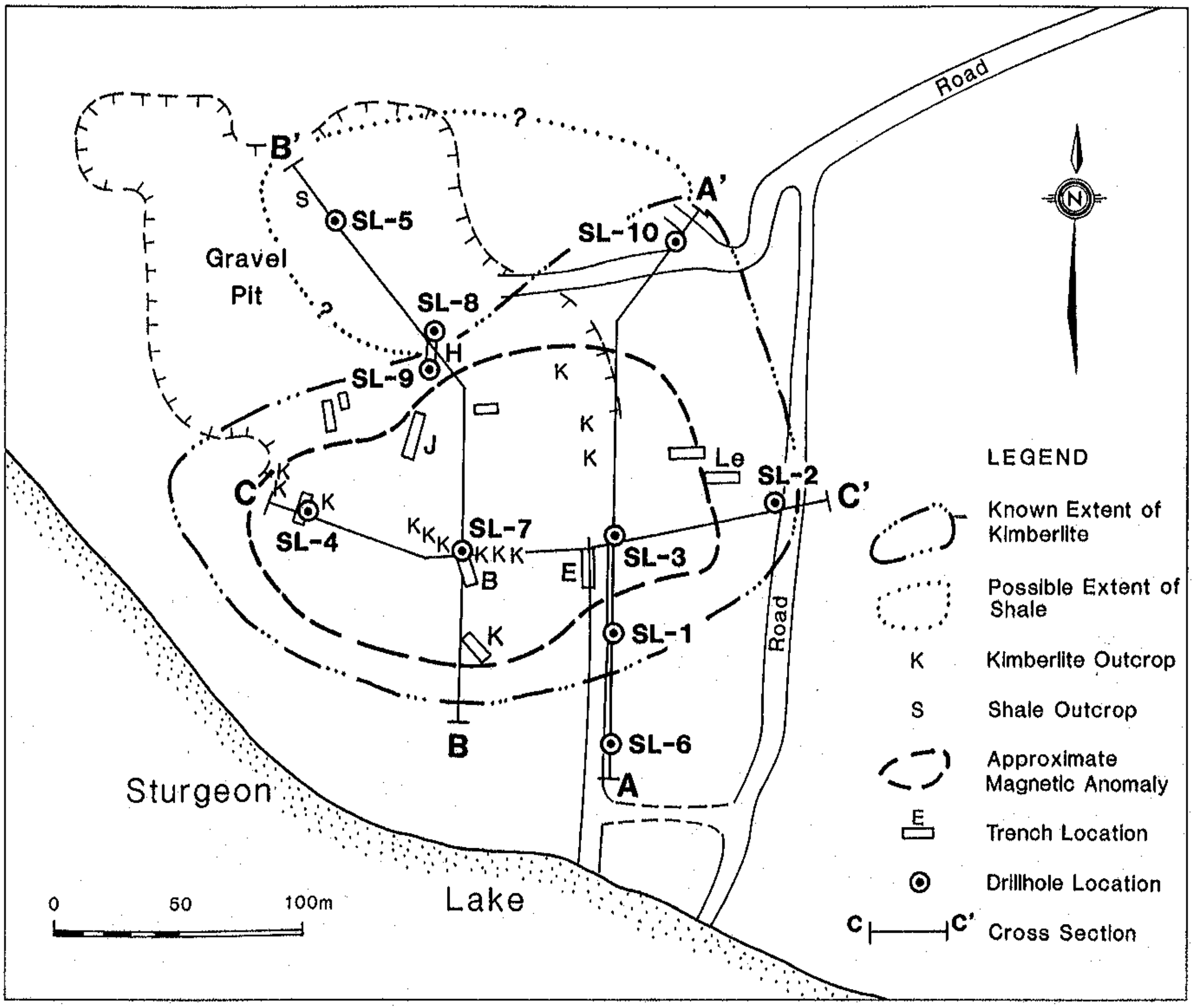

Fig. 2. Summary of the exploration work undertaken on the Sturgeon Lake 01 kimberlite. The cross sections shown by lines A, B and C are presented in Figure 4.

ure 3. Broadly similar anomalies were obtained for Ca, Cr, Co, and Mg. The samples on the southern flank of the body are clearly anomalous.

A biogeochemical study (Dunn, 1993) was conducted using vegetation samples collected from an array of sites similar to those shown in Figure 3. Geobotanical expression of the kimberlite was not evident, but ashed tissue samples from the three dominant woodland species adjacent to the kimberlite did show some enrichment in Ni, Rb, Sr, Cr, Nb, Mg, and P (and depletion in Mn and Ba).

Geology of the Kimberlite Block

Megascopic Features

Both the trenching and drilling results (summarized in Fig. 4) show that the Sturgeon Lake 01 kimberlite is at least 200 m by 125 m in size and up to 40 m thick. The kimberlite is somewhat larger than the magnetic anomaly (Fig. 2). The kimberlite margins dip steeply under the glacial till along the northern, northwestern, and eastern margins; in the south the margin dips under glaciofluvial sediments. In many drillholes, the Quaternary sediments were found above, and more importantly, below the kimberlite (Fig. 4). This indicates that the kimberlite occurs within Quaternary glacial deposits. Soft shale (at least 110m by 90 m and up to 16 m thick) occurs adjacent to the kimberlite at its northern margin. Part of the kimberlite-shale contact (in Trench H) appeared to be sheared. Thin bodies of hard shale are present within the kimberlite and one occurs immediately below the kimberlite in drillhole SL-3 (Fig. 4). Two other shale bodies occur within the glacial overburden below the kimberlite in holes SL-1 and SL-2. In all the trenches and most of the drillholes, no contacts with bedrock were observed. In drillhole SL-2, bedrock was reached at 99.1 m below surface (Fig. 4).

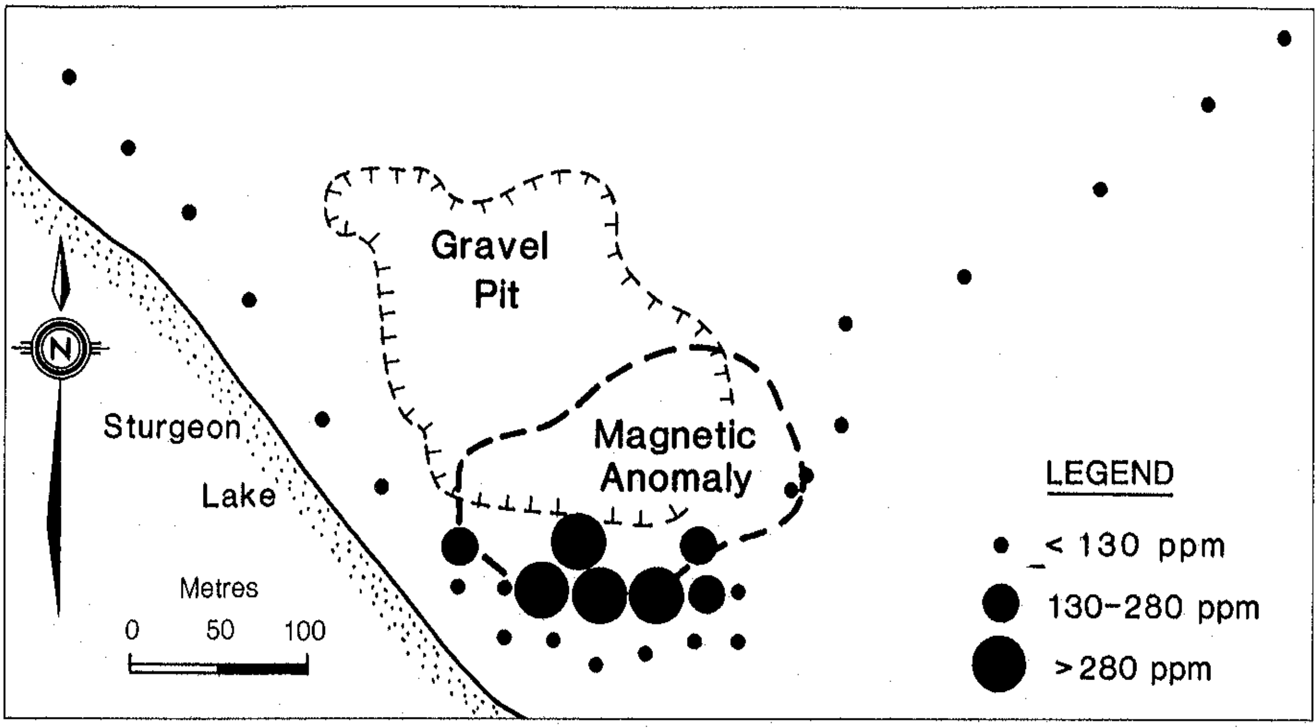

Fig. 3. Ni anomalies from geochemical soil sampling in the vicinity of the Sturgeon Lake 01 kimberlite.

The kimberlite observed in outcrop and in the trenches is variable in character and most conspicuously in the degree of alteration. Weathering of the kimberlite is most pronounced near the edges of the body. In some areas the kimberlite is very fresh (e.g., Trench B and adjacent outcrops) while in others it is very altered (e.g., Trench E). As a result, it was difficult to correlate the kimberlite between trenches. Most of the kimberlite contains minor amounts of xenoliths of shale and carbonates (mainly <5 cm in size). In contrast, the kimberlite in Trench K contained 20% xenoliths, while in Trench E it contained up to 50% black shale xenoliths. In Trench J the kimberlite displays plane parallel layering (up to 60 cm thick with a dip of 35 degrees to NNW) which reflects variation in grain size (Fig. 5). Xenoliths are less common in the finer grained kimberlite. A few examples of similar layering occur elsewhere in the kimberlite block.

Macroscopic Features

Representative kimberlite samples were collected from the trenches and divided into two broad groups. The first group of samples represents the most common rock type. These samples range from partly to extremely altered. The partly altered samples have an overall medium green-gray color and discernible primary features show that they are clast-supported fragmental rocks composed of igneous fragments, single mineral grains and country rock xenoliths (Fig. 6). The proportions of the different constituents vary among the samples. Green igneous fragments up to 3 cm in size form up to 50% of the rock. The fragments have sharp irregular outlines and are composed of pseudomorphs after olivine set in a fine grained matrix. The next most common constituent of these rocks are single grains of olivine, which range up to 7 mm in size. Some primary brown mica, ilmenite and garnet occurs, both within the fragments and as single grains. The garnet grains have variable colors typical of those found in kimberlites, and some have thin kelyphitic rims. Mantle-derived minerals in heavy mineral concentrates prepared from rock samples include peridotitic and eclogitic garnets, picro-ilmenite, chromite and clinopyroxene (GSC Open File, 1989). Xenoliths of Cretaceous shale and Palaeozoic carbonate have angular shapes. The interclast matrix comprises a lighter colored material. Where layering was observed there is a variation in clast size (from <2 mm up to 5 cm) between adjacent layers. The alteration in these samples includes carbonatization as well as patchy replacement by both magnetite and another more abundant mineral which occurs as elongate green grains that can have a distinctive vermiform habit (Fig. 7D). Although less well preserved, the primary features in the extremely altered samples suggest that they are similar rock types to those just described. These samples have a lighter green-gray color and the secondary vermiform mineral is more common and conspicuous. This mineral can completely replace the original rock, obliterating all primary features. An X-ray diffraction pattern for this mineral suggests that it is clinochrysotile. In contrast, Nixon et al. (1993) suggest that an optically similar mineral from this locality is antigorite. It should be noted, however, that such secondary material is commonly composed of more than one mineral. Some apparently finer portions in some samples may reflect origi-

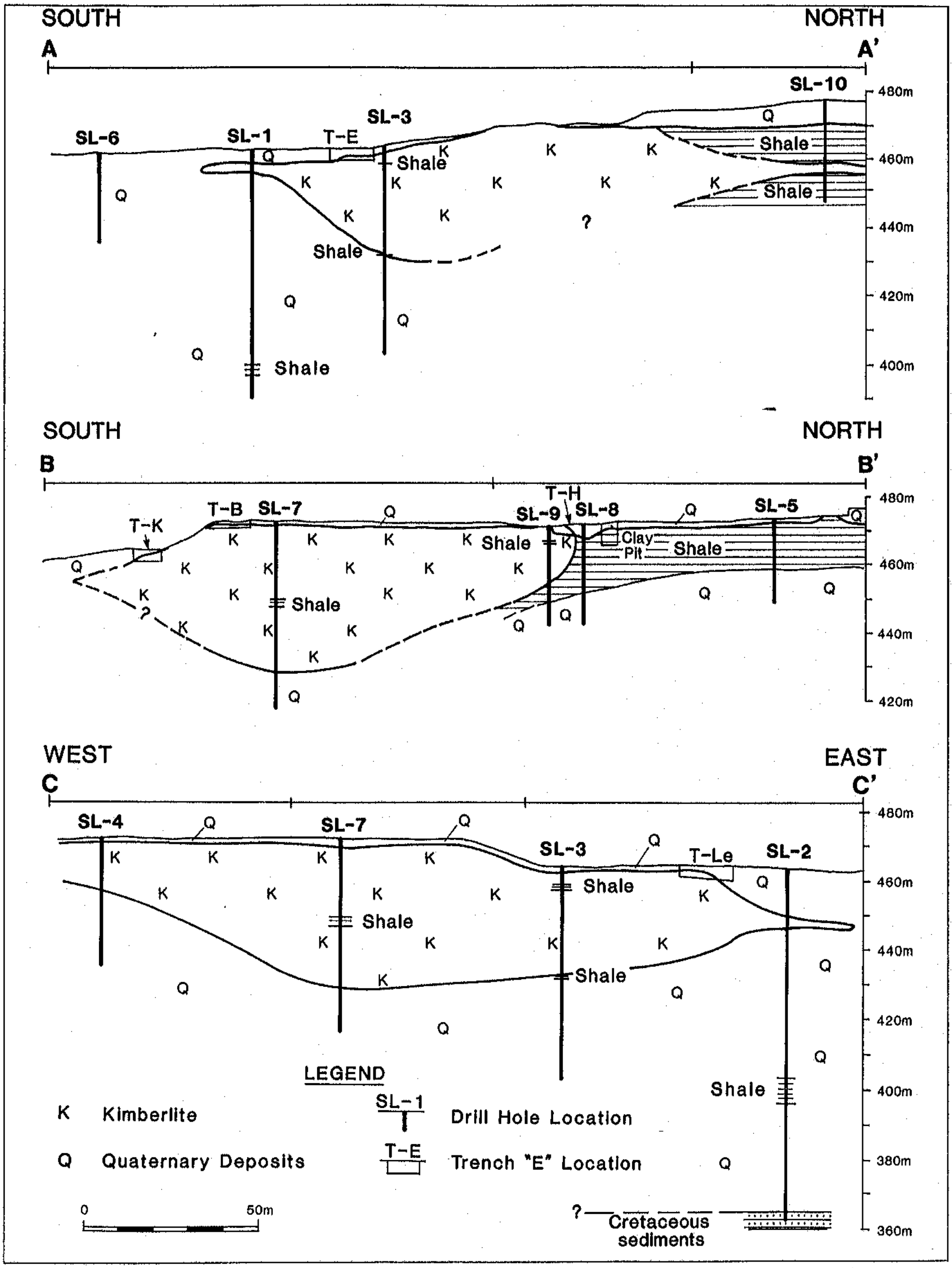

Fig. 4. Cross sections of the Sturgeon Lake 01 kimberlite summarizing the main geological features based on information from the outcrops, trenches and drillholes shown in Figure 2.

nal layering. Interestingly, the secondary vermiform mineral can be oriented perpendicular to the layering.

The second group of samples is fresh and very dark green-gray in color. Although primary features are difficult to observe due to the lack of color contrast, they are similar to those described for the first group of samples. In contrast to the altered samples, fresh olivine is very common, both within the igneous clasts and as single grains.

Fig. 5. Bedding in Trench J of the Sturgeon Lake 01 kimberlite (location shown in Fig. 2). Pocket knife for scale.

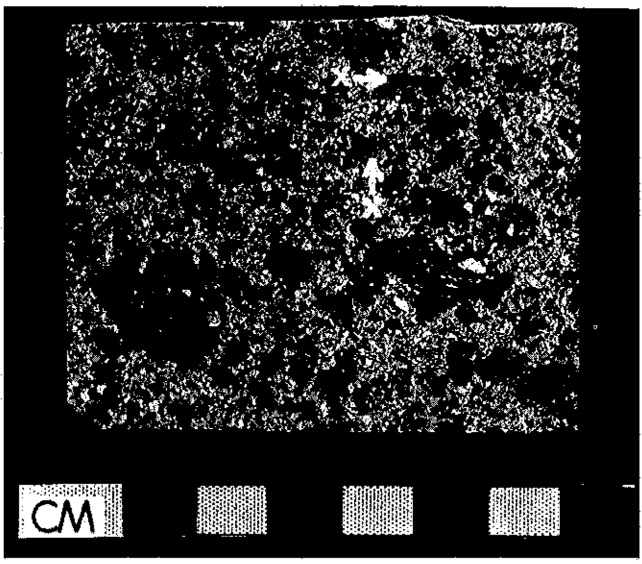

Fig. 6. Volcaniclastic kimberlite composed of dark colored irregular kimberlite fragments and common single grains of altered olivine that dominate the lighter colored areas between the fragments. Similar light colored olivine pseudomorphs occur within the kimberlite fragments. Two small xenoliths (x) of Palaeozoic carbonates are present.

Age

An Rb/Sr age determination was carried out for the freshest kimberlite available, a sample from Trench B (analysis by E. Barton and C.B. Smith of the Bernard Price Institute of Geophysics, University of the Witwatersrand). Two mica macrocryst separates were prepared from the sample (which contained abundant fresh olivine). Rb/Sr isotopic model ages of 105 Ma and 104 Ma were determined for the two separates assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.704. The agreement between the two values suggests that the determinations are reliable. If an initial ratio of 0.708 is used, the determined age decreases to 95 Ma. Hegner et al. (in press) report a five-point Rb/Sr isochron age of 98+/-0.5 Ma (mswd = 1.4) for micas taken from very fresh kimberlite in the outcrop near Trench B (the initial $^{87}Sr/^{86}Sr$ ratio was found to be 0.7063). The ages determined in these studies are therefore roughly comparable. It is presumed that the age of 98 Ma (Hegner et al., in press) is the most accurate.

Table 2. Whole rock analyses of the Sturgeon Lake 01 kimberlite

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5			
1	31.4	0.49	0.45	5.71	0.12	27.4	10.7	0.06	0.04	0.09			
2	28.9	0.49	0.60	7.34	0.13	22.8	16.2	0.06	0.22	0.10			
3	30.3	0.43	0.60	6.57	0.10	30.2	8.91	0.04	0.05	0.08			
4	23.5	0.43	0.35	5.80	0.14	17.9	22.9	0.03	0.08	0.08			
	Y	**U**	**Th**	**Rb**	**Sr**	**Ba**	**Zr**	**Nb**	**Ni**	**Cr**	**Co**	**Cu**	**Zn**
1	10	<10	11	13	177	121	46	83	1100	998	57	<10	45
2	<10	<10	<10	14	273	232	16	61	1270	984	68	17	49
3	<10	<10	<10	<10	266	71	26	62	1120	965	60	<10	47
4	<10	<10	<10	22	252	58	10	41	1230	911	65	<10	44

Analyses by X-ray Assay Laboratories, Don Mills, Ontario.
Major elements are in wt% and trace elements in ppm. Samples are from the trenches shown in Figure 2.

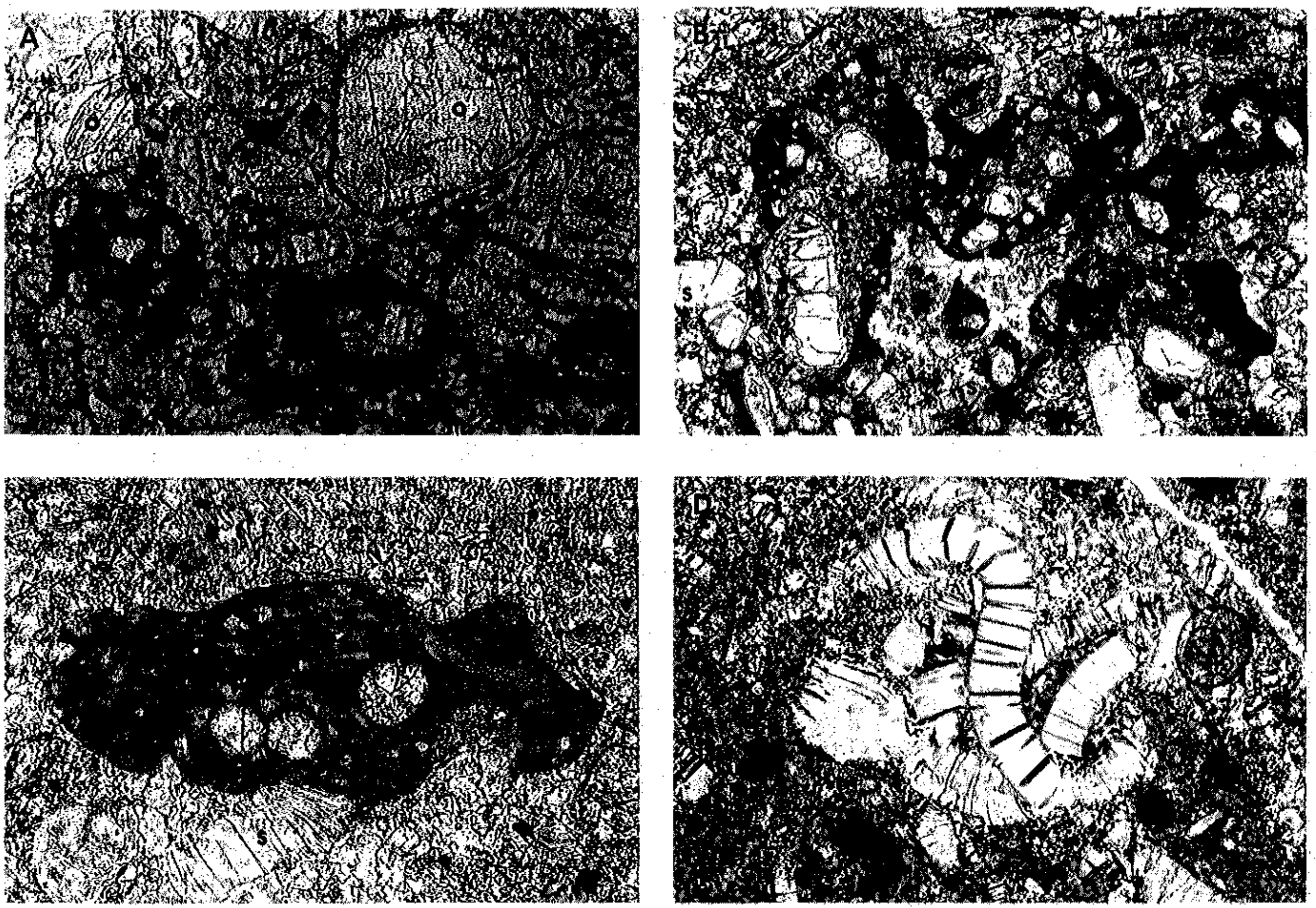

Fig. 7(A). Photomicrograph of fresh kimberlite from Trench B showing the volcaniclastic texture. The rock consists mainly of clast supported single grains of fresh olivine (o) which are mostly anhedral macrocrysts but some smaller euhedral grains are present. Other constituents include a single grain of opaque ilmenite and a large dark fragment of kimberlite (f) composed of matrix supported olivines in a fine grained groundmass. One much smaller clast of the second type is shown by the arrow. The inter-clast matrix is composed of mainly carbonate. Field of view = 4 mm [plane polarized light (PPL)].
Fig. 7(B) This sample is similar to that shown in (A) but contains more abundant dark fragments of kimberlite, all of which comprise the larger type. These fragments have outlines ranging from relatively smooth sub-rounded to more irregular curvilinear or amoeboid. A few spherical vesicle-like structures occur within the largest clast and distorted grains of a secondary vermiform mineral(s) are also present. Field of view = 4 mm (PPL).
Fig. 7(C). An example of the smaller type of kimberlite clast as in Fig. 7A. It has a curvilinear outline and is composed of fine opaque grains of spinel in a groundmass of cryptocrystalline carbonate. Some spherical vesicle-like structures are also present. The inter-clast matrix is composed of much coarser grained carbonate. Minor amounts of the secondary vermiform mineral(s) are also present. Field of view = 1.5 mm (PPL). Sample is from Trench B.
Fig. 7(D). Vermiform secondary mineral showing distinctive texture. Preliminary XRD data suggests that it is clinochrysotile. Field of view = 1.6 mm (PPL).

Palynology

Three samples from the main shale outcrop to the north of the kimberlite outcrop (shown in Fig. 2) were examined by S. de Gasparis of Palynex, Calgary, Alberta (ages after Williams et al., 1993). One sample was assessed as late Albian (~ 99 Ma to 97 Ma) and a second as late Albian or possibly Cenomanian (~ 99 Ma to 93 Ma). All three shales were deposited under marine conditions. The two dated shales were deposited in an open marine environment, probably in relatively deep water.

Two samples of shale xenoliths from within the kimberlite were also examined by S. de Gasparis. One was assessed to be Albian or older (Trench E) and the other middle to late Albian (~ 102.5 Ma to 97 Ma; from Trench K). The latter shale was deposited in a relatively deep marine setting while the former was probably deposited in shallower water, perhaps in an estuarine environment. The thermal maturation of the shale within the kimberlite and the shale to the north are similar, both suggesting that the shales have only been subjected to temperatures of less than 30°C (TAI = 1.5). This suggests that the host kimberlitic material was 'cold' before association with any of the shale. Limited work on the limestone xenoliths from within the kimberlite suggest that at least some are derived from the Middle Devonian Winnepegosis Formation, while a single sample may be Silurian-Ordovician in age (D.M. Lane, Saskatchewan Energy and Mines, pers. comm., 1989).

Two of three samples of kimberlite from the trenches yielded only sparse organic remains which consisted of mainly degraded plant fragments and very few microfossils.

The age of the assemblages could not be accurately determined but it is tentatively suggested to be Maastrichtian to Late Cretaceous. One sample yielded only non-marine organic material, while the other contained both marine and non-marine remains. The thermal maturation of all samples is similar (TAI = 1.5 to 2) suggesting that the kimberlite attained maximum temperatures of only 50°C since incorporation of the organic material.

Whole Rock Geochemistry

Samples of kimberlite from the trenches were analyzed for major and trace elements by XRF spectrometry (Table 2). Although these samples are volcaniclastic rocks displaying variable alteration, many aspects of these compositions (e.g., SiO_2, MgO, CaO, Na_2O, K_2O, Ni, and Cr) are generally in keeping with values reported from other kimberlite occurrences (e.g., Smith et al., 1985). Other elements have lower concentrations than those typical of kimberlites (see Discussion).

Microscopic Features

The kimberlitic rocks are composed of two main types of igneous fragments intermixed with abundant single mineral grains (Fig. 7A). The larger, and most conspicuous, type of igneous fragment (Figs. 6 and 7B) is composed of two generations of olivine (macrocrysts and more common phenocrysts) in a fine-grained groundmass (grains <0.2 mm in size) which contains common spinel, less common pale orange-brown phlogopite laths, minor apatite and altered perovskite. These minerals are set in an interstitial base composed of very fine grained carbonate (<0.02 mm) and/or serpentine. No evidence for groundmass monticellite was observed. A few phenocrysts of mica (up to 0.5 mm) are present in some samples. The igneous fragments have sharp outlines which may be smooth to irregular and, in some instances, curvilinear (Fig. 7B). The olivines within the igneous fragments have a matrix-supported texture. The modally less abundant and smaller second type of fragment (<0.5 mm in size) is isolated from the larger type (Fig. 7A) and no composite examples were observed. The smaller fragments are composed of a few olivine grains, usually pseudomorphs, in a groundmass of spinel and phlogopite set in a base which commonly comprises cryptocrystalline carbonate as well as serpentine (Fig. 7C). There is considerable variation in the texture of these clasts. Both types of fragments contain spherical vesicle-like structures which are now infilled by carbonate or serpentine (Figs. 7B and C). The small fragment type in particular resembles vesicular glassy lapilli. The nature of the kimberlite from Trenches E and K appears to be different and could reflect the large megascopic variations in content of xenoliths.

Single mineral grains, mainly olivine, are usually more common than the igneous fragments (Fig. 7A). The olivine grains are mainly anhedral and belong to the macrocryst suite, although some occur as phenocrysts. The olivines, when altered, are mostly composed of serpentine or carbonate. Undulose extinction in some fresh olivine macrocrysts shows that they are xenocrysts. Other mantle-derived xenocrysts occur in variable proportions and include ilmenite, garnet, and spinel. Neither the igneous clasts nor the mineral grains appear to be fragmented or abraded. Xenolithic material is not common and occurs as separate clasts. Most of the samples are poorly-sorted (Figs. 7A and B) but variation in overall clast size between samples (and occasionally within them) reflects the megascopic layering. The inter-clast matrix in the fresh samples is composed mainly of carbonate (Figs. 7A and B), whereas in the altered samples it appears to be dominated by probable 'primary' serpentine.

Carbonate has different modes of occurrence in these rocks. It occurs as a coarse-grained mosaic in the inter-clast matrix and as a very fine-grained mosaic in the groundmass of the igneous clasts. In both these cases the carbonate appears to be the original constituent. However, the paragenesis of carbonate in kimberlites is notoriously difficult to determine. Secondary carbonate also occurs both within olivine pseudomorphs (where it has a different texture with an intermediate grain size) and along cleavage partings within some of the secondary vermiform mineral.

The kimberlite pebbles from 10 km to the SE of the Sturgeon Lake 01 kimberlite closely resemble both the fresh and the altered rocks described above. The altered rocks contain some of the secondary vermiform mineral.

Discussion

Rock Type Classification

Primary features in these rocks include anhedral macrocrysts and/or xenocrysts of olivine and smaller euhedral phenocrysts which resemble the two generations of olivine that are characteristic of kimberlites. Other macrocrysts include ilmenite, garnet, spinel and phlogopite. The appearance of the garnets and the compositions of garnet, ilmenite, spinel and clinopyroxene macrocrysts are similar to those found in other kimberlites worldwide (GSC Open File, 1989). The lack of a crystalline groundmass precludes strict petrological or mineralogical classification. Observed groundmass minerals in the igneous clasts include spinel, phlogopite, perovskite, apatite, serpentine and carbonate. All the observed features are characteristic of kimberlites, although the small vesicular clasts are atypical of most kimberlites elsewhere. The nature of the groundmass minerals and mantle-derived xenocrysts suggests that these rocks are archetypal or Group 1 kimberlites (cf. Woolley et al., 1996). The determined initial $^{87}Sr/^{86}Sr$ ratio of 0.706, however, is intermediate between that of Group 1 and Group 2 kimberlites.

Textural Classification

The rocks are composed of varied igneous fragments, single mineral grains and some xenoliths, and can be termed volcaniclastic (AGI Glossary) kimberlites. The macroscopic layering, which reflects clast size variations, represents bedding and shows that the rocks are crater-facies kimberlite. This conclusion is supported by the irregular-to-curvilinear outlines or amoeboid shapes of the larger kimberlite fragment type, which show that they must be extrusive lapilli rather than globular segregations, pelletal lapilli or autoliths as occur in diatreme- and hypabyssal-facies kimberlites. No hypabyssal-facies kimberlite appears to be present at this locality (in contrast to preliminary results by Scott Smith, in GSC Open File, 1989). The igneous fragments also have cryptocrystalline or quenched groundmasses that sometimes contain vesicle-like structures. In addition, the olivines within the igneous clasts are matrix supported, as typically found in magmatic kimberlite, whereas the single olivine grains are clast supported. The smaller more vesicular and glassy-looking clast type (Fig. 7C) strongly resembles juvenile lapilli in many crater-facies rocks. These various features show that the kimberlite fragments have formed by pyroclastic processes and, as such, can be termed juvenile lapilli.

Outside of the igneous clasts, the single grains are predominantly olivine macrocrysts. There is a notable paucity of olivine phenocrysts and groundmass material that should be associated with these macrocrysts. The missing groundmass and olivine phenocrysts were probably present during eruption as coarse ash-sized material that was physically separated from the coarser constituents. These features show that some sorting must have occurred, as indicated by the bedding. Interestingly, the contents of some of the whole rock major and minor elements (TiO_2, Al_2O_3, Rb, Sr, Ba, Zr, and Nb; Table 2) are lower than those in a typical kimberlite. In hypabyssal kimberlites, these elements mainly reside in groundmass constituents rather than in the macrocrystal phases. The reduced values are probably a reflection of the lack of kimberlite groundmass in these rocks. Classification of the Sturgeon Lake 01 body as crater-facies kimberlite is further supported by palynological evidence which shows the rocks cannot have been subjected to temperatures greater than 50°C since incorporation of the organic material both in the kimberlite and the associated shale.

Mode of Emplacement

The general geological relationships of the Sturgeon Lake 01 kimberlite (Fig. 4) are similar to those of the Sturgeon Lake 02 kimberlite (Scott Smith, 1995), suggesting that the former is also a glacially-transported megablock. This conclusion is supported by the 98 Ma age of the Sturgeon Lake 01 kimberlite, which is much older than the surrounding Quaternary glacial sediments. It is not clear if the kimberlite is formed of one or more glacial blocks.

The 99 Ma to 93 Ma marine shales adjacent to the northern limit of the Sturgeon Lake 01 kimberlite must also represent glacially transported material. The shale is similar in age to the kimberlite and must represent either the upper country rock to the kimberlite crater from which this block was derived, or sediments overlying the kimberlite crater. The probable shearing observed in one part of the shale-kimberlite contact suggests that the shale represents one or more juxtaposed glacial blocks, as also found at Sturgeon Lake 02 (Scott Smith, 1995). The other separate shale intersections deeper within the glacial sediments presumably represent earlier glacially transported blocks (Fig. 4). The shales occurring outside the kimberlite are soft while the small intersections of shale within the kimberlite are hard, and probably older, suggesting that they are xenolithic fragments incorporated into the kimberlite at the time of eruption. The different environments of deposition show that the xenoliths were probably derived from different stratigraphic levels within the country rock.

The Sturgeon Lake 01 and 02 kimberlites occur at the same level, about 460 m above sea level, and therefore are probably at a similar stratigraphic position within the glacial sediments. Sturgeon Lake 02 is overlain by 50 m of glacial material, but very little of this occurs over the Sturgeon Lake 01 body. This suggests that the kimberlites occur within Quarternary Strata (Table 1) of either the Floral Formation or the Sutherland Group, as the Battleford Formation is not known to reach this thickness. Interestingly, the glacial megablock at Red Deer Hill appears to have been formed by the Battleford glacier (Christiansen and Sauer, 1993). Isolated shale blocks occur about 50 m below the kimberlite at 400 m above sea level at both Sturgeon Lake 01 and 02, and therefore appear to be at a similar but earlier stratigraphic level within the deeper glacial sediments. The basal shear plane of the Red Deer Hill megablock also occurs at 400 m above sea level.

Mode of Formation

It was suggested above that the igneous fragments which occur in the kimberlitic rocks formed by pyroclastic processes. In this part of Saskatchewan at around 98 Ma, marine conditions prevailed in the Great Western Interior Seaway (Caldwell and Kauffman, 1993). Based on the close association of marine shales of a similar age, both as apparent country rock and as xenoliths within the kimberlite, it has been suggested that these kimberlites were submarine eruptions (Gent, 1992; Nixon et al., 1993). However, the presence of highly vesicular lapilli, the smooth curvilinear or amoeboid shapes of some of the larger lapilli, the paucity of inter-mixed shale, and the lack of reworking (see below) instead imply that at least some of the eruptions forming this body were subaerial. This suggestion is supported by the fact that one kimberlite sample contained only non-marine organic remains.

Various features suggest that these crater-facies deposits have not undergone significant reworking. These features include the lack of abrasion or breakage of the often fragile juvenile lapilli, the presence of angular xenoliths and internally cracked high pressure mantle-derived minerals (olivine and garnet), the paucity of fines and extraneous material, the low packing density, the presence of plane parallel bedding, and the absence of other sedimentary structures. Many of the rocks can therefore be termed lapilli tuffs and coarse ash. Two very different types of juvenile lapilli are present in most of the samples examined (Fig. 7B versus 7C), which shows that at least two different phases or styles of eruption were involved in the formation of the kimberlite. Both types of juvenile lapilli occur in most of the rocks examined. Variations in their proportions may result, at least in part, from physical sorting due to their very different clast sizes. The larger clasts are generally dominant and fairly uniform in nature, suggesting that they represent juvenile lapilli formed during the eruptions from which these rocks were deposited. In contrast to the larger clast type, the smaller clasts are quite varied and could be derived from one or more earlier eruptions. It seems most likely that this mixing occurred by pyroclastic processes, but no composite lapilli were observed. Vesicular lapilli have not been observed previously in kimberlites (*sensu stricto*), except those at Sturgeon Lake 02 and Fort à la Corne. The nature of the lapilli in all these kimberlites suggests that they result from a different style of eruption which deviates from the main kimberlite model (as reviewed by Mitchell, 1986). A second kimberlite emplacement model has been proposed for the Fort à la Corne province (Scott Smith et al., 1994) which probably also applies to the Sturgeon Lake kimberlites.

Comparison with Sturgeon Lake 02

The overall nature of the rocks and the resulting conclusions relating to the formation and emplacement of the Sturgeon Lake 01 and 02 kimberlites are very similar. The marine shale which occurs just below the Sturgeon Lake 02 kimberlite was dated at Albian, possibly late Albian (Scott Smith, 1995), which is similar in age to the shale adjacent to Sturgeon Lake 01 block. These two (or more) kimberlite blocks and associated shales probably were derived from within the same kimberlite province and transported by the same glacial event. The larger juvenile lapilli found in the Sturgeon Lake 01 kimberlite were not observed in samples examined from the Sturgeon Lake 02 body. This suggests that the two kimberlite blocks are derived from different areas of a kimberlite pipe or pipes.

Conclusions

The Sturgeon Lake 01 body was the first kimberlite to be discovered in the Canadian Prairies. The body was discovered by heavy mineral sampling, but it also has associated geophysical and geochemical anomalies. The kimberlite, which is diamondiferous but sub-economic, represents a glacially transported megablock of crater-facies volcaniclastic kimberlite, which has an age of 98 Ma. The block is at least 200 m by 125 m in size and up to 40 m thick, and occurs within 100 m of glacial sediments which overlie Cretaceous bedrock shale. Marine shale of Albian age (99 Ma to 93 Ma) occurs adjacent to the kimberlite on its northern side and extends for at least 110 m by 90 m (up to 16 m thick). This shale appears to represent a separately transported glacial block which was deposited adjacent to the kimberlite. It is not clear if the kimberlite and the adjacent shale each represent single or compound glacial blocks.

Although the kimberlite was formed during a period of general marine deposition, it is composed of volcaniclastic material that formed in subaerial conditions. The Sturgeon Lake kimberlites are partly bedded pyroclastic airfall lapilli tuffs and coarse ash composed mainly of juvenile lapilli and single grains of olivine. The rocks display variations in the relative proportions of the two main types of juvenile lapilli, and in the abundance of mantle-derived xenocrysts and country rock xenoliths. It is not clear if these variations represent different kimberlite rock types or result from physical sorting during deposition. A preliminary identification of an unusual, but commonly abundant, vermiform secondary mineral suggests that it is clinochrysotile.

Both the Sturgeon Lake 01 and 02 kimberlites contain vesicular lapilli which have not been documented in kimberlites outside Saskatchewan. These lapilli were probably formed during a style of eruption similar to that suggested for the Fort à la Corne province (Scott Smith et al., 1994) which contrasts to that of most other documented kimberlites and the 'classic' kimberlite model. The Fort à la Corne bodies are shallow maar-like craters which have no associated diatreme. The Sturgeon Lake rocks are most similar to one type of kimberlites at Fort à la Corne which are considered to have infilled craters during Hawaiian and Strombolian style eruptions. The presence of two types of juvenile lapilli at Sturgeon Lake 01 suggests that the kimberlites formed from at least two different phases of eruption. There is no evidence at Sturgeon Lake for the other type of Fort à la Corne kimberlite, one which is considered to have formed from much more explosive eruptions resulting in mega-graded beds of pyroclastic material that contain a different type of pelletal lapilli.

The overall geology of the kimberlite and shale glacial blocks at Sturgeon Lake 01 is analagous to that at Sturgeon Lake 02 (Scott Smith, 1995) suggesting that they probably were derived from within one kimberlite province located somewhere in the extensive area of Cretaceous bedrock shale in central Saskatchewan. A different type of juvenile lapilli, however, dominates at Sturgeon Lake 01, suggesting that the two kimberlite blocks represent different areas within one or more of the original kimberlite pipes. The rocks at Sturgeon Lake and Fort à la Corne have (1) formed from similar 'typical' Group 1 kimberlite magmas which cannot be distinguished based on available information, and (2) display unique textures reflecting a similar mode of near surface emplacement which contrasts to that of the 'classic' kimberlite model. These similarities suggest that the glacially transported blocks at Sturgeon Lake were derived from the Fort à la Corne province. If so, these megablocks must have been transported a minimum of 45 km, an unusually large distance which is much greater than the 10 km proposed for the nearby Red Deer Hill thrust block (Christiansen and Sauer, 1993). However, Scott Smith (1995) suggests that the different mode of emplacement of these kimberlites is most likely to be a reflection of the country rock geology and not the nature of the kimberlite. If so, any kimberlites erupting in this general area of Saskatchewan under similar near surface conditions could form texturally similar rocks. During the Cretaceous, however, marine conditions prevailed in this general area and submarine kimberlites would presumably be very different texturally.

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