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LAKE ELLEN KIMBERLITE, MICHIGAN, U.S.A.

by

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ABSTRACT

The recently discovered Lake Ellen kimberlite, in northern Michigan, indicates that bedrock sources of diamonds found in glacial deposits in the Great Lakes area could lie within the northern U.S. Magnetic surveys show a main kimberlite 200 m in diameter and an adjacent body 25 x 90 m(?). The kimberlite cuts Proterozoic volcanic rocks that overlie Archean basement, but is post-Ordovician in age based on abundant Ordovician(?) dolomite inclusions. Xenocrysts and megacrysts are ilmenite (abundant, 12.5-19% MgO), pyrope-almandine and Cr-pyrope (up to 9.3% Cr_2O_3), Cr-diopside (up to 4.5% Cr_2O_3), olivine (Fo 91), enstatite and phlogopite. The kimberlite contains fragments of crustal schist and granulite, as well as disaggregated crystals and rare xenoliths of eclogites, garnet pyroxenites and garnet peridotites from a heterogeneous upper mantle. Eclogites, up to 3 cm size, show granoblastic equant or tabular textures and consist of jadeitic cpx (up to 8.4% Na_2O, 15.3% Al_2O_3), pyrope-almandine, ± rutile ± kyanite ± sanidine ± sulfide. Garnet pyroxenite contains pyrope (0.44% Cr_2O_3) + cpx (0.85% Na_2O, 0.53% Cr_2O_3) + Mg-Al spinel. Mineral compositions of rare composite xenocrysts of garnet + cpx are distinctively peridotitic, pyroxenitic or eclogitic. Calculated temperatures of equilibration are 920-1060 °C for the eclogites and 820-910 °C for the garnet pyroxenite using the Ellis-Green method. Five peridotite garnet-clinopyroxene composite xenocrysts have calculated temperatures of 980-1120 °C using the Lindsley-Dixon 20 kb solvus. Spinel pyroxenite and clinopyroxene-orthopyroxene composites have lower calculated temperatures of 735 °C and 820-900 °C, respectively. Kyanite-bearing eclogites must have formed at pressures greater than 18-20 kb. Using the present shield geotherm with a heat flow value of $44 mW/m^2$ for the time of kimberlite emplacement, the eclogite temperatures imply pressures of 35-48 kb (105-140 km) and the garnet pyroxenite temperatures indicate pressures of 24-29 kb (75-90 km). Temperatures of two peridotitic garnet-cpx composite xenocrysts if on a shield geotherm, imply pressures within the diamond stability field.

INTRODUCTION

The Lake Ellen kimberlite is located in the upper peninsula of Michigan, near the Wisconsin-Michigan border (Fig. 1). It is about 15 km northeast of Crystal Falls, Michigan and about 1.5 km west of Lake Ellen. The kimberlite was first recognized about 15 years ago by an exploration geologist. A recent description of the kimberlite, its geologic setting, and magnetic and gravity traverses (Cannon and Mudrey, 1981) emphasizes its significance as indicative of possible bedrock sources of the widespread diamond finds in alluvial and glacial deposits in the Great Lakes area. Cannon and Mudrey (1981) also summarize other occurrences of localized subsidence or intense deformation in the region that may be related to emplacement of kimberlite or to other diatreme-forming processes. In the early 1950's, a ground magnetometer survey found erratic high values over part of the kimberlite, but there were no exposures of kimberlite at that time and the erratic values were ascribed to the common problem of boulders of iron formation in the glacial deposits (Gair and Wier, 1956).

The kimberlite cuts across lower Proterozoic X metavolcanic rocks, southeast of the Amasa dome of Archean gneiss. The age of the kimberlite has not yet been determined, but it is post-Ordovician as it contains abundant inclusions of fossiliferous Ordovician(?) dolomite similar to the Black River Group. The nearest exposure of the Black River Group is now about 60 km away, and the Black River Group would have been at least 200 m stratigraphically above the present surface when the kimberlite was intruded (Cannon and Mudrey, 1981).

Most of the area is covered by glacial till and alluvium, and the kimberlite has only four outcrops, three of which are in a logging road. The largest outcrop is 2 by 4 m in size, and like the others, consists mainly of small fragments of altered kimberlite.

A ground magnetometer survey was done by the authors July 12-15 and August 12, 1980, and August 9, 1981 using a Geometrics model G-812/826 proton magnetometer. A grid of stations at intervals of 50 feet (15 m) and locally 25 feet (7.5 m) or less, was marked by measuring distances with a tape along lines established using a Brunton compass. East-west lines 100 feet (30.5 m) apart were surveyed on each side of a central north-south line. Additional stations halfway between those east-west lines were located by tape measurement from each line. Readings every 1-1.5 hours at a primary base station 370 feet (115 m) south of the kimberlite, or at a secondary base station, were used to make linear corrections for diurnal variations. Magnetic values are believed to be accurate to $\pm$ 3 gammas. Two pipes have been identified and contoured (fig. 2) from the survey. The main pipe is roughly circular and about 200 m in diameter. A smaller, satellitic body to the northeast is less well defined, but is about 25 by 90 m in size.

The kimberlite in the outcrops is mainly a rubbly, partially clayey material with many xenocrysts, lithic inclusions from shallow levels, and a few xenoliths of deeper origin. Several shallow pits were dug, and in a few, hard kimberlite was reached. The hard kimberlite is extensively serpentinized, and contains xenocrysts and xenoliths like those found in the loose rubble of the outcrops.

MEGACRYST-XENOCRYST SUITE

The suite of megacrysts (greater than 1 cm) are distinguished from the suite of xenocrysts (less than 1 cm) by their grain size. Megacrysts and xenocrysts which are contained in the kimberlite have been primarily selected from panned concentrates and from bag samples of loose material. Xenocrysts average 2-4 mm in size. The megacryst suite is composed of ilmenite, clinopyroxene, and garnet. Representative analyses of each are shown in Table 1. The xenocryst suite is more diverse, being composed of: ilmenite, garnet, clinopyroxene, orthopyroxene, phlogopite, and olivine. In addition, several composite xenocrysts of garnet-clinopyroxene and clinopyroxene-orthopyroxene have been found. These composites are equant mineral pairs, 1-2mm in size, which are embedded in each other as coexisting grains and are not intergrowths.

ILMENITES

The ilmenites analyzed thus far are mainly megacrysts. The megacrysts range in size from 1-3 cm, with most falling in the range 1-1.5 cm. The megacrysts are both multigranular and single grains. Many of the ilmenite megacrysts have a single grain 'core' surrounded by a multigranular rim. Four xenocrysts from panned concentrate (2-4 mm) and 5 xenocrysts (1 mm) picked from the kimberlite matrix have been analyzed. The MgO content in megacrysts and xenocrysts is high, ranging from 12.54 to 19.10 wt. %. The ilmenite grains have 45-60% geikelite component and 2-7% hematite component (Fig. 3A). This hematite component is slightly lower than other ilmenites from North American kimberlites (Fig. 3B). There is no distinct difference between Lake Ellen xenocryst and megacryst compositions, indicating that they may have been derived from the same region at depth. Cr_2O_3 - MgO compositions (Fig. 4) show a wide range of Cr_2O_3 contents (0.35-1.52 wt. %), and are more MgO rich than the ilmenites used by Haggerty (1975) in constructing the ilmenite parabola. Again, the ilmenite xenocrysts and megacrysts are not compositionally distinct. The MgO-rich, and Fe_2O_3-poor nature of these ilmenites indicates that they formed under reducing conditions and have not undergone extensive oxidation.

GARNETS

Garnets from Lake Ellen are predominantly found as xenocrysts. These xenocrysts encompass a range of colors and have been subdivided on the basis of color to identify any relationships or trends. The techniques of sorting and constraints on identifying the colors of the garnets were the same as those discussed by Hearn and McGee (1982). The color groupings used were: purple, red, pink, orange, red-orange, and light orange. The purple, red, and pink garnet groups tend to be more Mg-and Cr-rich than the three orange garnet groups (Figs 5 & 6). The orange, red-orange, and light orange garnets are close in Ca-Mg-Fe composition to the garnets from eclogite xenoliths (Fig. 5) and many are probably fragments from disaggregated eclogite inclusions. All of the purple, red, and pink garnets fall within the Ca-Mg-Fe field of garnets from Montana garnet peridotites (fig. 5) which is similar to peridotite garnets from other kimberlites. The purple, red, and pink garnets also are within or close to the CaO-Cr_2O_3 field of lherzolitic garnets (Sobolev, et. al, 1973) (Fig 6). This, combined with the higher Mg content (Fig. 5) indicates a peridotitic affinity for the purple, red, and pink garnets. No Cr-rich, Ca-poor garnets typical of garnets from diamond-bearing harzburgites (Boyd and Finnerty, 1980) have been found at Lake Ellen, perhaps because of the somewhat limited sampling of garnet xenocrysts and megacrysts.

Garnet megacrysts, not as abundant as xenocrysts, have been found in the loose rubbly material of the outcrops and in chunks of the hard kimberlite, dug from shallow pits. The megacryst analyzed so far is more similar to the peridotitic than to the eclogitic garnets (Figs. 5 and 6).

PYROXENES

The xenocryst suite from Lake Ellen includes abundant clinopyroxene and rare orthopyroxene. Several clinopyroxene megacrysts have also been analyzed (Table 1). The Na_2O and Cr_2O_3 contents of the megacryst and xenocryst clinopyroxenes can be used to distinguish associated xenolith types. The clinopyroxenes are eclogitic, pyroxenitic, and peridotitic in affinity (Fig. 7). Clinopyroxenes from eclogites have Na_2O contents which range from 4-8 wt. % and low Cr_2O_3 (less than 0.5 wt. %). Peridotitic clinopyroxenes have lower Na_2O (less than 5 wt. %) and high Cr_2O_3 contents (0.5-4.5 wt. %). Pyroxenitic clinopyroxenes have low Na_2O (less than 1 wt. %) and low Cr_2O_3 (about 0.5 wt. %) which respectively distinguishes them from eclogitic and peridotitic clinopyroxenes. Two groups of clinopyroxene xenocrysts, shown as dashed-line fields in Fig. 7, are similar, particularly in Cr_2O_3 content, to the clinopyroxenes from peridotites or to the clinopyroxenes from pyroxenites and megacrysts.

Orthopyroxene xenocrysts are rare compared to the clinopyroxenes. They contain about 4 wt. % Al_2O_3 and about 0.5 wt. % CaO. One orthopyroxene xenocryst appears anomalous because it contains 1.2 wt. % Al_2O_3 and 1.5 wt. % CaO, which is unlike any other orthopyroxene analyzed thus far from this kimberlite. The high CaO content indicates a high temperature of crystallization. All of the orthopyroxenes contain approximately 1 wt. % Cr_2O_3, suggesting disaggregation from a Cr-rich assemblage similar to that of the Cr-rich composite garnet-clinopyroxene xenocrysts.

OLIVINES

Most of the olivines in the kimberlite have been serpentinized, but a few fresh olivines have been found in kimberlite matrix and in panned concentrates. The olivines have a narrow range of forsterite content from $Fo_{90.5}$ to $Fo_{91.0}$, and contain an average of 0.38 wt. % NiO, suggesting that they are xenocrysts rather than phenocrysts (Dawson, 1980). They show no zonation from core to rim.

COMPOSITE XENOCRYSTS

The composite xenocryst suite is composed of two types of pairs: clinopyroxene-garnet and clinopyroxene-orthopyroxene. Although the grain size of the members of the pairs is rarely equal, they appear to be in equilibrium with one another. They are most likely grains from disaggregated xenoliths because 1) there is no alteration or kimberlite matrix between the grains, 2) they have an equant rather than intergrowth texture, and 3) neither is totally surrounded by the other as an inclusion. The compositions (Table 2) of the composite xenocrysts indicate derivation from eclogites, garnet pyroxenites, and peridotites.

In the garnet-clinopyroxene composites the color of the garnet grains was used as a guide to the xenolith type: purple garnets for peridotitic composites, and orange garnets for eclogitic composites. A greater number of peridotitic pairs were selected for analysis because garnet peridotite xenoliths have not yet been found and the composite grains have been used to represent a 'missing portion' of the xenolith population. As with the xenocrysts, the chromium content of both the garnet and clinopyroxene, and the sodium in the clinopyroxene are characteristic of the rock type from which they were derived. The clinopyroxenes from the garnet-clinopyroxene composites are higher in Na_2O and Cr_2O_3 than the clinopyroxene xenocrysts which have been analyzed (Fig. 7). This is most likely a result of limited or biased selection of the xenocrysts. Four of the five clinopyroxenes from composites are also distinctly more Cr-rich and Na-rich than clinopyroxenes from Montana garnet peridotites (Fig. 7) (Hearn and McGee, 1983), indicating an unusually Cr-Na-rich bulk composition for garnet peridotites represented in the Lake Ellen kimberlite.

The clinopyroxene-orthopyroxene pairs are peridotitic in nature with the clinopyroxenes containing about 1 wt. % Na_2O and 1 wt. % Cr_2O_3. The orthopyroxenes are very similar in composition to most of the orthopyroxenes found as xenocrysts (Al_2O_3 = 4 wt. %; CaO = 0.5 wt. %). On a Cr_2O_3 vs Na_2O plot (Fig. 7) the clinopyroxenes from cpx-opx composites fall within the field of clinopyroxenes from Montana garnet peridotites, unlike the clinopyroxenes from the clinopyroxene-garnet pairs which are much richer in both Na_2O and Cr_2O_3. These clinopyroxenes indicate two groups of peridotites at the Lake Ellen kimberlite.

The composite xenocrysts have been included with the xenoliths in plots and in temperature-pressure calculations. Although the composite xenocrysts give limited information compared to the complete mineral assemblage in xenoliths, the composite xenocrysts represent rock types which must also be present in the upper mantle.

LITHIC INCLUSIONS

Lithic inclusions in the Lake Ellen kimberlite consist of both crustal and upper mantle rock types. The crustal inclusion suite predominates and consists of dolomite, phyllite, amphibolite, altered gabbro, and a few granulites. This study has concentrated on the less abundant upper mantle inclusion suite consisting of eclogite, garnet pyroxenite, a spinel pyroxenite-peridotite, and a serpentinized peridotite inclusion containing clinopyroxene as the only remaining fresh phase. Representative analyses of phases are given in Tables 3,4,5, and 6.

ECLOGITE INCLUSIONS

The eclogite suite is the largest group of xenoliths collected from Lake Ellen, comprising about 85% of all the upper mantle xenoliths collected. The eclogites range in size from 0.5 cm fragments of inclusions to 3.0 cm inclusions. They have a granulitic texture, and most show a distinctive alteration of the clinopyroxenes. The eclogite assemblage consists of garnet + clinopyroxene + rutile ± kyanite ± sanidine ± corundum ± sulfide. The majority of eclogite samples contain only garnet, clinopyroxene, and rutile. The compositions of the garnets and clinopyroxenes in the eclogites are not significantly different when kyanite or sanidine are also present.

The garnets in the eclogites are generally orange, contain more iron than magnesium, and are widely scattered near the central part of a Ca-Mg-Fe ternary (Fig. 5), showing a range of 30% Fe component. This lack of clustering of garnet compositions from eclogites has been observed in other kimberlites as well (Meyer, 1977). The chromium content of the garnets is low (about 0.1 wt. %).

The clinopyroxenes in the eclogites, are mostly altered, appearing cloudy light green or almost white in hand specimen, and showing a very fine network of alteration in thin section (Fig. 8A). In most samples the grains still have unaltered cores which are visible in thin section and can be analyzed. The clinopyroxenes are very rich in sodium and aluminum. The sodium content ranges from 3-8 wt. % with most falling between 6 and 7 wt. % (Fig. 7). The aluminum content parallels the sodium, ranging from 10-16 wt. % with the average around 14 wt. % Al_2O_3. Chromium content of eclogitic clinopyroxenes is low, rarely reaching 0.10 wt. % (Fig. 7).

Rutile ranges in size from grains nearly 1.5 mm long to tiny needles included in clinopyroxenes. The rutile is red-brown to yellow-brown and is fairly pure although some contain as much as 1.5 wt. % FeO (Table 5). Kyanite occurs as small (1 mm), bladed grains which are very pale blue to white. In one sample (KB2-3), the kyanite has a preferred orientation (Fig. 8B). Kyanite contains approximately 0.3 wt. % FeO and up to 0.2 wt. % Cr_2O_3 (Table 5). Corundum has been found in only two samples so far, both of which also contain kyanite. The corundum occurs as small (0.05-0.6 mm) blades near kyanite and may be part of a reaction occurring during kimberlite ascent. It contains only minor amounts of Cr_2O_3 (0.2 wt. %), TiO_2 (0.2 wt. %), and FeO (0.3 wt. %). Sulfides occur as rounded grains (up to 0.8 mm size) and as smaller patches within the alteration between pyroxenes. They have not yet been analyzed but preliminary observations indicate that they contain more than one phase.

Potassium feldspar is present in 5 of the eclogites studied. The grains are up to 1.8 mm in size. A few of the feldspars show twinning, and a few also have minor alteration along the edges. The feldspar is very potassium-rich, containing 14-16 wt. % K_2O and only 0.3-1.3 wt. % Na_2O (Table 6). Barium content of these feldspars is significant; in four samples BaO is about 0.5 wt. % and in one it is about 2.0 wt. % (Table 6). Within each eclogite the barium in the feldspars is constant from grain to grain, and it does not appear to be zoned within the grains. The small grain size of the feldspars has precluded study by x-ray diffraction to determine the structural state. Based on the findings of other workers (Smyth and Hatton, 1977; Prinz, et al, 1975) and on the high calculated temperatures from garnet-pyroxene pairs, the feldspar is probably sanidine rather than orthoclase.

GARNET PYROXENITE

Garnet pyroxenite (1.5 cm size) has a granulitic texture and is partially serpentinized (Fig. 8C). It consists of garnet + clinopyroxene + spinel + sulfide. Although the garnet is slightly richer in MgO than many of the eclogitic garnets, it is not clearly distinguishable from them. However, the pyroxene can be used to distinguish the garnet pyroxenite and eclogite xenoliths because sodium is 0.8 wt. % and aluminum is 4 wt. % in the garnet pyroxenitic clinopyroxenes, much lower than they are in the eclogitic clinopyroxenes (Fig. 7; Table 4). The low chromium content of the pyroxene in garnet pyroxenite, 0.5 wt. %, distinguishes it from peridotitic clinopyroxene. The spinel in the garnet pyroxenite is red-brown to dark brown, has a grain size of 0.5 mm, and is nearly surrounded by garnet in the sample (Fig. 8C). It is Al-rich and Cr-poor, containing 55.7 wt. % Al_2O_3 and 9.7 wt. % Cr_2O_3 (Table 5).

SPINEL PYROXENITE-PERIDOTITE

One small (about 1.5 cm) sample has a fine-grained (0.25-1 mm) tabular to granular texture and is extensively altered to serpentine in the olivine rich part, giving it a banded appearance (Fig. 8D). Two thirds of the sample contains altered olivine, spinel, and clinopyroxene and was probably peridotitic when fresh. The remaining third of the sample is pyroxenitic containing spinel, clinopyroxene, orthopyroxene and a few fresh olivines. Black spinel occurs throughout the section, and shows some tendency to be concentrated in layers (Fig. 8D). It is an aluminum-rich spinel with about 8.5 wt. % Cr_2O_3, (Table 5) and slightly more iron than the spinel in the garnet pyroxenite. The clinopyroxene is fresh and its Cr_2O_3 and Na_2O contents are close to some of the clinopyroxene megacrysts and most of the clinopyroxene xenocrysts (Fig. 7). It contains about 1 wt. % Na_2O, 4.5 wt. % Al_2O_3, and 0.35 wt. % Cr_2O_3 (Table 4). The orthopyroxene is less abundant than the clinopyroxene and contains slightly less Al_2O_3 and CaO (3 and 0.2 wt. %, respectively) than most of the orthopyroxenes found as xenocrysts or as members of composite grains (Tables 2B,4).

TEMPERATURE AND PRESSURE CONSIDERATIONS

Temperatures were calculated for the xenoliths and composite xenocrysts using A.A. Finnerty's TEMPEST program. The Lindsley and Dixon (1976) 20 kb clinopyroxene thermometer was used for the peridotitic garnet-clinopyroxene composite xenocrysts. However, the Lindsley and Dixon thermometer could not be used for the other xenolith types because of the high Ca/(Ca+Mg) values of the clinopyroxenes. The Ellis and Green (1979) 30 kb garnet-clinopyroxene thermometer was used for the eclogites and garnet pyroxenites. The Wells (1977) thermometer, which does not require garnet and extends to lower temperatures than the Lindsley-Dixon thermometer, was used for clinopyroxene-orthopyroxene composite xenocrysts and for the spinel pyroxenite-peridotite. The Boyd and Nixon (1973) calcium in orthopyroxene thermometer was used for one high calcium orthopyroxene xenocryst.

Pressures can be directly determined only for those samples which contain orthopyroxene. The MacGregor (1974) barometer, which uses Al_2O_3 in enstatite, indicated pressure of 12.3 kb for the spinel pyroxenite-peridotite, and a pressure range of 13 to 17 kb for the clinopyroxene-orthopyroxene composite xenocrysts. Both are within the spinel stability field. However, because there is disagreement about the direction of slope of the Al_2O_3 isopleths in the spinel stability field (MacGregor, 1974; Obata, 1976; Dixon and Presnall, 1977), the pressures estimated using MacGregor's (1974) barometer may be incorrect or controversial. Although the pressures are useful for indicating derivation from the spinel stability field, rather than from the garnet stability field, the pressures were not used in constructing a pressure-temperature diagram for inclusions in the Lake Ellen kimberlite. Only the pressure calculated for the high calcium orthopyroxene xenocryst was used, as it indicated derivation from the garnet stability field.

Calculated temperatures have been projected onto the present day shield geotherm of 44 mW/m^2 for northern Michigan (Fig. 9). Assumption of a shield geothermal gradient is based on the lack of igneous activity in northern Michigan after Keweenawan volcanism in the late Proterozoic, except for post-Ordovician emplacement of kimberlite.

Highest equilibration temperatures were calculated for a clinopyroxene from an altered peridotite (1292 °C) and for a high calcium orthopyroxene xenocryst (1350 °C). High equilibration temperatures (980-1120 °C) were also calculated for composite xenocrysts of garnet peridotitic affinity. The eclogites equilibrated at intermediate temperatures (920-1060 °C), and the garnet pyroxenites have the lowest range of calculated temperatures (820-910 °C) for garnet-bearing samples. The clinopyroxene-orthopyroxene composites have a temperature range (820-900 °C), which is similar to that of the garnet pyroxenite samples. The lowest equilibration temperature was calculated for the spinel pyroxenite-peridotite (735 °C).

Fields for garnet peridotites from Montana and garnet peridotites and garnet pyroxenites from Colorado-Wyoming are shown for reference in Fig. 9. Two of the composite garnet-clinopyroxene pairs fall within the field of garnet peridotites from Colorado-Wyoming. Without an independent pressure determination for peridotitic xenocrysts, the presence of an "inflected geotherm" of high temperature-pressure peridotites in northern Michigan is uncertain. Two pyroxenes possibly indicate an inflected geotherm. The clinopyroxene from an altered peridotite and the high calcium orthopyroxene xenocryst are similar in temperature to the high temperature peridotites from Montana and South Africa.

Within the eclogite group, the kyanite and sanidine bearing samples are intermingled with other eclogites throughout the temperature range covered. Based on only four samples, there is an apparent trend of increasing temperature from kyanite eclogite (928 °C) to kyanite-sanidine eclogite (984 °C) to sanidine eclogites (1044, 1058 °C). This trend suggests increasing potassium and decreasing aluminum content with depth, indicating derivation of the eclogites from a layered upper mantle.

Calculation of pressure remains a problem with all of these samples. The presence of kyanite in the eclogite samples indicates pressures were at least 18-20kb (Green, 1969). Projecting the calculated temperatures onto the shield geotherm is reasonable if the geotherm is the same today as it was at the time of kimberlite emplacement. If the MacGregor (1974) spinel facies pressures are correct, the spinel pyroxenite-peridotite and the clinopyroxene-orthopyroxene composite xenocrysts indicate that the geotherm may have been higher during emplacement. Without reliable pressure calculations and with only one high temperature-pressure point the position and shape of the emplacement geotherm cannot be adequately described.

The relationship of the Lake Ellen samples to the diamond-graphite stability curve is of interest, particularly because diamonds have been found in the glacial drift of Wisconsin, Michigan, Illinois, Indiana, and Ohio. If the present day geotherm is a realistic estimate of the temperatures and pressures of origin, some of the garnet-clinopyroxene pairs and some eclogites indicate derivation from within the diamond stability field (Fig. 9). This could mean that the kimberlite could be a source for some of the diamonds found in glacial drift in southern Wisconsin, but only if carbon were present at depth, below about 120-135 km, and if diamond were preserved during kimberlite ascent. A further constraint to note, is that if the emplacement geotherm was 100 to 150 degrees higher than the present day geotherm, the highest temperature composite pairs and eclogites would fall within the graphite stability field. So far, no diamonds have been found at this kimberlite, and more conclusive evidence is needed to evaluate the probability of their occurrence here.

The ranges of temperature for eclogites and garnet peridotitic composite xenocrysts overlap. Two samples of garnet pyroxenite and several clinopyroxene-orthopyroxene composite xenocrysts occupy a temperature range just below the lowest temperature eclogite, and the lowest temperature of 750 °C is given by a spinel pyroxenite-peridotite. Assuming that the temperatures are directly related to depth, the upper mantle section consisted of intermixed eclogite and garnet-peridotite overlain by garnet pyroxenite and spinel peridotite. Potassium was high enough to form feldspar in eclogites from a range of depths from at least 120 to 140 km, suggesting that the upper mantle in that depth range was enriched in potassium and probably in other elements easily removed by small degrees of partial melting. Thus the 120-140 km depth range of the upper mantle had not undergone partial melting after eclogite formation.

CONCLUSIONS

The Lake Ellen kimberlite, although poorly exposed, contains samples which reveal characteristics of a heterogeneous upper mantle. A wide range of xenocryst and xenolith types and compositions indicate that the kimberlite has sampled eclogite, garnet pyroxenite, spinel pyroxenite-peridotite, and garnet peridotite similar to upper mantle sections in other portions of the United States. Calculated temperatures for the inclusions show that they represent a range of equilibration temperatures of 700-1300 °C, and thus were derived from depths from 55 to 160 km or more assuming a shield geotherm. Some of the higher temperature samples indicate that the kimberlite could contain diamond.

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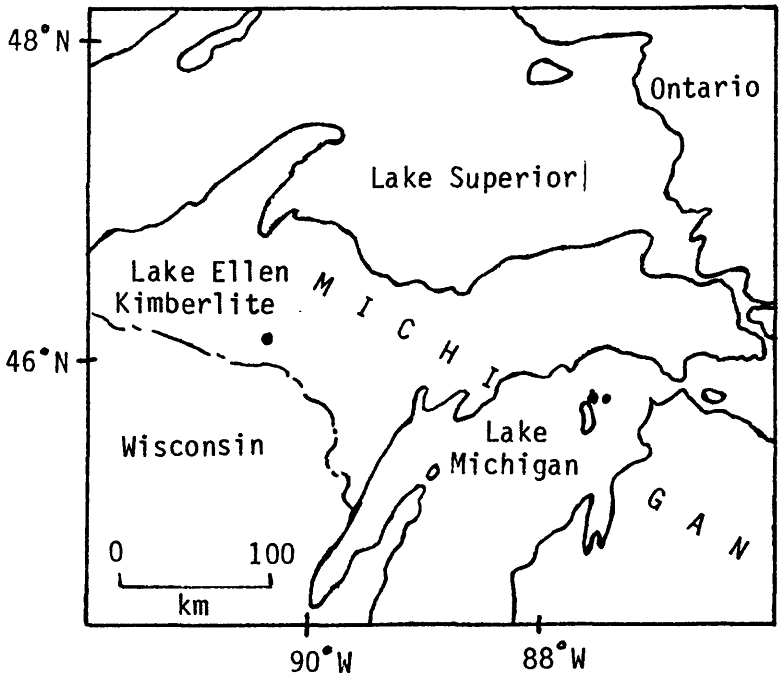


Figure 1. Location map for the Lake Ellen Kimberlite.

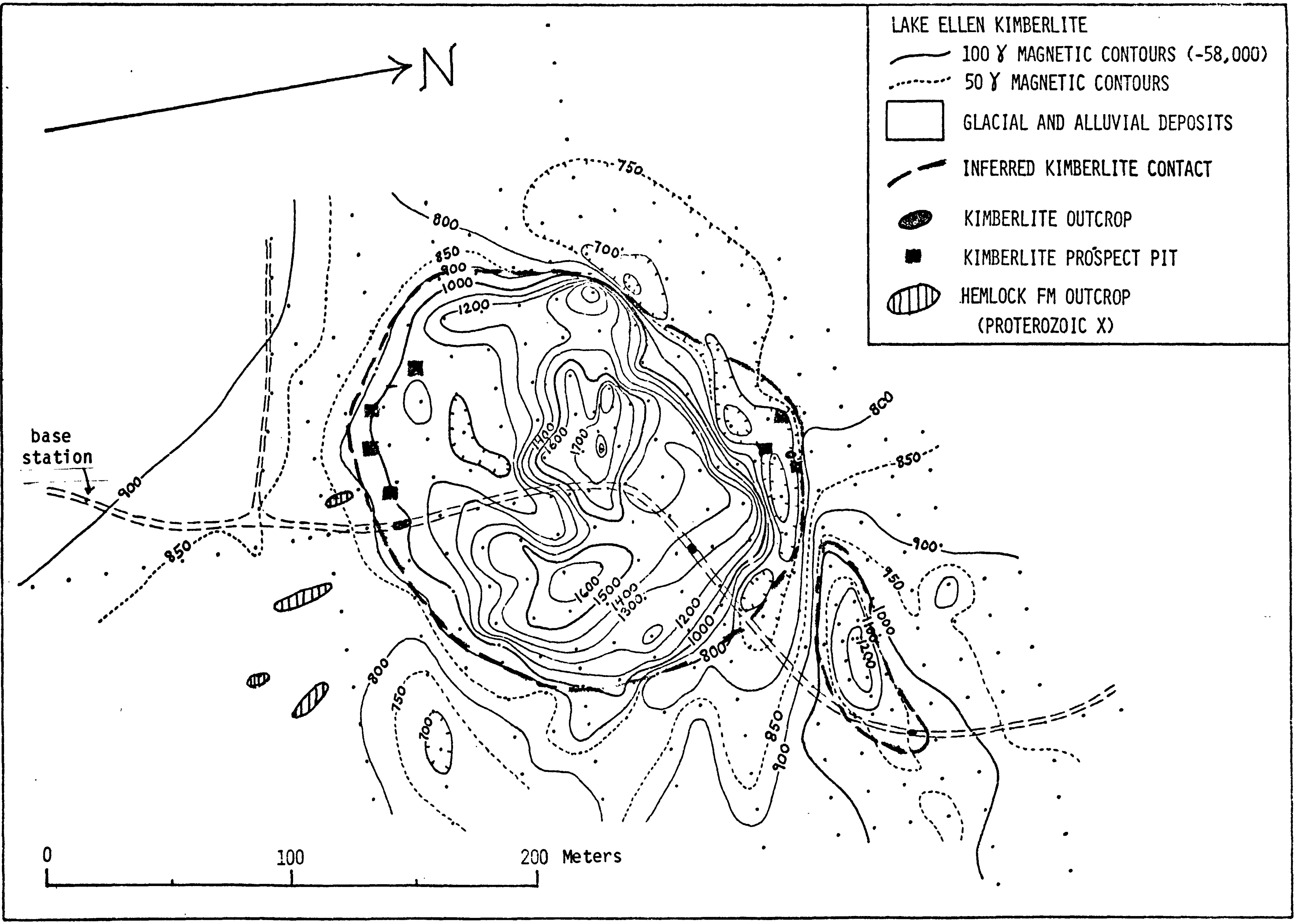


Figure 2. Magnetic map of the Lake Ellen kimberlite, showing outcrops and prospect pits. Contours are total intensity in gammas minus 58,000 gammas.

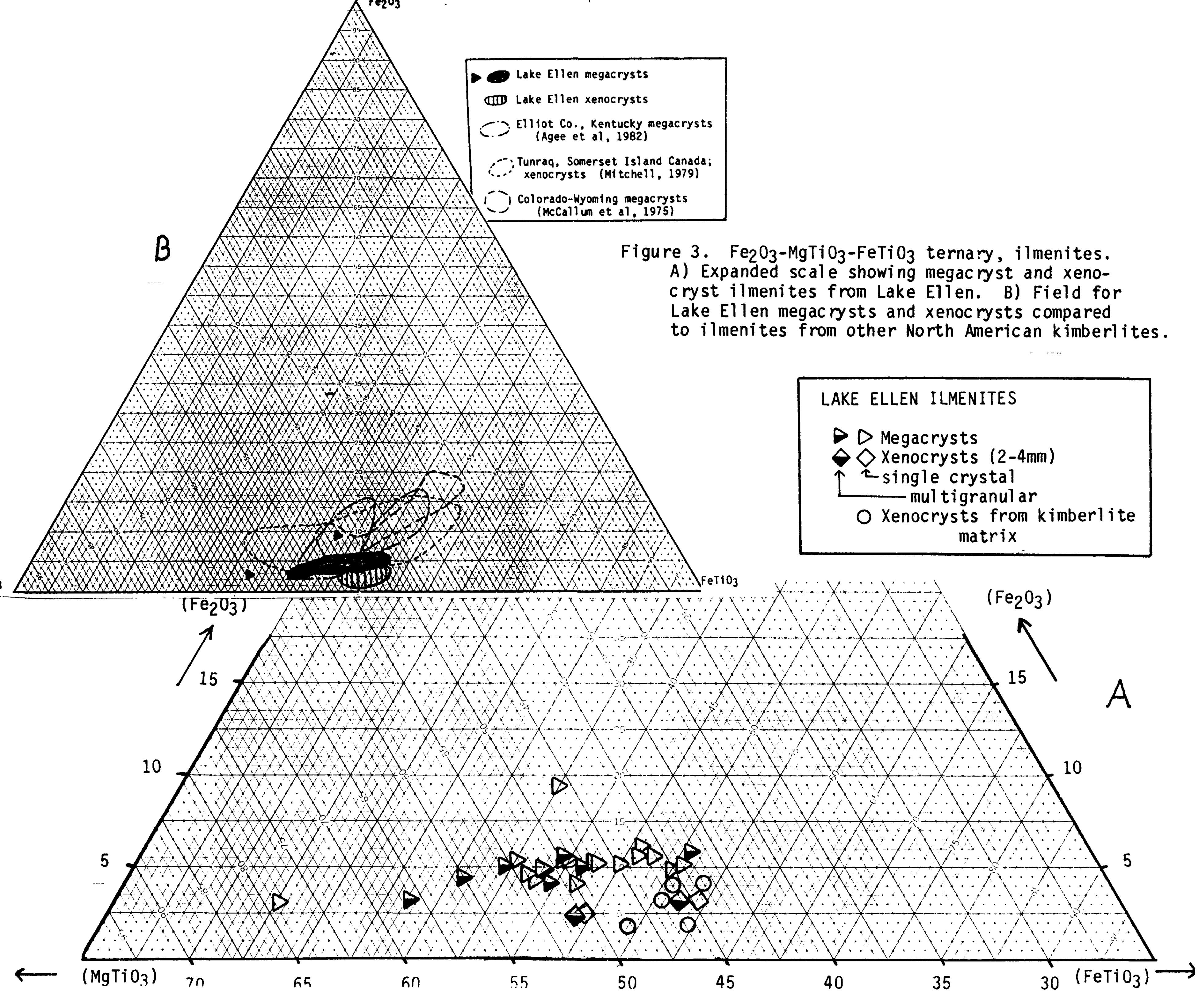


Figure 3. Fe_2O_3-$MgTiO_3$-$FeTiO_3$ ternary, ilmenites. A) Expanded scale showing megacryst and xenocryst ilmenites from Lake Ellen. B) Field for Lake Ellen megacrysts and xenocrysts compared to ilmenites from other North American kimberlites.

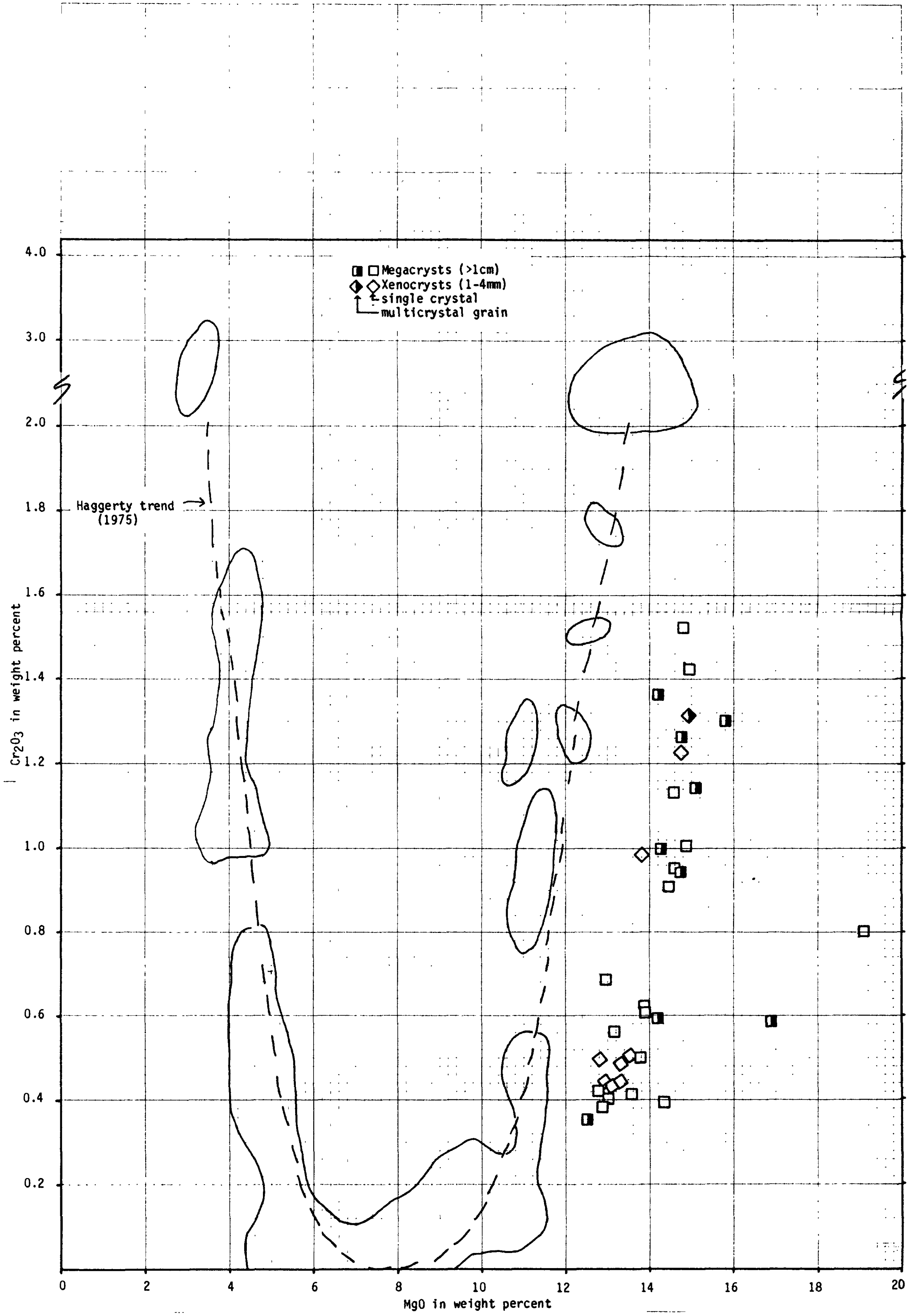
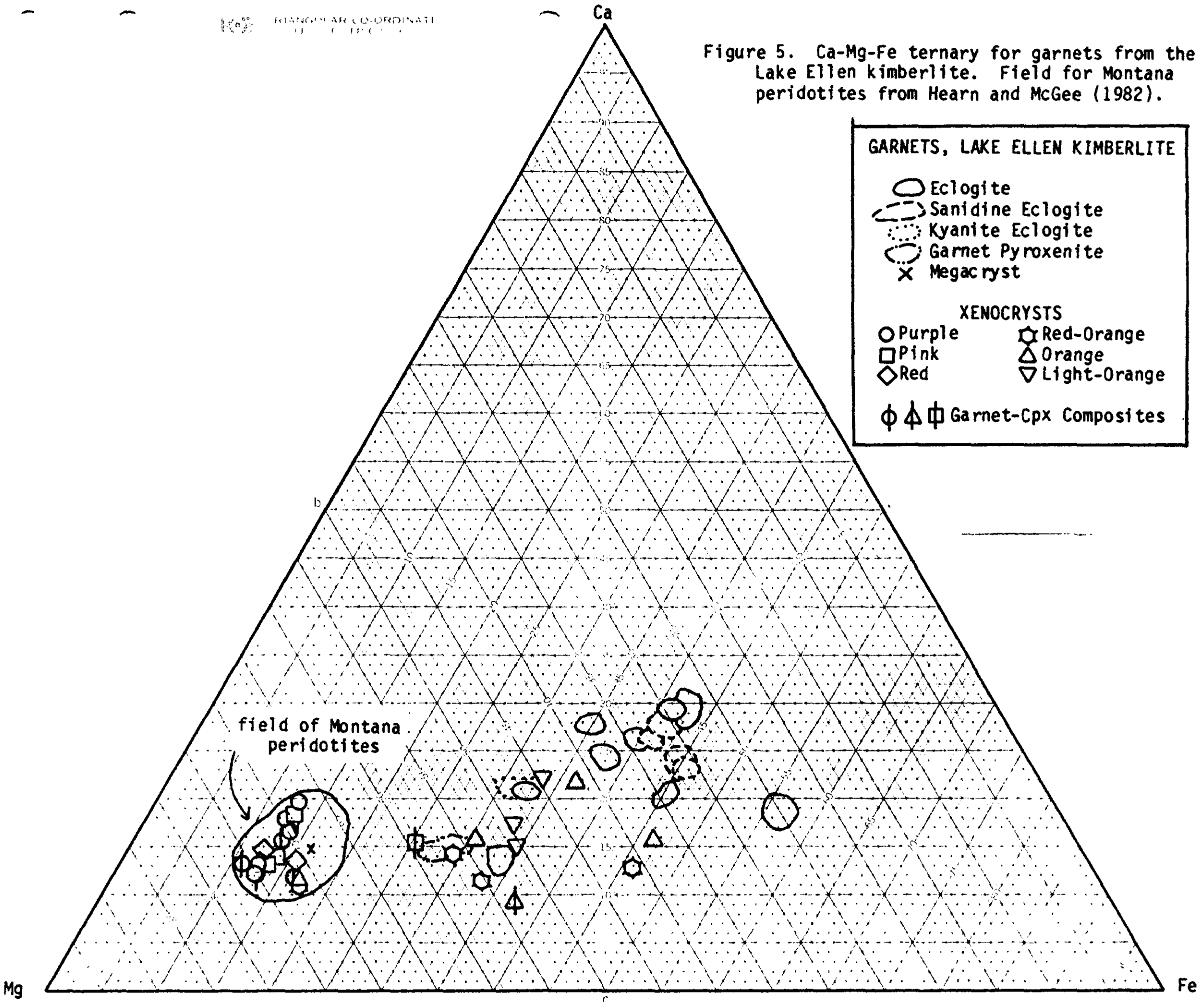


Figure 4. Wt. % Cr_2O_3 vs wt. % MgO of ilmenites from the Lake Ellen kimberlite.

Figure 5. Ca-Mg-Fe ternary for garnets from the Lake Ellen kimberlite. Field for Montana peridotites from Hearn and McGee (1982).



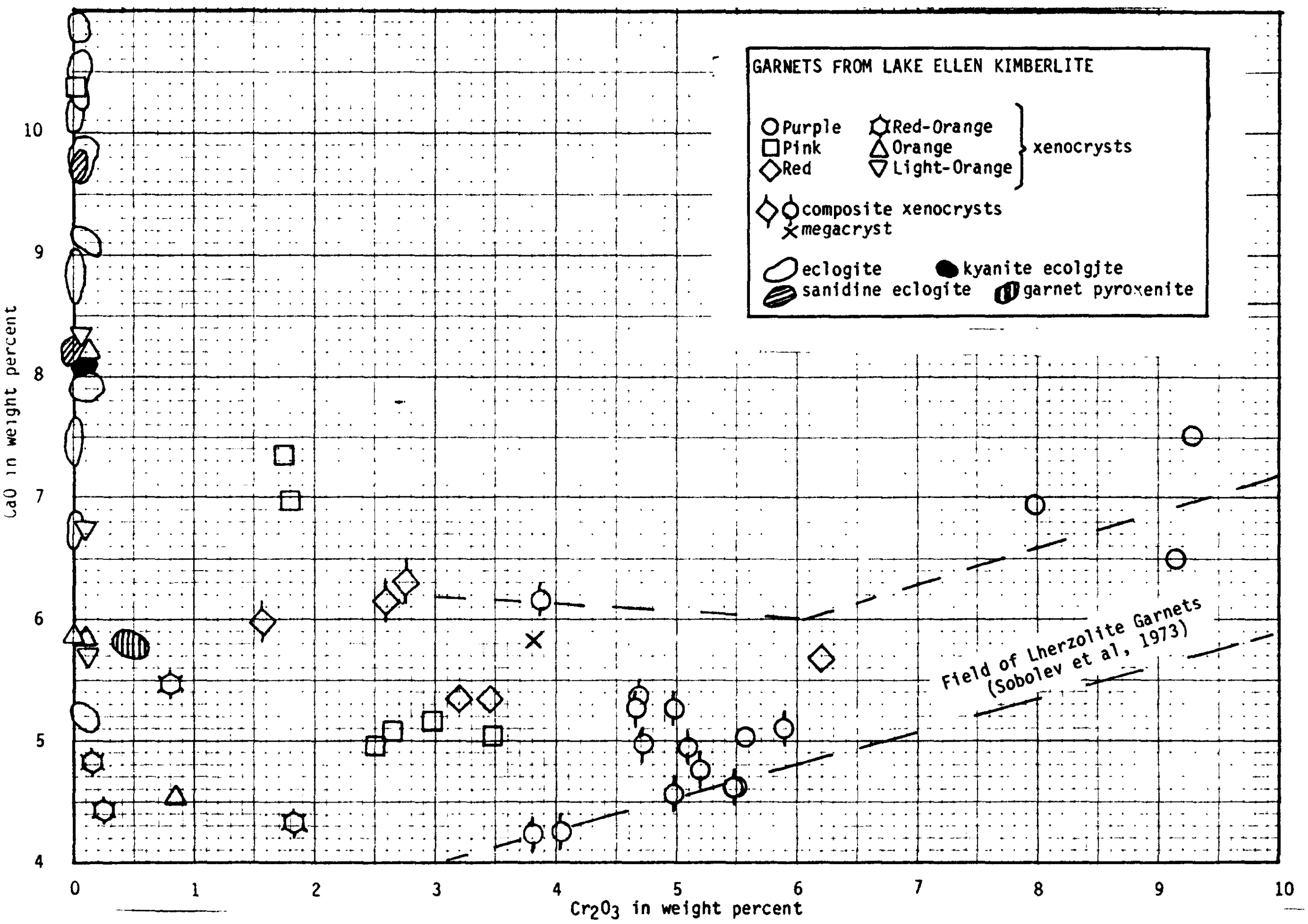


Figure 6. Wt. % CaO vs wt. % Cr_2O_3 plot of xenocryst and xenolith garnets.

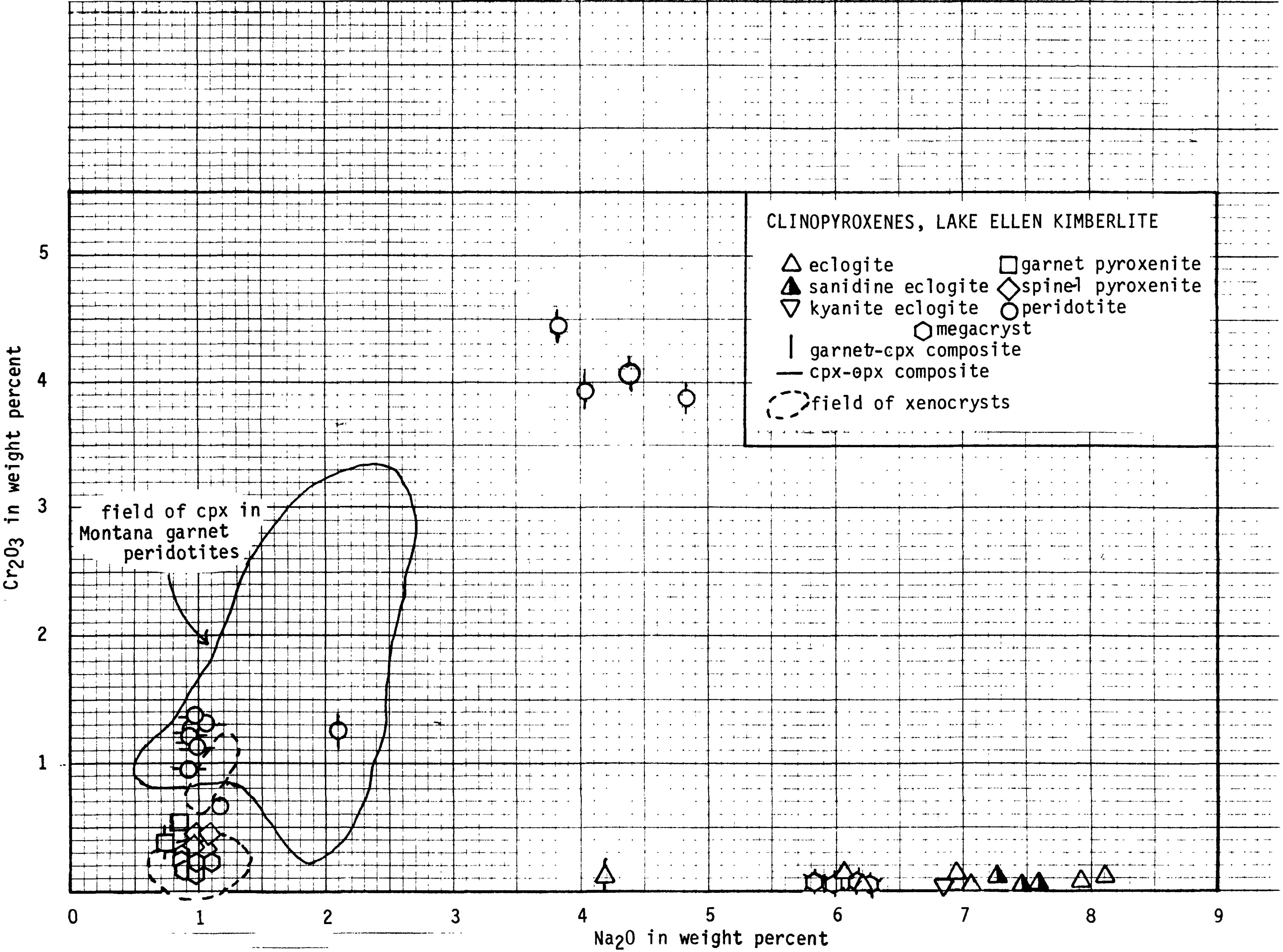


Figure 7. Wt. % Cr_2O_3 vs wt. % Na_2O of clinopyroxenes. Field for clinopyroxenes from Montana garnet peridotites from Hearn and McGee, 1983.

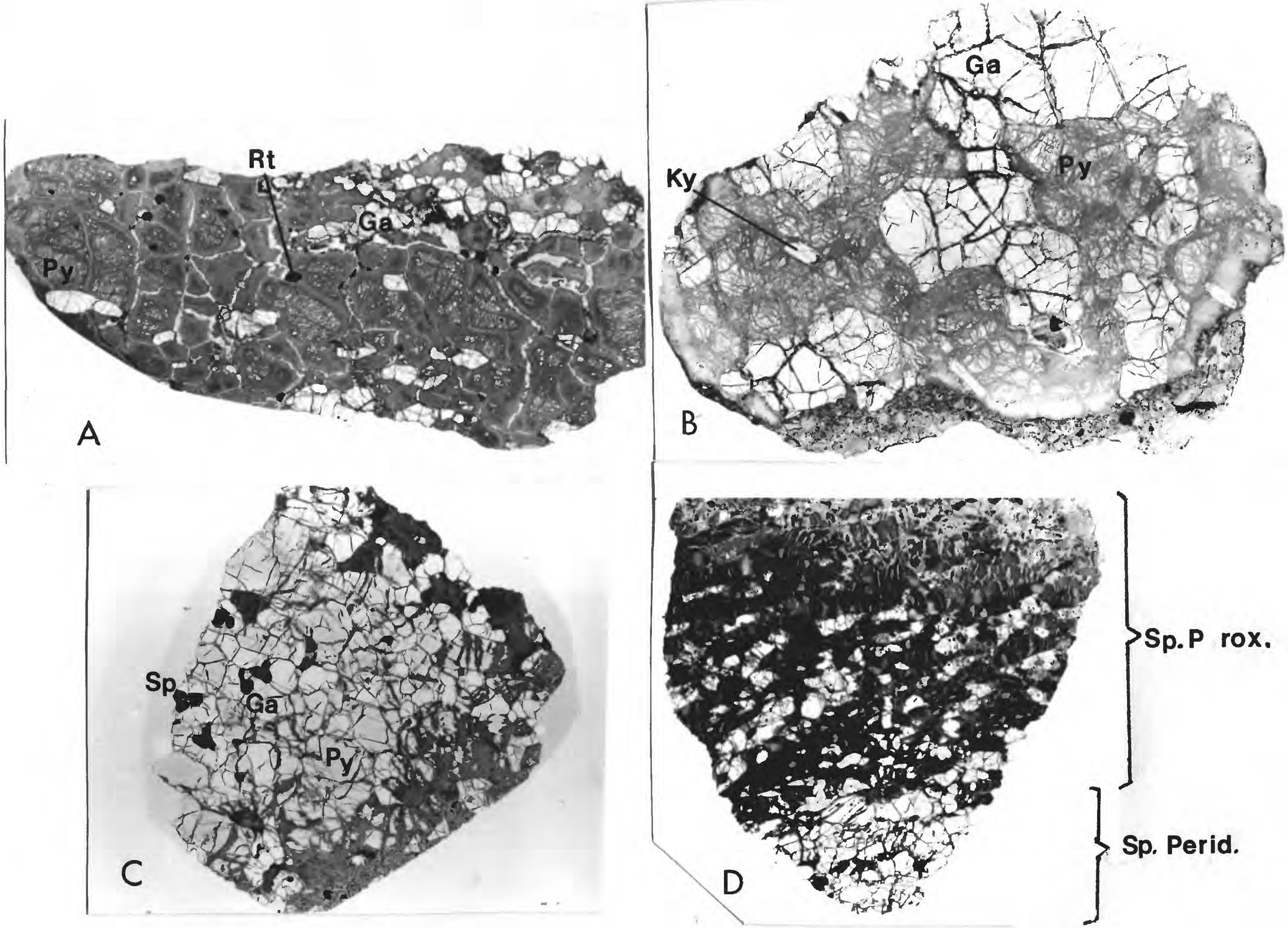


Figure 8. Thin section photos of xenoliths from the Lake Ellen kimberlite. Ga = garnet, Py = pyroxene, Ky = kyanite, Rt = rutile, Sp = spinel. A) Eclogite (3 cm); B) Kyanite Eclogite (1.3 cm) rimmed by kimberlite matrix on lower edge; C) Garnet Pyroxenite (1 cm) serpenitne in lower right portion; D) Spinel Pyroxenite - Peridotite (1.3 cm) serpentine in upper portion.

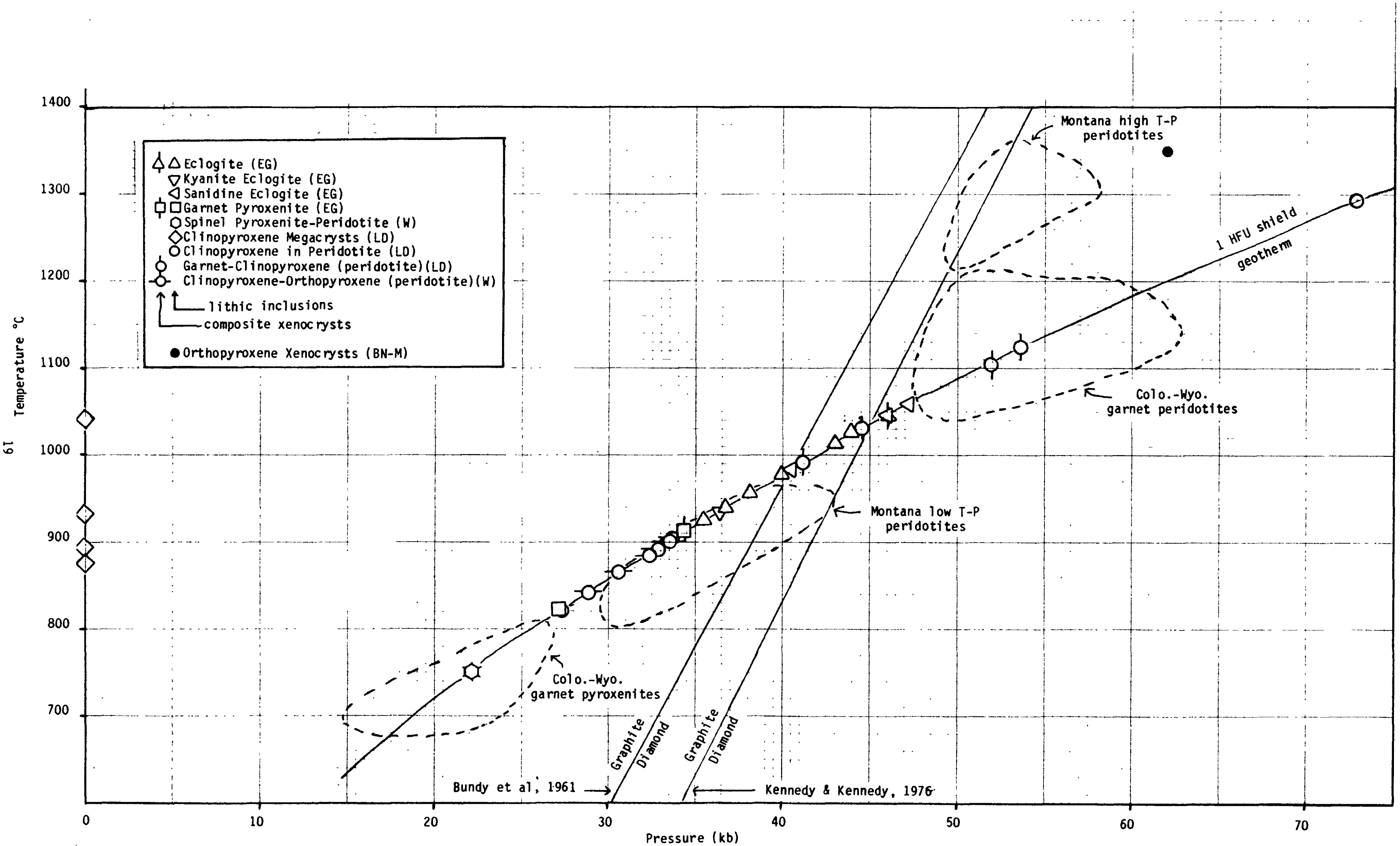


Figure 9. Temperature-Pressure Diagram. Thermobarometer keys: EG= Ellis & Green, 1979; LD= Lindsley & Dixon, 1976; M= MacGregor, 1974; W= Wells, 1977; BN= Boyd & Nixon, 1973. Diamond-graphite boundaries from Bundy and others (1961) and Kennedy & Kennedy (1976). P-T fields for Colorado-Wyoming garnet pyroxenites and garnet peridotites from Eggler, McCallum, and Smith (1979). P-T fields for Montana garnet peridotites from Hearn and McGee (1983).

Table 1.* Megacrysts from the Lake Ellen Kimberlite

	GAR H80-2A-2 (3)	PYX H80-6AB-1 (3)	ILM H80-9 (3)	ILM H80-2AI-1 (3)
SiO_2	41.42	54.45	.09	.05
Al_2O_3	20.99	1.22	.51	.39
FeO	8.23	2.90	27.57	28.81
MgO	19.25	17.30	14.62	13.94
CaO	5.81	21.36	.03	.02
Na_2O	--	.89	--	--
TiO_2	.85	.22	54.37	55.22
MnO	.50	.11	.37	.36
Cr_2O_3	3.80	.19	1.13	.60
NiO	--	--	.17	.10
	100.85	98.64	98.69	99.39
	[12]	[6]	[3]	[3]
Si	2.959	1.996	.002	.001
Al	1.767	.053	.014	.011
Fe	.491	.089	.534	.557
Mg	2.050	.945	.505	.480
Ca	.444	.839	.001	.001
Na	--	.063	--	--
Ti	.045	.006	.947	.959
Mn	.030	.003	.007	.007
Cr	.214	.006	.021	.011
Ni	--	--	.003	.002
	8.000	4.000	2.031	2.027
(FeO)			22.36	24.38
(Fe_2O_3)			5.79	4.92

GAR= garnet, PYX= pyroxene, ILM= ilmenite
()= number of points per grain.
[]= number of oxygens used for cation calculation.
(FeO) and (Fe_2O_3) are calculated values.
-- not analyzed

* All analyses in tables 1-6 were done using an ARL-EMX or ARL-SEMQ electron microprobe operating at 15 kv with a 1 micron beam and with on-line data reduction using the Bence-Albee (1968) method. Standards used were all natural or synthetic minerals with the exception of a barium silica glass standard (used for Ba). In tables 1 & 2 all the analyses are averages of several points on a grain. The analyses in tables 3-6 are averages of several grains in a sample, with 3 points analyzed on each grain.

Table 2A. Composite Xenocrysts: Garnet-Clinopyroxene

	Garnets					
	E GTG-2 (3)	P GTG-1 (3)	L GTG-4 (3)	L GP5-3 (3)	L GP9-2 (3)	L GS-1A (3)
SiO_2	40.38	40.93	41.79	41.33	41.50	42.45
Al_2O_3	21.80	20.52	20.65	19.43	20.40	19.83
FeO	18.16	12.67	6.81	6.30	6.37	8.14
MgO	14.51	16.43	20.06	20.51	20.84	19.97
CaO	3.46	5.97	6.15	4.61	4.22	4.53
TiO_2	0.11	0.08	0.42	0.03	0.00	0.10
MnO	0.41	0.40	0.24	0.71	1.08	0.46
Cr_2O_3	0.00	1.57	2.56	5.48	4.00	4.95
	98.83	98.57	98.68	98.40	98.41	100.43
Si	3.022	3.032	3.020	3.007	3.006	3.035
Al	1.922	1.791	1.757	1.666	1.742	1.671
Fe	1.136	0.785	0.411	0.383	0.386	0.486
Mg	1.619	1.814	2.159	2.224	2.250	2.129
Ca	0.277	0.473	0.475	0.359	0.327	0.347
Ti	0.006	0.004	0.023	0.001	0.000	0.005
Mn	0.025	0.024	0.015	0.043	0.066	0.028
Cr	0.000	0.091	0.146	0.315	0.228	0.279
	8.007	8.014	8.006	7.998	8.005	7.980

	Clinopyroxenes					
	PY6-2 (3)	PY6-1 (3)	PY6-4 (3)	GP5-3 (3)	GP9-2 (3)	GS-1A (3)
SiO_2	55.11	55.30	55.98	53.96	55.08	54.01
Al_2O_3	5.26	.92	3.26	3.60	4.78	6.10
FeO	6.56	3.46	3.18	1.87	2.84	2.47
MgO	12.34	16 96	16.58	14.00	13.78	12.36
CaO	16.16	22.68	17.77	16.74	16.00	15.65
Na_2O	4.20	.73	2.11	3 84	4.40	4.83
TiO_2	.30	.13	.26	.15	.08	.24
MnO	.02	.08	.00	.29	.36	.11
Cr_2O_3	.10	.37	1.23	4.45	4.08	3.87
	100.05	100.63	100.37	98.90	101.40	99.64
Si	2.001	1.997	1.998	1.970	1.973	1.954
Al	.225	.039	.137	.154	.202	.260
Fe	.199	.104	.094	.056	.060	.074
Mg	.665	.913	.882	.762	.735	.666
Ca	.627	.877	.679	.654	.614	.606
Na	.295	.050	.145	.272	.305	.338
Ti	.008	.003	.006	.004	.002	.006
Mn	.001	.002	.000	.008	.005	.003
Cr	.003	.010	.034	.128	.115	.110
	4.024	3.995	3.975	4.008	4.011	4.017

E= eclogite, P= garnet pyroxenite, L= garnet peridotite
()= number of points per grain.

Table 2B. Composite xenocrysts: Clinopyroxene-Orthopyroxene

	Clinopyroxenes						
	1BP-1 (3)	1BP-2 (3)	1BP-3 (3)	1A-22 (3)	4A-13 (3)	1A-11 (3)	81-4F (3)
SiO_2	52.08	52.22	51.81	52.55	52.28	52.64	52.72
Al_2O_3	4.60	4.41	4.60	4.69	4.72	4.34	4.13
FeO	1.70	1.58	1.65	1.60	1.68	1.45	1.65
MgO	15.74	15.76	15.60	15.49	15.66	15.94	16.02
CaO	22.05	22.42	22.17	21.67	21.80	22.04	21.91
Na_2O	.99	1.00	.96	1.08	.94	.94	.92
TiO_2	.07	.06	.10	.10	.09	.08	.06
MnO	.11	.11	.09	.10	.10	.10	.12
Cr_2O_3	1.35	1.11	1.16	1.30	1.22	1.19	.96
	98.69	98.67	98.14	98.58	98.49	98.72	98.49
Si	1.910	1.916	1.911	1.924	1.918	1.925	1.932
Al	.199	.191	.200	.202	.204	.187	.178
Fe	.052	.048	.051	.049	.051	.044	.051
Mg	.860	.862	.858	.846	.856	.869	.875
Ca	.867	.881	.876	.850	.857	.863	.860
Na	.071	.071	.068	.077	.067	.066	.066
Ti	.002	.002	.003	.003	.002	.002	.002
Mn	.003	.003	.003	.003	.003	.003	.004
Cr	.039	.032	.034	.038	.035	.034	.028
	4.003	4.006	4.004	3.992	3.993	3.993	3.996

	Orthopyroxenes						
	(6)	(6)	(2)	(3)	(3)	(3)	(6)
SiO_2	54.38	54.26	54.17	54.89	55.05	54.84	54.80
Al_2O_3	4.48	4.51	4.16	4.10	4.60	4.12	4.41
FeO	5.37	5.25	5.44	5.30	5.52	5.35	5.40
MgO	33.08	32.71	33.02	33.48	33.12	33.48	33.38
CaO	.60	.80	.38	.32	.41	.26	.29
Na_2O	.04	.04	.02	.02	.02	.01	.03
TiO_2	.04	.04	.00	.02	.01	.02	.05
MnO	.14	.14	.15	.14	.13	.13	.13
Cr_2O_3	.78	.83	.79	.72	.69	.65	.74
	98.91	98.58	98.13	98.99	99.55	98.86	99.23
Si	1.894	1.896	1.901	1.907	1.902	1.907	1.900
Al	.184	.186	.172	.168	.188	.169	.180
Fe	.156	.153	.160	.154	.160	.156	.157
Mg	1.718	1.704	1.728	1.733	1.706	1.735	1.725
Ca	.022	.030	.014	.012	.015	.010	.011
Na	.003	.003	.001	.002	.001	.001	.002
Ti	.001	.001	.000	.001	.000	.000	.001
Mn	.004	.004	.004	.004	.004	.004	.004
Cr	.022	.023	.022	.020	.019	.018	.020
	4.004	4.000	4.002	4.001	3.995	4.000	4.000

()= number of points per grain.

TABLE 3. Garnets from Lithic Inclusions, Lake Ellen Kimberlite

	KB2-1 E (8)	KB2-2 E (7)	KB2-3 K (7)	H80-1A-2 P (5)	H80-1A-1 E (9)	H80-2A-1 E (6)	H80-1A-4 E (4)	H80-6A-3 S (3)	H81-4D-1 S (2)	H81-4A-1 S (4)
SiO_2	40.08	40.69	40.51	41.45	40.50	39.73	40.58	40.75	39.64	39.34
Al_2O_3	22.72	22.75	22.48	23.11	22.81	22.78	23.15	23.58	22.81	22.38
FeO	17.78	15.49	15.14	13.92	16.61	18.69	16.22	15.90	19.58	20.83
MgO	10.10	12.70	12.69	15.51	10.02	9.07	14.41	12.60	8.80	8.13
CaO	9.15	7.88	8.13	5.71	10.45	9.80	5.28	8.23	9.73	8.82
Na_2O	--	--	--	--	--	--	--	.06	.07	.07
TiO_2	.09	.09	.10	.05	.13	.11	.09	.09	.15	.10
MnO	.29	.20	.21	.34	.30	.44	.32	.22	.41	.43
Cr_2O_3	.11	.09	.06	.44	.06	.08	.13	.04	.04	.01
	100.32	99.89	99.32	100.53	100.88	100.70	100.18	101.47	101.23	100.11
Si	2.997	3.010	3.013	3.007	3.004	2.982	2.983	2.974	2.971	2.993
Al	2.000	1.981	1.968	1.974	1.992	2.012	2.019	2.026	2.012	2.005
Fe	1.110	.956	.940	.843	1.029	1.171	.995	969	1.225	1.323
Mg	1.125	1.399	1.406	1.676	1.107	1.014	1.578	1.370	.982	.921
Ca	.732	.623	.646	.443	.829	.786	.415	.642	.780	.717
Na	--	--	--	--	--	--	--	.009	.010	.010
Ti	.005	.005	.006	.003	.007	.006	.005	.005	.008	.006
Mn	.018	.012	.013	.021	.019	.028	.020	.014	.026	.028
Cr	.007	.005	.004	.025	.003	.005	.008	.002	.004	.006
	7.994	7.991	7.996	7.992	7.990	8.004	8.023	8.011	8.018	8.009

E= eclogite, K= kyanite eclogite, P= garnet pyroxenite, S= sanidine eclogite
Cations are based on 12 oxygens.
Sample H80-6A-3 contains both kyanite and sanidine.
()= number of grains per sample.
-- not analyzed.

Table 4. Pyroxenes from Lithic Inclusions, Lake Ellen Kimberlite

	KB2-1 E (10)	KB2-2 E (17)	KB2-3 K (16)	H80-1A-2 P (8)	H80-1A-1 E (8)	H80-1A-4 E (5)	H80-2A-1 E (8)	H80-6A-3 S (6)	H81-4D-1 S (2)	H81-4A-1 S (2)	H80-4B-1 B (10)	H80-4B-1 B (4)
SiO_2	54.21	55.75	54.86	53.59	55.21	55.46	56.01	55.79	56.61	55.84	52.64	54.75
Al_2O_3	13.93	13.39	14.65	3.97	14.30	9.97	15.07	13.99	14.56	12.62	4.38	3.14
FeO	4.00	2.52	2.39	2.90	3.11	3.54	3.24	2.44	3.84	4.82	3.32	8.96
MgO	8.33	8.69	8.29	15.77	7.23	10.13	6.59	7.11	5.87	6.42	15.59	31.72
CaO	13.44	13.07	12.78	22.81	12.61	14.20	11.12	12.05	11.13	12.15	22.69	.25
Na_2O	6.22	6.96	6.88	.85	7.08	6.08	8.11	7.42	7.62	7.24	1.02	.00
TiO_2	.33	.19	.30	.37	.28	.26	.27	.18	.24	.20	.34	.07
MnO	.07	.05	.08	.06	.08	.07	.11	.07	.08	.11	.11	.22
Cr_2O_3	.04	.13	.05	.53	.03	.13	.13	.02	.07	.12	.38	.16
	100.57	100.75	100.28	100.85	99.93	99.84	100.65	99.07	100.02	99.52	100.47	99.27
Si	1 916	1.957	1.927	1.931	1.950	1.978	1.959	1.977	1.990	1 993	1.911	1.927
Al	.579	.552	.606	.168	.594	.418	.620	.584	.603	.530	.187	.130
Fe	.118	.074	.070	.087	.092	.105	.094	.072	.113	.144	.100	.263
Mg	.439	.453	.434	.846	.380	.538	.343	.375	.307	.341	.843	1.662
Ca	.508	.489	.480	.879	.476	.542	416	.456	.418	.464	.880	.009
Na	.425	.471	.467	.059	.484	.419	.549	.509	.518	.500	.072	.000
Ti	.009	.005	.008	.010	.007	.007	.007	.005	.006	.005	.009	.002
Mn	.002	.002	.003	.022	.002	.002	.003	.002	.002	.003	.003	.006
Cr	.001	.004	.001	.015	.001	.004	.004	.001	.002	.003	.011	.004
	3.997	4.007	3.996	4.017	3.986	4.013	3.995	3.981	3.959	3.983	4.016	4.003

E= eclogite, K= kyanite eclogite, P= garnet pyroxenite, S= sanidine eclogite, B= spinel pyroxenite
Cations are based on 6 oxygens.
Sample H80-6A-3 contains both kyanite and sanidine.
Sample H80-4B-1 analyses are for clinopyroxene and orthopyroxene.
()= number of grains analyzed per sample.

Table 5. Oxides and kyanite from lithic inclusions, Lake Ellen Kimberlite

	RUT	RUT	RUT	RUT	RUT	RUT	SPN	SPN	COR	KY
				H80-	H80-	H80-	H80-	H80-		
	K82-1	KB2-2	KB2-3	1A-1	1A-4	2A-1	1A-2	4B-1	KB2-3	KB2-3
	E	E	K	E	E	E	P	B	K	K
	(1)	(1)	(2)	(6)	(2)	(4)	(3)	(7)	(2)	(9)
SiO_2	--	--	--	.84	.98	.97	.00	.00	--	37.56
Al_2O_3	.27	.17	.30	.33	.14	.28	55.69	55.34	98.39	62.89
FeO	.82	.26	.32	1.14	.58	.51	16.69	18.92	.35	.34
MgO	.00	.00	.00	.06	.06	.04	17.55	16.67	.18	.08
CaO	--	--	--	.05	.42	.20	.11	--	--	.08
TiO_2	99.98	98.12	98.80	96.24	97.04	97.26	.04	.05	.25	--
MnO	.00	.00	.00	.06	.05	.07	.00	--	.00	--
Cr_2O_3	.08	.32	.12	.11	.25	.20	9.72	8.76	.24	.09
NiO	.00	.13	.18	.01	.04	.01	.46	.35	.08	--
	101.15	99.00	99.72	98.84	99.56	99.54	100.26	100.09	99.49	101.04
Si	--	--	--	.011	.013	.013	.000	.000	--	1.005
Al	.004	.002	.005	.005	.002	.004	1.743	1.748	1.985	1.982
Fe	.009	.002	.004	.013	.006	.006	.370	.424	.005	.008
Mg	.000	.000	.000	.001	.001	.001	.695	.666	.005	.003
Ca	--	--	--	.001	.006	.003	.003	--	--	.002
Ti	.991	.993	.993	.976	.976	.977	.001	.001	.003	--
Mn	.000	.000	.000	.001	.001	.001	.000	--	--	--
Cr	.000	.003	.001	.001	.003	.002	.204	.185	.003	.002
Ni	.000	.001	.002	.000	.000	.000	.010	.008	.001	--
	1.004	1.001	1.005	1.009	1.008	1.007	3.026	3.032	2.002	3.002
(FeO)							13.59	15.09		
(Fe_2O_3)							3.44	4.25		

RUT= rutile (2); SPN= spinel (4); COR= corundum (3); KY= kyanite (5); number indicates the number of oxygens used to calculate cations.
(FeO) and (Fe_2O_3) are calculated values.
E= eclogite, K= kyanite eclogite, P= garnet pyroxenite, B= spinel pyroxenite
()= number of grains per sample.
-- not analyzed.

Table 6. Feldspars from eclogite inclusions, Lake Ellen Kimberlite.

	H80-	H80-	H81-	H81-	H81-4A-6-	
	6A-3	6A-4	4A-1	4D-1	2-2	2-3
	(2)	(4)	(1)	(3)		
SiO_2	62.70	64.14	64.95	63.91	64.13	65.71
Al_2O_3	19.21	18.72	18.75	18.68	18.83	19.00
FeO	.00	.01	.01	.00	.00	.02
MgO	.00	.00	.00	.00	.00	.00
CaO	.02	.00	.02	.00	.00	.00
Na_2O	.30	.39	1.30	.34	.79	2.40
K_2O	15.48	16.01	14.47	16.07	14.93	12.83
BaO	1.98	.38	.41	.37	.57	.66
	99.69	99.65	99.91	99.37	99.25	100.62
Si	2.946	2.982	2.991	2.981	2.982	2.990
Al	1.063	1.025	1.018	1.026	1.032	1.019
Fe	.000	.000	.000	.000	.000	.001
Mg	.000	.000	.000	.000	.000	.000
Ca	.001	.000	.001	.000	.000	.000
Na	.027	.035	.116	.031	.071	.212
K	.926	.948	.850	.954	.885	.745
Ba	.036	.007	.007	.007	.010	.012
	4.999	4.997	4.983	4.999	4.980	4.979
Or	97.1	96.4	87.9	96.8	92.6	77.8
Ab	2.8	3.6	12.0	3.1	7.4	22.2
An	0.1	0.0	0.1	0.0	0.0	0.0

Cations are based on 8 oxygens.
H81-4A-6 showed some zoning in the feldspar, single analyses of the two extremes within one grain are shown above.
()= number of grains per sample.