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# Petrochemistry of eclogites from the Koidu Kimberlite Complex, Sierra Leone

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**Abstract.** Petrography, mineral and bulk chemistry of upper mantle-derived eclogites (garnet and clinopyroxene) from the Koidu Kimberlite Complex, Sierra Leone, are presented in the first comprehensive study of these xenoliths from West Africa. Although peridotite-suite xenoliths are generally more common in kimberlites, the upper mantle sample preserved in Pipe Number 1 at Koidu is exclusively eclogitic, making this the fifth locality in which eclogite is the sole polymineralic xenolith in kimberlite. Over 2000 xenoliths were collected, of which 47 are described in detail that include diamond, graphite, kyanite, corundum, quartz after coesite, and amphibole eclogites. Grossular-pyrope-almandine garnets are chromium-poor (<0.72 wt% $Cr_2O_3$) and fall into two distinct groups based on magnesium content. High-MgO garnets have an average composition of $Pyr_{67}Alm_{22}Gross_{11}$, low-MgO garnets are grossular- and almandine-rich with an average composition of $Gross_{34}Pyr_{33}Alm_{33}$. Clinopyroxenes are omphacitic with a range in jadeite contents from 7.7 to 70.1 mol%. Three eclogites contain zoned and mantled garnets with almandine-rich cores and pyrope-rich rims, and zoned clinopyroxenes with diopside-rich cores and jadeite-rich rims, and are among a very rare group of eclogites reported on a world-wide basis. The bulk compositions of eclogites have ranges comparable to that of basalts. High-MgO eclogites (16–20 wt% MgO) have close chemical affinities to picrites, whereas low-MgO eclogites (6–13 wt% MgO) are similar to alkali basalts. High-MgO eclogites contain high-MgO garnets and jadeite-rich clinopyroxenes. Low-MgO eclogites contain low-MgO garnets, diopside and omphacite, and the group of primary accessory phases (diamond, graphite, quartz after coesite, kyanite, and corundum); grospydites are peraluminous. Estimated temperatures and pressures of equilibration of diamond-bearing eclogites, using the diamond-graphite stability curve and the Ellis and Green (1979) geothermometer, are 1031°–1363° C at 45–50 kb. $K_D$ values of Fe–Mg in garnet and clinopyroxene range from 2.3 to 12.2. Diamonds in eclogites are green, yellow, and clear, and range from cube to octahedral morphologies; the entire spectrum in color and morphology is present in a single metasomatized eclogite with zoned garnet and clinopyroxene. Ages estimated from Sm–Nd mineral isochrons range from 92–247 Ma. $\varepsilon_{Nd}$ values range from +4.05 to 5.23. Values of specific gravity range from 3.06–3.60 g/cc, with calculated seismic Vp of 7.4–8.7 km/s. Petrographic, mineral, and bulk chemical data demonstrate an overall close similarity between the Koidu xenolith suite and upper mantle eclogites from other districts in Africa, Siberia and the United States. At least two origins are implied by $P-T$, bulk chemistry and mineral compositions: low-MgO eclogites, with diamond and other accessory minerals, are considered to have formed from melts trapped and metamorphically equilibrated in the lithosphere; high-MgO eclogites are picritic and are the products of large degrees of partial melting, with equilibration in the asthenosphere. Fluid or diluted melt metasomatism is pervasive and contributed here and elsewhere to the LIL and refractory silicate incompatible element signature in kimberlites and lamproites, and to secondary diamond growth.

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## Introduction

Entrained ultramafic xenoliths in igneous rocks have been widely used to infer the conditions of temperature, pressure, gas fugacity, and stress in the upper mantle (e.g. Nixon and Boyd 1973; Dawson 1980; Nixon et al. 1981; Haggerty and Tompkins 1983; Eggler and McCallum 1974). The $P$ wave seismic velocity for most of the upper mantle is $8.2 \pm 0.2$ km/s (Ringwood 1975; Anderson 1981), and combined with a variety of chemical and physical properties, limits the mineralogical composition of the upper mantle to some combination of olivine, pyroxene, and garnet. The main rock types proposed are peridotites (olivine + two pyroxenes + garnet), and eclogites (garnet + clinopyroxene), in agreement with phase equilibria studies at high temperatures and pressures on natural rocks and synthetic silicate systems, and with observed upper mantle xenolith suites in alkali basalts, kimberlites and lamproites (Dawson 1980; Mitchell 1986).

Most mantle models favor olivine-rich garnet peridotite or lherzolite as the major component of the upper mantle (e.g. Ringwood 1975; Yoder 1976), but Anderson (1981) has proposed eclogite, or piclogite (olivine eclogite) as an alternative, particularly for the lower portions of the upper mantle. Eclogites, however, are relatively rare (e.g. Schulze 1989) and are previously reported as the sole polymineralic xenolith in kimberlite from only four localities worldwide (Roberts Victor and Bobbejaan, South Africa, Orapa in Botswana, and Zagadochnaya, USSR). This restricted distribution is surprising given that all kimberlites and lamproites contain diamonds of eclogitic affinity (e.g. Meyer 1987; Gurney 1989), and given that eclogites are the high pressure analogs of basalts so widespread in space and time (Yoder and Tilley 1962; Green and Ringwood 1967; O'Hara and Yoder 1967). Some additionally unusual features of eclogites that remain inadequately explained are the following: (1) most of the largest diamonds recovered are eclogitic; (2) boron-substituted diamonds are exclusively eclogitic; (3) diamond, non-diamond, and diamond+graphite eclogites are recognized in the same pipe, and more rarely in the same xenolith (Hatton and Gurney 1979; Shee and Gurney 1979); (4) the carbon isotopes of eclogitic diamonds have $\delta^{13}C$ values ranging from +2 to −35‰, whereas those of ultramafic affinity cluster around −5‰ (Milledge et al. 1983); (5) garnets and clinopyroxenes from diamond-bearing eclogites are alkali-bearing and typically enriched in $Na_2O$ and $K_2O$, respectively (McCandless and Gurney 1989); (b) some eclogites may have an excessively high pressure origin (>200 km), based on a pyroxene solid solution component in garnet (Ringwood 1977; Moore and Gurney 1985); and (7) available ages for eclogitic diamonds are approximately 1.5 Ga (Richardson 1986), in contrast to ultramafic diamonds of about 3.2 Ga (Richardson et al. 1984).

There are at least five possibilities and no consensus for the origin of upper mantle-derived eclogites: (1) metamorphic reaction from basalt to eclogite, by either transformation of gabbro previously underplated onto the lower crust, or, by subduction of ancient oceanic crust; (2) direct high pressure crystallization; (3) exsolution of garnet from clinopyroxene; (4) decomposition of majorite; or (5) restite from the extraction of a high-Si component. Helmstaedt et al. (1972), Smyth and Hatton (1977), Helmstaedt and Schultze (1979), Ater et al. (1984), Jagoutz et al. (1984), MacGregor and Manton (1986) and Shervais et al. (1988) have interpreted some eclogites as possible subducted relicts of an Archean oceanic crust, based on the chemical similarities between eclogites and altered ocean floor basalts. The subduction hypothesis may explain the spread in carbon isotopes, but on several other accounts is unsupported. O'Hara and Yoder (1967), Kushiro and Aoki (1968), MacGregor and Carter (1970), Hatton and Gurney (1979) cite experimental studies showing that mafic magmas may crystallize both garnet and clinopyroxene with textures suggestive of a cumulate igneous origin. Smyth et al. (1984) cite exsolution assemblages in clinopyroxenes that suggest that some kyanite-bearing eclogites have crystallized, or recrystallized, at near dry solidus temperatures at pressures in excess of 30 kb. While it is generally accepted that eclogites are broadly equivalent to basalts in composition (Yoder 1976), such compositions can evidently not be derived from fertile garnet lherzolite by anhydrous partial melting at $P-T$ conditions in the diamond stability field. As reviewed and demonstrated by Takahashi and Scarfe (1985), partial melts become increasingly olivine normative with increasing $P$, with basalts forming at pressures less than 30 kb, picrites at approximately 30–40 kb, and komatiitic magmas at approximately 50–70 kb. Diamond-bearing eclogites, therefore, should be komatiitic in composition if formed by direct partial melting of garnet lherzolite and not basaltic as is generally the case.

The uncertainties in origin, the several unexplained peculiarities of eclogitic xenoliths, and the proposition of piclogite, have given the study of eclogites a renewed impetus. The Koidu Kimberlite Complex in Sierra Leone is a new eclogite source that broadens the geographical distribution to the Man Shield of the West African Craton. First reports of eclogite from Koidu and the geological setting are given in Tompkins (1983) and Tompkins and Haggerty (1984). Three Mesozoic kimberlite pipes and en echelon kimberlite dikes intrude 2.7 Ga basement of the Liberian Age Province. The kimberlites are massive Type 1 and the xenolith suite is eclogitic in association with discrete garnet, pyroxene, ilmenite and ilmenite-pyroxene intergrowths. Although peridotites are absent, ultramafic suite diamonds are recorded (Harris and Gurney 1979), so that in spite of the fertile nature of the xenoliths, the kimberlite has in fact also sampled depleted subcontinental lithosphere. For this study, 47 eclogites and 2 lower crustal garnet granulites were selected from a collection of approximately 2,000 samples from Pipe Number 1 at Koidu. Some data from the present study are integrated into a companion study of the Sample Creek Kimberlite in Liberia where the emphasis is on lower crustal granulites and crust-upper mantle structure (Toft et al. 1989); other data are in Hills (1988).

## Petrography

A detailed petrographic description of the eclogites from Koidu is provided because neither the fabric classification of McGregor and Carter (1970), nor the chemical groupings of McCandless and Gurney (1989) are clearly applicable. The majority (29) of the 46 eclogites studied in detail (Analytical Techniques, Appendix 1) from Koidu are bimineralic garnet and clinopyroxene. The remainder have in addition to garnet and clinopyroxene, one or a combination of kyanite, corundum, coesite (quartz), amphibole, diamond or graphite as an associated mineral.

### *Bimineralic eclogites*

In hand specimen, bimineralic eclogites are coarse grained, equigranular, and have garnet to pyroxene modal ratios typically ranging between 40:60 and 60:40. Clinopyroxenes (≈5 mm) are subhedral and dark green to pale cream in color. Garnets are rounded and irregular in habit (8 mm max) and range from deep red to shades of orange and pale pink. Foliated xenoliths are rare at Koidu, unlike those described from the Kao kimberlite pipe in Lesotho (MacGregor 1979) and elsewhere. Examined in thin section, pyroxene is pale green in color, weakly pleochroic, and generally more altered than coexisting garnet. In some eclogites, clinopyroxene has altered completely to a turbid, optically irresolvable assemblage. Pristine pyroxene grains are optically homogeneous, with the exception of two eclogites discussed below. Garnets are typically pale pink and subhedral to irregular. Individual garnet grains are typically unzoned, although discontinuous and continuous concentric zoning is present in three eclogites.

Figure 1a, b are representatives of the possible end members of the entire suite of xenoliths examined in this study, in terms of alteration, preservation of silicates, texture, and fabric. Figure 1a (KEC-81-DB-1) shows highly altered opaque clinopyroxene with small pristine relict areas in the centers of crystals. Garnets are anhedral to rounded. A strong fabric pervades the entire xenolith, cross-cutting garnet and clinopyroxene grains. This veined assemblage is predominantly pargasite, phlogopite, rutile, sulfide, spinel, calcite, and plagioclase. By comparison, the eclogite in Fig. 1b (KEC-86-90) has pristine irregular pink garnets and well preserved colorless to pale green clinopyroxenes. Grain boundaries display near-perfect triple junctions. There is no preferred fabric, but amphibole and phlogopite are present along grain boundaries. In several xenoliths (Table 1), garnet and clinopyroxene grains contain very fine-grained (30–100 μ), oriented rutile inclusions (Fig. 1c). Acicular needles or squat prisms located in the center

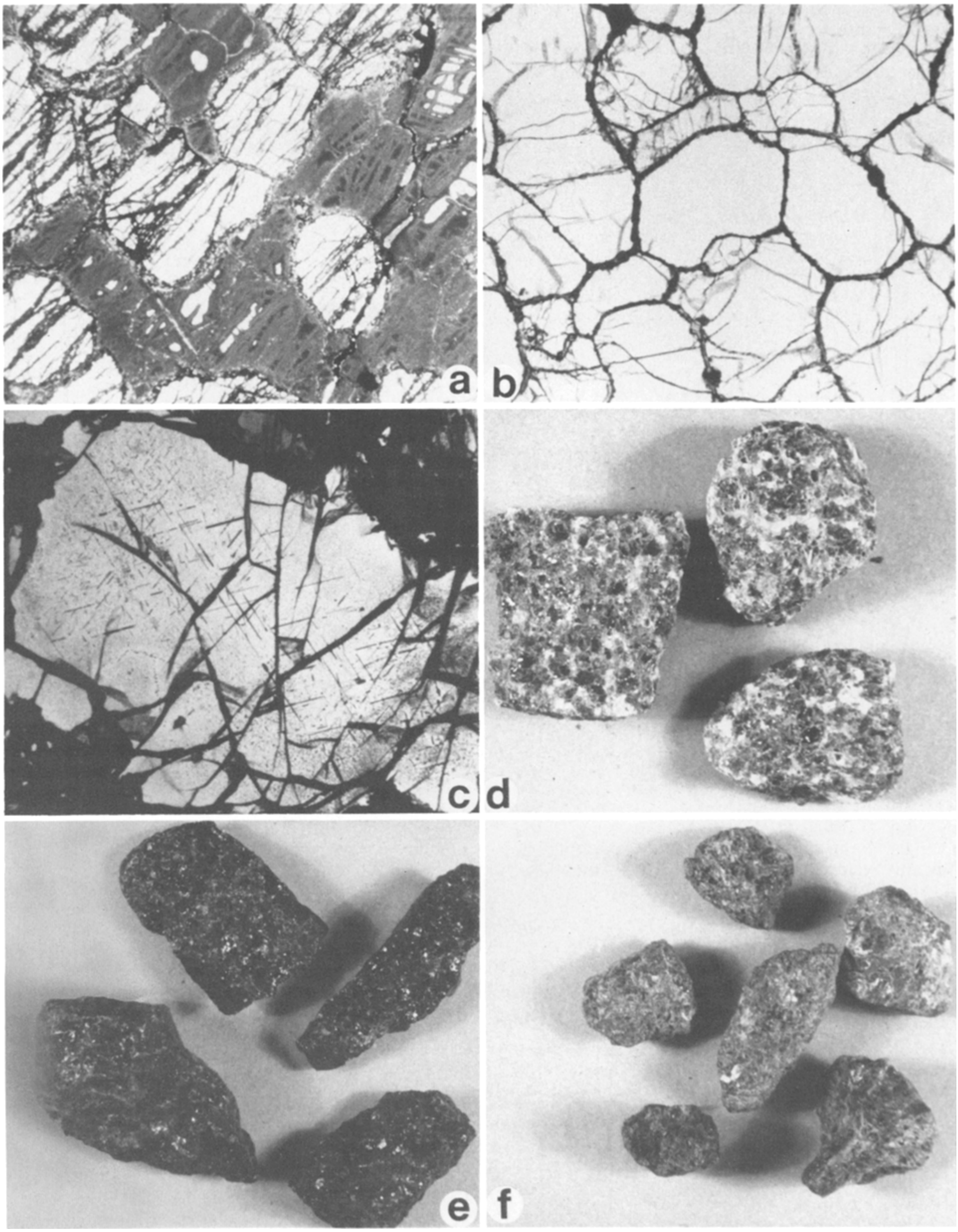


**Fig. 1.** **a** Photomicrograph of Koidu eclogite KEC-81-DB-1 showing highly altered clinopyroxene (opaque) and garnet (white) with a veined assemblage cross-cutting grain boundaries. Transmitted plane polarized light. Width of photomicrograph = 22 mm. **b** Photomicrograph of Koidu eclogite KEC-86-90 showing pristine and unaltered clinopyroxene and garnet with alteration restricted to grain boundaries. Transmitted plane polarized light. Width of photomicrograph = 22 mm. **c** Garnet from KEC-81-12 with fine-grained, oriented rutile inclusions. Width of photomicrograph = 8 mm. **d** A representative collection of the first group of eclogites represented by KEC-86-71A and KEC-86-71B (see text). **e** A representative collection of the second group of eclogites represented by KEC-86-72A and KEC-86-72B (see text). **f** A representative collection of the third group of eclogites represented by KEC-86-73A and KEC-86-73B (see text)

**Table 1.** Petrographic summary of Koidu eclogites

| Xenolith | Gt:Px | Texture | Fabric | Rutile lamellae | Oxides | Matrix | Average grain size (mm) | | Mode % | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Gt | Cpx | Gt | Px | Opaq | Carb | Amph Phlo | Alt | Acc |
| Bimineralic (29) | | | | | | | | | | | | | | | |
| KEC-80-A2 | 1.1 | Gran | No | No | R | No | 5 | 3 | 45 | 42 | 1 | – | 5 | 7 | – |
| KEC-80-B1 | 1.0 | Gran | Strong | Few | I | No | 5 | 5 | 46 | 47 | 4 | – | 1 | 2 | – |
| KEC-80-5 | 1.0 | Gran | Weak | No | S | No | 5 | 4 | 47 | 47 | <1 | – | 3 | 3 | – |
| KEC-81-2 | 1.0 | Gran | Weak | Few | S | No | 6–7 | 3–4 | 41 | 41 | 6 | – | 2 | 10 | – |
| KEC-81-3 | 1.1 | Gran | Weak | Few | S+R | No | 8 | 4 | 48 | 43 | 3 | – | 1 | 5 | – |
| KEC-81-4 | 0.8 | Gran | No | No | R | No | 5 | 2–6 | 38 | 48 | 2 | – | 5 | 7 | – |
| KEC-81-5 | 1.4 | Gran | Weak | No | R | No | 6 | 5 | 53 | 37 | 5 | – | <1 | 5 | – |
| KEC-81-7 | 1.4 | Gran | Strong | No | S+R | No | 4 | 3 | 47 | 34 | 2 | – | 2 | 15 | – |
| KEC-81-8 | 1.0 | Gran | Weak | No | S+R | No | 4 | 4 | 38 | 37 | 3 | 2 | 3 | 17 | – |
| KEC-81-10A | 1.0 | Gran | Weak | No | S | No | 6 | 8 | 42 | 42 | <1 | 1 | 1 | 14 | – |
| KEC-81-12 | 1.0 | Gran | No | Yes | S+R | No | 3 | 2 | 45 | 43 | 3 | – | – | 2 | 7 |
| KEC-81-18 | 0.9 | Gran | No | No | S+R | No | 6 | 10 | 34 | 40 | 1 | – | 5 | 20 | – |
| KEC-81-21 | 1.0 | Gran | Weak | No | S+R | No | 7 | 4–10 | 47 | 49 | 1 | – | <1 | 3 | – |
| KEC-86-2 | 1.5 | Gran | Weak | Yes | S | No | 5 | 3 | 57 | 39 | 2 | – | – | 2 | – |
| KEC-86-6 | 0.7 | Gran | No | No | R | No | 2–7 | 3 | 40 | 55 | <1 | – | – | 5 | – |
| KEC-86-8 | 1.0 | Gran | Weak | Few | S | No | 4 | 3 | 48 | 49 | <1 | – | <1 | 3 | – |
| KEC-86-11 | 1.1 | Gran | Strong | No | S | No | 5 | 3 | 50 | 45 | <1 | – | – | 5 | – |
| KEC-86-13 | 0.6 | Gran | Weak | No | I | No | 10 | 4 | 36 | 60 | 1 | – | <1 | 3 | 2 |
| KEC-86-15 | 1.1 | Gran | Strong | Yes | S | No | 4 | 6 | 50 | 44 | 1 | – | 3 | 2 | – |
| KEC-86-19 | 1.0 | Gran | No | No | S | No | 3 | 3 | 46 | 47 | <1 | – | 5 | 2 | – |
| KEC-86-58 | 1.0 | Gran | Weak | Yes | S | No | 2 | 2 | 48 | 48 | <1 | – | 2 | 2 | – |
| KEC-86-71A | 1.2 | Gran | No | No | R | No | 5 | 3 | 49 | 40 | <1 | 1 | <1 | 10 | – |
| KEC-86-71B | 1.1 | Gran | No | No | S | No | 5 | 3 | 40 | 35 | <1 | 10 | – | 15 | – |
| KEC-86-72A | 0.9 | Gran | No | No | S+R | No | 7 | 8 | 37 | 40 | 3 | – | 10 | 10 | – |
| KEC-86-72B | 0.7 | Gran | No | No | S+R | No | 3–6 | 1–4 | 41 | 56 | 1 | – | <1 | 2 | – |
| KEC-86-73A | 1.0 | Gran | Strong | Yes | S | No | 5 | 5 | 47 | 46 | 2 | – | <1 | 5 | – |
| KEC-86-73B | 1.1 | Gran | Strong | No | S | No | 3 | 3 | 47 | 43 | <1 | – | 5 | 5 | – |
| KEC-86-90 | 1.4 | Gran | No | No | S | No | 4 | 3 | 55 | 38 | 1 | – | 1 | 5 | – |
| KEC-86-107 | 2.0 | Gran | Strong | Yes | S | No | 3 | 3 | 60 | 30 | <1 | – | 6 | 4 | – |
| Kyanite-bearing (4) | | | | | | | | | | | | | | | |
| KEC-86-QB-1 | 2.3 | Gran | No | No | – | Yes | 3 | 3 | 45 | 20 | <1 | – | 2 | 7 | 26 |
| KEC-86-KB-3 | 1.0 | Folia | Weak | No | S+R | Yes | 2 | 3 | 34 | 34 | 1 | 1 | – | 6 | 25 |
| KEC-86-KB-4 | 1.0 | Fol/Gran | Weak | No | S+R | Yes | 4 | 2 | 25 | 24 | 1 | – | – | 20 | 30 |
| KEC-86-KB-74B | 1.0 | Fol/Gran | Weak | No | S+R | Yes | 3 | 2 | 32 | 33 | 2 | – | <1 | 5 | 28 |
| Corundum-bearing | | | | | | | | | | | | | | | |
| KEC-86-CB-68 | 1.0 | Folia | Weak | No | – | No | 10 | 5 | 43 | 42 | – | – | – | 5 | 10 |
| Amphibole-bearing | | | | | | | | | | | | | | | |
| KEC-81-AB-11 | 1.0 | Gran | No | Few | S | No | 3 | 2 | 30 | 30 | <1 | – | (30) | 10 | 30 |
| Carbonaceous eclogites (9) | | | | | | | | | | | | | | | |
| KEC-80-DB-D1 | 1.1 | Gran | Strong | No | S+R+I | No | 10 | 10 | 48 | 45 | 1 | 1 | 1 | 2 | 2 |
| KEC-80-DB-2 | 1.4 | Gran | Weak | No | S+R | No | 4 | 4 | 52 | 38 | 1 | – | 2 | 3 | 4 |
| KEC-80-DB-3 | 0.8 | Gran | Weak | No | S+R | No | 7 | 4 | 37 | 49 | 4 | – | 5 | 3 | 2 |
| KEC-80-DB-40 | 1.3 | Gran | Weak | No | S+R | No | 4 | 4 | 51 | 40 | <1 | – | – | 3 | 6 |
| KEC-81-DB-1 | 1.1 | Gran | Strong | No | S+R | No | 5–10 | 5 | 47 | 41 | 1 | – | 2 | 4 | 5 |
| KEC-86-DB-9 | 1.0 | Gran | Strong | No | S | No | 8 | 3–7 | 41 | 43 | <1 | 4 | 5 | 5 | 2 |
| KEC-86-DB-10 | 1.2 | Gran | Strong | No | S | No | 10 | 4 | 48 | 39 | 1 | <1 | 3 | 8 | 1 |
| KEC-86-GB-12 | 1.0 | Gran | No | No | S+R | No | 4 | 4 | 40 | 40 | 2 | – | – | 15 | 5 |
| KEC-86-GB-70 | 0.8 | Gran | Weak | Yes | S+R | No | 4 | 6 | 37 | 48 | 3 | – | – | 2 | 10 |
| Lower crustal granulites (2) | | | | | | | | | | | | | | | |
| KGR-86-75 | 1.0 | Gran | No | Yes | R | No | 2 | 2 | 30 | 30 | 2 | – | – | 8 | 30 |
| KGR-86-76 | 1.0 | Gran | No | Yes | S+R | No | 4–15 | 3 | 32 | 32 | 1 | – | – | 15 | 20 |

*Gran* = Granular, *Fol* = Foliated, *S* = Sulfide, *R* = Rutile, *I* = Ilmenite, *Opaq* = Opaques, *Carb* = Carbonate, *Amph* = Amphibole, *Phlo* = Phlogopite, *Alt* = Alteration, *Acc* = Accessory of host grains are oriented along planes at approximately 60°. Similar inclusions are reported in garnets and pyroxenes from eclogites by Griffin et al. (1971), Meyer and Brookins (1971), and Tollo (1982). Griffin et al. (1971) attribute these inclusions to exsolution and cite as evidence the preliminary experimental work of O'Hara and Yoder (1967) who homogenized presumed rutile inclusions and host garnet in a natural eclogite at 30 kb.

Of the initital 2000 eclogites from Koidu, three distinct groups of bimineralic eclogites are identified, based on hand specimen identification. These are characterized below and shown in Fig. 1d–f. Two representatives from each group were studied in detail and are listed in Table 1.

The *first* group of eclogites, represented by KEC-86-71A and KEC-86-71B (Fig. 1d), are very light colored, have a leached and dull appearance, and are composed of approximately equal proportions of small (up to 5 mm) rounded garnet and milky, highly altered clinopyroxene with pristine relic cores. Distinguishing features of the *second* group, represented by KEC-86-72A and KEC-86-72B (Fig. 1e), are the overall very dark appearance, and the pristine nature of garnet and clinopyroxene. Dark red garnets are large (7 mm) and rounded and fresh dark green clinopyroxene makes up slightly more than 50 modal % of the xenolith. Sulfides are abundant whereas mica is rare. The *third* group of eclogites, represented by KEC-86-73A and KEC-86-73B (Fig. 1f), are micaceous, have a crumbly appearance and may be foliated. The most distinguishing feature is 'Granny-Smith' colored clinopyroxene which is pristine and up to 1 cm in length. Garnets vary in size, modal abundance (30–70%), and color from pinkish red to deep red.

Although quite similar to eclogites, crustal granulites contain abundant plagioclase ($\approx$20–40 modal%) with typically very altered clinopyroxene (5–30 modal %), and altered garnet ($\approx$40 modal%).

### *Kyanite-bearing eclogites*

Fifteen kyanite-bearing eclogites are identified ($4 \times 4 \times 3$ to $6 \times 4 \times 3$ cm) and four of these are described in detail. In three of these, kyanite is the only accessory mineral, but the fourth contains quartz pseudomorphs after coesite (Smyth 1977). Modes for specimens studied are listed in Table 1. In hand specimen, kyanite-bearing eclogites KEC-86-KB-3, KEC-86-KB-4, and KEC-86-KB-74B are characterized by highly altered clinopyroxene, orange-brown garnets and pale blue kyanite. Each of these three silicates comprises approximately 20–30 modal %. A black, fine-grained matrix (5–20 modal %) is present in all three samples and is atypical for bimineralic eclogites. Leached alteration on eclogite surfaces penetrates $\approx$1.5 mm into the xenoliths. Specimens KEC-86-KB-3 and KEC-86-KB-74B consist of tightly interlocking minerals with foliation resulting from the elongation and alignment of kyanite grains that are parallel to garnet- and clinopyroxene-rich layers. In thin section, colorless to pale orange garnets (2–4 mm) are anhedral (25–34 modal %) and are relatively unaltered except along conchoidal fractures filled by vermicular inclusions that appear to be glass. Pristine, subhedral omphacitic clinopyroxene, with no exsolution, and a 2V of 65°–70°, is rare and found only as relicts in centers of altered clinopyroxene grains (25–35 modal %). Where two or more clinopyroxene grains abut, a fine grained matrix now separates these crystals. Kyanite is abundant (25–30 modal %), is colorless in plane light, euhedral to subhedral, and has an average grain size of $\approx$3 mm in longest dimension. Broad elongated sections are parallel to (100), and narrower sections are parallel to (010) and (001). Paired twins with (100) as the twin plane, and multiple twins with (001) as the twin plane are present. Larger grains contain rounded and elliptical inclusions of colorless corundum (0.025 mm–0.20 mm) and fine feathered lamellae that remain unidentified. In some cases, a fine grained fibrous silicate has completely replaced kyanite and is possibly sapphirine, dumortierite, or glaucophane. Rutile is restricted to the fine grained matrix in euhedral to subhedral grains (0.5 mm max), and is bright orange-brown or very nearly opaque if ilmenite lamellae are present. Colorless to pale green pleochroic amphiboles adjacent to, and surrounding rutile grains have reacted with rutile and are pleochroic in orange-brown. The fine-grained matrix is dominated by feldspar, green spinel, glass, and pleochroic green, brown, and colorless amphibole with calcite in minor concentrations.

### *Kyanite + quartz eclogite*

Free $SiO_2$ (quartz or coesite) is relatively rare in eclogites (Dawson 1968; Wohletz and Smyth 1984; Schulze and Helmstaedt 1988). Only one kyanite + quartz-bearing eclogite (KEC-86-QB-1) is recognized at Koidu. The occurrence of coesite as a primary phase has been reported in a grospydite from Roberts Victor (Smyth and Hatton 1977). In hand specimen, xenolith KEC-86-QB-1 is distinct from other kyanite-bearing eclogites in displaying an overall dull, leached, and yet glassy appearance. Garnets (45 modal %) are a dull orange-yellow in association with interstitial pale-green clinopyroxene (20 modal %) and elongate, clear to pale blue kyanite and clear quartz (25 modal %) up to 4 and 7 mm in length, respectively. In thin section, colorless rounded garnets are altered along symplectite-textured cracks and are surrounded by "kelyphite" rims more typical of peridotites (Garvie and Robinson 1984). Interstitial clinopyroxene, highly altered by opaque, irresolvable alteration assemblages, surrounds garnet and quartz grains. Quartz, determined from refractive indices in grain oil-immersion mounts, comprises approximately 12 modal % of the xenolith. Microfractures radiating outwards from grain centers to crystal margins and recrystallization are typical of the coesite-quartz inversion (Smyth 1977). Quartz is pleochroic in yellow and pale pink and fluoresces orange under the electron microbeam. Kyanite is closely associated with quartz and rutile, and sulfide is absent in the xenolith.

### *Corundum-bearing eclogite*

Corundum-bearing eclogites are rare but are reported from Bobbejaan, Frank Smith, Newlands, Crown, Jagersfontein, and Roberts Victor, in South Africa (Rickwood et al. 1969), Zagadochnaya in Yakutia (Sobolev et al. 1968), Colorado/Wyoming (Eggler and McCallum 1974), and Orapa, Botswana (Shee and Gurney 1979). In hand specimen, the appearance of the single xenolith (KEC-86-CB-68) from Koidu is similar to the kyanite-bearing xenoliths, with orange-brown garnets, pale green clinopyroxenes, and pale-purple corundum. The specimen is a small fragment ($6 \times 3 \times 3$ cm) showing two apparent foliations: one formed by garnet-rich and clinopyroxene-rich layers, and a second by corundum grains aligned obliquely to garnet and clinopyroxene. In thin section, subrounded grains of pink garnet, up to 1 cm long, compose $\approx$43 modal % of the slide. The dominant alteration has a preferred orientation cross-cutting garnet grains, whereas a second, more subtle alteration has a distinct vermicular texture and fills larger cracks. Clinopyroxenes ($\approx$42 modal %) are anhedral (5 mm max), pale, blue-green in plane light and contain an orientated alteration product. Corundum ($\approx$10 modal %), is colorless, occurs as rounded and elliptical grains (5 mm max.) interstitial to garnet and clinopyroxene, and displays an abnormal 2V of approximately 15°–20°. Twin lamellae and a patchy distribution of colors are pronounced under crossed nicols. Twinning is so pronounced in some grains, that these are visible to the naked eye.

### *Amphibole-bearing eclogite*

Amphibole is present in a number of eclogites with concentrations from trace amounts to $\approx$5 modal %. Eclogite KEC-81-AB-11, however, contains $\approx$30 modal % of a colorless amphibole. This large eclogite ($15 \times 11 \times 6$ cm), is ovoid in shape, and is composed of $\approx$30 modal % each of garnet, clinopyroxene, and amphibole, and 10 modal % secondary interstitial alteration. In thin section, pink garnets are coarse-grained (3–5 mm), subhedral, and are cracked and filled by a dark irresolvable green material. Some garnets contain highly birefringent needle-shaped and/or opaque prismatic-shaped inclusions as long as 0.1 mm. Clinopyroxenes are pale blue-green, slightly pleochroic, elongated with straight edges, and generally present a fresh appearance but have cloudy patches due to a secondary fine grained alteration product. Clinopyroxenes have a prominent cleavage and contain numerous rodlike inclusions of clear, translucent garnet and rutile. Euhedral amphibole ($\approx 5$ mm) displays good basal cleavage and subtle brown-green pleochroism. Amphibole replaces both garnet and clinopyroxene but unlike other eclogites, amphibole is dominantly equigranular and is not confined to alteration cracks or grain boundaries.

*Carbonaceous eclogites*

This study includes six diamond-bearing eclogites, one diamond+graphite-bearing eclogite, and two graphite-bearing eclogites. Although no diamond inclusion studies were undertaken in this project, Harris and Gurney (1979) describe eight sulfide inclusions in discrete diamonds from the Koidu kimberlite. Two of these may be assigned to an eclogite paragenesis, and one to a peridotite paragenesis, based on coexisting minerals. Meyer and Boyd (1972) describe Zn-rich chromite as a diamond inclusion, which is of ultramafic origin.

*Diamond-bearing eclogites*

These samples (KEC-80-DB-D1, 2, 3, 40, KEC-81-DB-1, KEC-86-DB-10, and KEC-86-DB-9) range in size from $6 \times 4 \times 5$ cm to $15 \times 7 \times 6$ cm. Garnet to clinopyroxene ratios (Table 1) range from approximately 60:40 to 40:60. In hand specimen, all diamond-bearing eclogites have a granular texture, garnets range from pale orange to dark red brown, and are coarse grained (3–10 mm) and subhedral. In thin section, grains are colorless to pale pink and cracked with veinlets of secondary material cross-cutting and rimming grains. Coarse-grained (<10 mm) clinopyroxene is pale blue in thin section, subhedral, and is partially altered to a creamy pale green, optically irresolvable secondary assemblage. Pristine relicts are rare and restricted to grain centers, where very fine twin lamellae are evident. Eclogite KEC-81-DB-1 contains two distinct garnets and clinopyroxenes. A primary garnet, colorless in plane light, is rimmed by a second garnet, that is slightly orange in plane light. Always associated at the interface of these garnets are amphibole and phlogopite. Clinopyroxene grains contain 'blebby' interiors, more altered than surrounding, pristine margins. Accessory minerals include rutile, sulfide and less commonly ilmenite. Each of these minerals may constitute up to 3 modal % of the sample, and reach up to 2 mm in size. Rutile grains are subhedral and are a distinct translucent orange unless filled with squat ilmenite lamellae oriented at $\approx 60°$. Sulfides (0.2–2 mm in diam.) are deemed primary if rounded or subhedral, and secondary if present in veinlets.

A hopper crystal of diamond ($\approx 1$ mm) is present among altered clinopyroxene in KEC-80-DB-D1 (Tompkins 1983). One half of this xenolith ($\approx 0.5$ kg) was treated in HF acid and forty-two diamonds were recovered. KEC-81-DB-1 is unusual in the collection in that it contains a stepped clear octahedral and a flat green octahedral diamond only 3 mm apart, as is KEC-86-DB-9 which contains both diamond and graphite. In thin section, 3 grains of layered clear octahedral and flat green octahedral diamonds, approximately 0.3 mm in diameter and smaller, are embedded in altered clinopyroxene. Opaque mineral inclusions in these diamonds appear to be sulfide but some may be graphite. Exposed on the surface of the eclogite are two clear diamonds (3 mm), also embedded in altered clinopyroxene, and a massive graphite crystal (2 mm), in fresh clinopyroxene.

*Graphite-bearing eclogites*

In hand specimen and thin section, graphite-bearing eclogites KEC-86-BG-12 and KEC-86-GB-70 are very similar in texture, fabric, and state of silicate preservation to the diamond-bearing eclogites. Small pits (<1 mm), always associated with altered clinopyroxene, crater the surface of these xenoliths where graphite has been removed. Graphite (5–10 modal %) is present as discrete crystals (0.1 mm to 4.0 mm) but is primarily massive or granular.

## Mineral chemistry

Mineral chemistry was determined in 46 polished-thin sections, consisting of 44 eclogites (KEC) and 2 granulites (KGR). Twenty-nine of the eclogites are bimineralic with garnet and clinopyroxene, 9 are diamond and/or graphite-bearing eclogites (DB and GB), 4 are kyanite-bearing eclogites (KB), one is corundum-bearing (CB), and one contains 30 modal % amphibole (AB). Garnet, and to a lesser extent clinopyroxene, fall chemically into two distinct subgroups based on bulk chemical magnesium contents.

*Garnet*

Taken as group, Koidu eclogitic garnets (Table 2) are chromium and manganese-poor with variable pyrope (20.3–75.7 mole %), grossular (9.6–55.6 mole %) and almandine (14.5–55.0 mole %). Application of the statistical classification of Dawson and Stephens (1976) shows that: twenty three garnets are classified as calcic pyrope-almandine, 9 as pyrope-grossular-almandine, 5 are chrome-pyrope, and 4 fall in other classifications.

The Ca–Mg–Fe plot in Fig. 2a, b illustrates the wide variation in garnet composition. The trend is dominantly from Mg towards Ca and Fe-enrichment. Koidu garnets differ from garnets in peridotite-pyroxenite groups (Dawson 1980) in which Fe is relatively constant, and variations are mainly in Ca relative to Mg. Garnets from kyanite-bearing eclogites are the most calcic containing 42.4, 45.0, and 55.6 mole % grossular. Eclogite KEC-86-KB-3 is a grospydite with 55.6 mole % grossular. Garnet from the kyanite+quartz eclogite contains only 33.7 mole % grossular and is magnesium-rich and iron-poor relative to garnets in other kyanite-bearing eclogites. Garnet from the corundum-bearing eclogite has a high grossular component (44.7 mol %), but is less iron-rich than garnets from kyanite-bearing eclogites.

Diamondiferous eclogites cluster in the center of the ternary, with restricted Mg, Fe and Ca compositions ranging from 33.7–49.7, 19.9–35.6, and 21.2–32.7, respectively. Garnets from the two graphite-bearing eclogites fall outside this field, towards more iron-rich compositions. The remaining garnets are from bimineralic eclogites and are split into two distinct groups. High-MgO garnets (60.2–75.7 pyrope), have relatively constant grossular contents (9.6–13.8), and slightly variable almandine (14.5–28.1) components. Low-MgO garnets, enriched in Fe and Ca bridge the gap between garnets in kyanite-bearing eclogites and garnets in diamond-bearing eclogites.

With respect to minor element chemistry, garnets have low $Cr_2O_3$ contents (0.01–0.72 wt%) and are low to moderate in $TiO_2$ (0.02–0.90 wt%). $K_2O$ and $Na_2O$ contents are extremely low. Garnets from diamond eclogites contain the highest $Na_2O$, (0.24 wt%) but contain no detectable $K_2O$. High $Na_2O$ concentrations in garnets are described by Reid et al. (1976) and McCandless and Gurney (1989), in diamond-bearing eclogites from Roberts Victor, with compositions ranging from 0.07–0.15 wt% with an average of 0.10 wt%. The small, but significant amount of $Na_2O$ in

**Table 2.** Garnet analyses from Koidu eclogites

| | High-MgO garnets from bimineralic eclogites | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-80-B1 | KEC-81-2 | KEC-81-AB-11 | KEC-86-2 | KEC-86-8 | KEC-86-15 | KEC-86-58 | KEC-86-73A | KEC-86-73B | KEC-86-90 | KEC-86-107 |
| $SiO_2$ | 41.56 | 41.44 | 42.48 | 42.08 | 41.95 | 42.09 | 42.90 | 42.26 | 42.03 | 42.05 | 42.38 |
| $TiO_2$ | 0.15 | 0.14 | 0.19 | 0.08 | 0.22 | 0.24 | 0.19 | 0.20 | 0.02 | 0.07 | 0.15 |
| $Al_2O_3$ | 23.03 | 22.86 | 23.24 | 22.94 | 23.40 | 21.58 | 22.48 | 22.36 | 21.99 | 22.01 | 22.42 |
| $Cr_2O_3$ | 0.13 | 0.08 | 0.40 | 0.09 | 0.62 | 0.25 | 0.28 | 0.44 | 0.72 | 0.23 | 0.43 |
| FeO | 13.49 | 13.95 | 7.84 | 12.60 | 9.19 | 14.30 | 7.54 | 11.91 | 11.84 | 12.48 | 7.55 |
| MgO | 17.79 | 16.80 | 21.90 | 18.40 | 20.05 | 17.49 | 22.06 | 19.10 | 19.05 | 18.60 | 20.33 |
| MnO | 0.35 | 0.40 | 0.38 | 0.41 | 0.44 | 0.36 | 0.33 | 0.41 | 0.61 | 0.32 | 0.33 |
| CaO | 3.81 | 4.54 | 3.94 | 4.00 | 4.27 | 4.16 | 3.99 | 3.79 | 3.91 | 4.24 | 5.45 |
| $Na_2O$ | 0.05 | 0.05 | 0.01 | 0.02 | 0.00 | 0.09 | 0.01 | 0.05 | 0.03 | 0.02 | 0.06 |
| $K_2O$ | – | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 100.36 | 100.27 | 100.39 | 100.62 | 100.15 | 100.56 | 99.78 | 100.52 | 100.20 | 100.02 | 99.10 |

| | Low-MgO garnets from bimineralic eclogites | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-80-A2 | KEC-81-3 | KEC-81-4 | KEC-81-5 | KEC-81-7 | KEC-81-8 | KEC-81-10A | KEC-81-12 | KEC-81-18 | KEC-81-21 | KEC-86-6 |
| $SiO_2$ | 39.41 | 39.89 | 39.65 | 39.06 | 40.13 | 39.59 | 40.27 | 39.13 | 39.69 | 40.07 | 39.19 |
| $TiO_2$ | 0.10 | 0.35 | 0.07 | 0.06 | 0.30 | 0.13 | 0.36 | 0.05 | 0.21 | 0.24 | 0.11 |
| $Al_2O_3$ | 22.42 | 21.75 | 21.63 | 21.27 | 21.73 | 21.90 | 21.58 | 20.86 | 21.18 | 21.91 | 22.25 |
| $Cr_2O_3$ | 0.01 | 0.08 | 0.15 | 0.18 | 0.20 | 0.10 | 0.09 | 0.08 | 0.11 | 0.13 | 0.03 |
| FeO | 19.08 | 15.70 | 23.16 | 21.51 | 17.23 | 17.37 | 16.77 | 26.23 | 21.32 | 19.30 | 19.21 |
| MgO | 7.35 | 7.79 | 11.35 | 8.04 | 10.69 | 8.88 | 11.73 | 6.34 | 6.11 | 11.45 | 7.25 |
| MnO | 0.50 | 0.29 | 0.51 | 0.44 | 0.41 | 0.34 | 0.38 | 0.58 | 0.52 | 0.50 | 0.42 |
| CaO | 11.13 | 14.80 | 3.68 | 8.84 | 9.73 | 11.71 | 8.81 | 7.93 | 12.05 | 6.57 | 11.92 |
| $Na_2O$ | 0.01 | 0.11 | 0.01 | 0.00 | 0.04 | 0.00 | 0.12 | 0.02 | 0.01 | 0.04 | 0.00 |
| $K_2O$ | – | 0.02 | 0.01 | 0.02 | 0.01 | 0.02 | 0.11 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 100.01 | 100.78 | 100.22 | 99.42 | 100.47 | 100.04 | 100.22 | 101.22 | 101.20 | 100.21 | 100.38 |

| | Low-MgO garnets from bimineralic eclogites | | | | | | Low-MgO garnets from diamond-bearing eclogites | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-86-11 | KEC-86-13 | KEC-86-71A | KEC-86-71B | KEC-88-72A | KEC-86-72B | KEC-86-DB-10 | KEC-80-DB-D1 | KEC-80-DB-2 | KEC-80-DB-3 | KEC-80-DB-40 | KEC-86-DB-9 |
| $SiO_2$ | 39.81 | 39.22 | 40.64 | 40.55 | 39.14 | 39.27 | 40.15 | 40.52 | 40.67 | 40.85 | 40.20 | 40.77 |
| $TiO_2$ | 0.09 | 0.07 | 0.12 | 0.10 | 0.20 | 0.11 | 0.21 | 0.37 | 0.59 | 0.28 | 0.29 | 0.90 |
| $Al_2O_3$ | 21.50 | 21.39 | 21.70 | 21.55 | 20.96 | 20.48 | 21.89 | 23.15 | 22.62 | 24.26 | 22.81 | 21.33 |
| $Cr_2O_3$ | 0.06 | 0.03 | 0.17 | 0.18 | 0.10 | 0.20 | 0.05 | 0.05 | 0.02 | 0.08 | 0.03 | 0.09 |
| FeO | 15.64 | 21.95 | 16.24 | 16.65 | 23.15 | 21.76 | 17.59 | 13.40 | 16.26 | 9.56 | 13.99 | 15.28 |
| MgO | 6.74 | 8.26 | 10.04 | 9.49 | 6.03 | 7.55 | 11.09 | 10.89 | 11.54 | 13.42 | 10.77 | 11.14 |
| MnO | 0.28 | 0.57 | 0.30 | 0.35 | 0.59 | 0.43 | 0.34 | 0.26 | 0.43 | 0.22 | 0.33 | 0.33 |
| CaO | 15.44 | 8.29 | 11.74 | 12.26 | 10.59 | 9.94 | 9.40 | 11.78 | 7.72 | 11.42 | 11.02 | 11.40 |
| $Na_2O$ | 0.01 | 0.00 | 0.01 | 0.02 | 0.01 | 0.04 | 0.02 | 0.17 | 0.24 | 0.09 | 0.03 | 0.19 |
| $K_2O$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | – | – | – | – | 0.00 |
| Total | 99.57 | 99.78 | 100.96 | 101.15 | 100.77 | 99.78 | 100.74 | 100.59 | 100.09 | 100.18 | 99.47 | 101.43 |

| | Graphite-bearing eclogites | | Low-MgO garnets from kyanite- and corundum eclogites | | | | | Granulites | |
|---|---|---|---|---|---|---|---|---|---|
| | KEC-86-GB-12 | KEC-86-GB-70 | KEC-86-QB-1 | KEC-86-KB-3 | KEC-86-KB-4 | KEC-86-KB-74B | KEC-86-CB-68 | KGR-86-75 | KGR-86-76 |
| $SiO_2$ | 38.96 | 40.63 | 41.73 | 39.65 | 39.22 | 39.85 | 42.25 | 39.97 | 40.51 |
| $TiO_2$ | 0.21 | 0.24 | 0.03 | 0.21 | 0.12 | 0.12 | 0.10 | 0.00 | 0.02 |
| $Al_2O_3$ | 22.17 | 21.99 | 22.90 | 21.02 | 22.95 | 21.40 | 20.33 | 21.35 | 21.60 |
| $Cr_2O_3$ | 0.08 | 0.18 | 0.14 | 0.05 | 0.16 | 0.14 | 0.07 | 0.29 | 0.19 |
| FeO | 20.99 | 21.37 | 7.46 | 11.70 | 14.78 | 14.45 | 6.91 | 24.79 | 19.89 |
| MgO | 8.20 | 11.75 | 14.49 | 5.53 | 7.13 | 6.82 | 11.90 | 11.54 | 12.17 |
| MnO | 0.44 | 0.48 | 0.14 | 0.26 | 0.18 | 0.28 | 0.19 | 0.42 | 0.29 |
| CaO | 10.29 | 4.76 | 13.22 | 21.08 | 15.80 | 16.97 | 17.75 | 2.58 | 6.04 |
| $Na_2O$ | 0.04 | 0.00 | 0.01 | 0.02 | 0.02 | 0.00 | 0.11 | 0.00 | 0.01 |
| $K_2O$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Total | 101.38 | 101.40 | 100.12 | 99.52 | 100.36 | 100.03 | 99.62 | 100.94 | 100.72 |

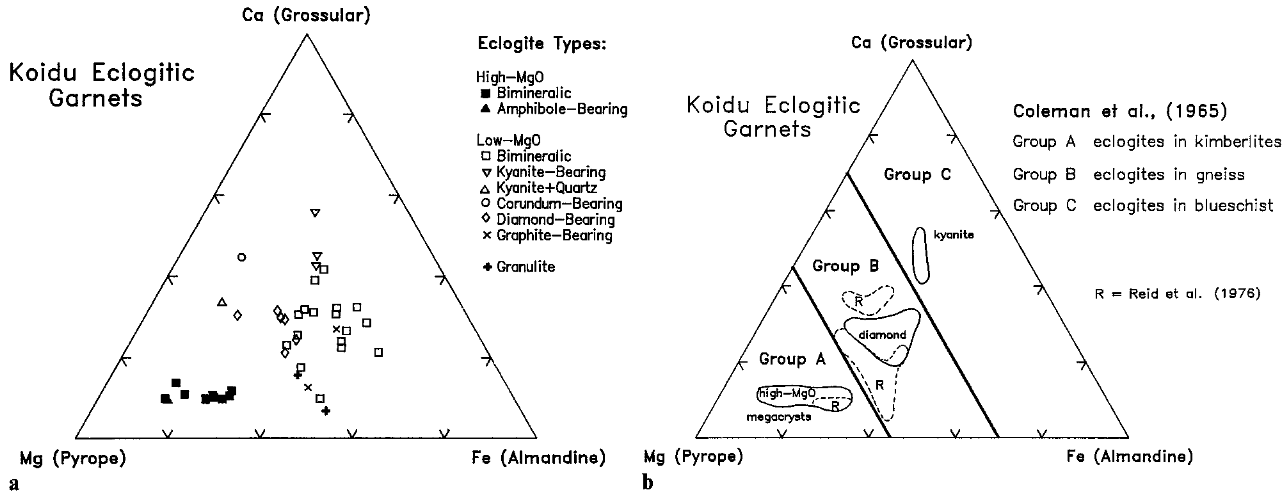



**Fig. 2.** **a** Garnet compositions from Koidu eclogites and granulites plotted as mole percent pyrope-grossular-almandine. **b** Fields of garnet compositions for diamond-bearing, kyanite-bearing and high-MgO eclogites from Koidu; discrete megacrysts from Koidu; and diamond-bearing eclogites from Reid et al. (1976), plotted as mol% pyrope-grossular-almandine

eclogitic garnets was first recognized by Sobolev and Lavrent'yer (1971), who proposed that high sodium contents were especially significant in diamond-bearing rocks, attributing elevated sodium contents to high pressures.

Eclogites containing accessory primary minerals of diamond, graphite, kyanite, quartz, and corundum are characterized by low-MgO almandine and grossular-rich garnets. Pyropic garnets are exclusively in bimineralic assemblages and contain the lowest amount of calcium, but the largest content of $Cr_2O_3$. Low-MgO garnets from kyanite-bearing eclogites contain significant calcium, but are lowest in $Cr_2O_3$ concentrations.

High-MgO garnets are very similar to discrete garnet megacrysts from Koidu (Tompkins and Haggerty 1984) in terms of Mg, Fe and Ca contents; however, discrete garnet megacrysts contain a substantially greater amount of $Cr_2O_3$ (0.46–5.40 wt%) than eclogitic garnets (0.08–0.72 wt%). Magnesium-rich, calcium-poor garnets are also present in the Thaba Putsoa Kimberlite, Lesotho, (Griffin et al. 1979). The compositional field for discrete garnet megacrysts are plotted in Fig. 2b, along with fields of low-MgO kyanite and diamond eclogite garnets, bimineralic high-MgO garnets, and garnets from diamond-bearing eclogites from Roberts Victor (Reid et al. 1976). Some of the diamond-bearing eclogitic garnets from Roberts Victor plot in the field of high-MgO Koidu garnets but the remainder straddle the Koidu diamond-bearing eclogitic fields. Fields A, B, and C in Fig. 2b are defined by Coleman et al. (1965) for eclogites from inclusions in kimberlites, basalts, and layers in ultramafic rocks (A), from lenses within migmatitic gneiss terrains (B), and from lenses within alpine-type metamorphic rocks (C). Bimineralic high-MgO garnets are restricted to field (A), bimineralic low-MgO garnets are restricted to fields (B) + (C), and garnets from diamond and kyanite eclogites fall in the fields of (B) + (C), respectively; no genetic significance to these fields is implied. Bimineralic, low magnesium eclogites contain garnets with the lowest Mg values (30.1–40.7), followed by kyanite-bearing eclogites (45.7–46.2), diamond-bearing eclogites (50.0–71.4), and bimineralic eclogites, with pyropic-rich garnets and Mg values of 68.2–83.9. Calcium ranges from 3.8–5.5 wt% CaO for high-MgO eclogitic garnets to the highest value of 21.1 wt% CaO for low-MgO kyanite-bearing eclogitic garnets.

Garnets from the two granulites are almandine- and pyrope-rich with 51.0 and 40.3% almandine, 42.3 and 44.0% pyrope and 6.8 and 15.7%grossular contents, respectively (Fig. 2a).

*Pyroxene*

Compositions for optical and chemically homogeneous pyroxene coexisting with garnet are presented in Table 3. Pyroxene analyses for KEC-86-71A and KGR-86-75 are precluded because of alteration. Pyroxenes range in jadeite contents (7.7–70.1%) as illustrated on the projection of the jadeite ($Na + Al^{VI} + Cr$), wollastonite (Ca), and hypersthene ($Mg + Fe + Mn$) ternary (Fig. 3a). Most data lie along the diopside-jadeite join showing that there are no major variations among these end members. Kyanite-bearing eclogites have jadeite-rich pyroxenes with an average composition of $Jd_{49}Di_{51}$, but pyroxenes in the corundum-bearing eclogite are $Jd_{70}Di_{30}$. Pyroxenes from diamond- and graphite-bearing eclogites are omphacitic, ranging from $Jd_{25}Di_{75}$ to $Jd_{46}Di_{54}$. High-MgO eclogites contain the most diopside-enriched pyroxenes, with an average of $Jd_{38}Di_{62}$, whereas low-MgO bimineralic eclogites have a range of pyroxene compositions, from diopside to omphacite (Fig. 3b, c).

Pyroxenes behave in a manner similar to that of garnets with a trend from Mg towards Fe- and to a lesser extent in Ca-enrichment with compositions that range from $Wo_{43}$-$Wo_{51}$, $En_{35}$-$En_{51}$, $Fs_2$-$Fs_{17}$. High-MgO garnets have coexisting high-MgO pyroxenes, diamond-bearing eclogites with almandine-grossular-rich garnets coexist with pyroxenes intermediate in Ca, Mg and Fe contents, and grossular-rich garnets from kyanite-bearing eclogites contain pyroxenes with the highest calcium contents. The sole granulite with an obtainable pyroxene analysis has a very high wollastonite content ($Wo_{51}$). Results from the statistical classification of Stephens and Dawson (1977) shows that ten clinopyroxenes may be classified as diopside, 14 as jadeite-diopside, 12 as omphacite, one as a low Cr-diopside, and another as chrome diopside. Pyroxenes from KEC-86-CB-68, KEC-86-QB-1, and KGR-86-76 are not classifiable.

In terms of minor elements, the highest Ti contents are present in omphacites from diamond-bearing eclogites

**Table 3.** Pyroxene analyses from Koidu eclogites

| | High-MgO pyroxenes from bimineralic eclogites | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-80-B1 | KEC-81-2 | KEC-81-AB-11 | KEC-86-2 | KEC-86-8 | KEC-86-15 | KEC-86-58 | KEC-86-73A | KEC-86-73B | KEC-86-90 | KEC-86-107 |
| $SiO_2$ | 54.54 | 54.95 | 55.68 | 54.95 | 54.89 | 55.30 | 55.96 | 55.97 | 56.00 | 55.09 | 55.74 |
| $TiO_2$ | 0.14 | 0.16 | 0.29 | 0.13 | 0.14 | 0.20 | 0.21 | 0.22 | 0.19 | 0.12 | 0.27 |
| $Al_2O_3$ | 2.97 | 2.85 | 3.93 | 3.02 | 2.54 | 4.35 | 2.78 | 3.65 | 3.02 | 2.68 | 4.08 |
| $Cr_2O_3$ | 0.07 | 0.02 | 0.22 | 0.08 | 0.42 | 0.17 | 0.12 | 0.21 | 0.30 | 0.09 | 0.16 |
| FeO | 4.46 | 4.24 | 2.44 | 3.51 | 1.76 | 4.80 | 1.56 | 3.67 | 2.98 | 3.99 | 2.09 |
| MgO | 14.55 | 14.44 | 15.38 | 15.16 | 16.17 | 13.54 | 16.66 | 15.03 | 15.24 | 15.67 | 15.29 |
| MnO | 0.02 | 0.04 | 0.06 | 0.05 | 0.05 | 0.07 | 0.02 | 0.07 | 0.02 | 0.06 | 0.01 |
| CaO | 20.15 | 20.73 | 19.32 | 20.85 | 21.30 | 17.34 | 20.76 | 18.70 | 20.82 | 19.83 | 19.41 |
| $Na_2O$ | 2.59 | 2.54 | 3.24 | 2.49 | 1.71 | 3.72 | 2.15 | 3.13 | 2.51 | 2.44 | 3.10 |
| $K_2O$ | – | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.01 | 0.00 |
| Total | 99.49 | 99.98 | 100.56 | 100.24 | 98.98 | 99.49 | 100.22 | 100.66 | 101.10 | 99.98 | 100.15 |

| | Low-MgO pyroxenes from bimineralic eclogites | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-80-A2 | KEC-81-3 | KEC-81-4 | KEC-81-5 | KEC-81-7 | KEC-81-8 | KEC-81-10A | KEC-81-12 | KEC-81-18 | KEC-81-21 | KEC-86-6 |
| $SiO_2$ | 55.02 | 55.19 | 55.74 | 54.23 | 55.47 | 56.79 | 56.90 | 50.91 | 55.13 | 55.20 | 55.58 |
| $TiO_2$ | 0.07 | 0.37 | 0.13 | 0.10 | 0.22 | 0.07 | 0.37 | 0.54 | 0.12 | 0.40 | 0.07 |
| $Al_2O_3$ | 6.69 | 9.78 | 5.19 | 2.52 | 8.41 | 10.31 | 10.58 | 4.85 | 7.15 | 8.39 | 6.22 |
| $Cr_2O_3$ | 0.03 | 0.01 | 0.09 | 0.09 | 0.11 | 0.03 | 0.00 | 0.03 | 0.00 | 0.08 | 0.06 |
| FeO | 5.34 | 3.74 | 5.81 | 6.58 | 4.12 | 3.59 | 3.96 | 9.76 | 6.32 | 5.49 | 5.06 |
| MgO | 10.82 | 9.53 | 12.89 | 14.32 | 10.91 | 9.61 | 9.45 | 11.18 | 10.18 | 10.50 | 11.75 |
| MnO | 0.03 | 0.01 | 0.04 | 0.05 | 0.01 | 0.02 | 0.03 | 0.03 | 0.04 | 0.05 | 0.08 |
| CaO | 17.23 | 15.74 | 17.08 | 22.14 | 15.07 | 14.34 | 12.23 | 21.53 | 16.65 | 14.40 | 17.86 |
| $Na_2O$ | 4.73 | 6.05 | 3.68 | 0.96 | 5.66 | 5.93 | 7.22 | 1.44 | 4.94 | 5.48 | 3.65 |
| $K_2O$ | – | 0.02 | 0.02 | 0.03 | 0.06 | 0.00 | 0.04 | 0.02 | 0.01 | 0.05 | 0.01 |
| Total | 99.96 | 100.44 | 100.67 | 101.02 | 100.04 | 100.69 | 100.78 | 100.29 | 100.54 | 100.04 | 100.34 |

| | Low-MgO pyroxenes from bimineralic eclogites | | | | | Low-MgO pyroxenes from diamond-bearing eclogites | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-86-11 | KEC-86-13 | KEC-86-71B | KEC-86-72A | KEC-86-72B | KEC-86-DB-10 | KEC-80-DB-D1 | KEC-80-DB-2 | KEC-80-DB-3 | KEC-80-DB-40 | KEC-86-DB-9 |
| $SiO_2$ | 53.90 | 55.43 | 56.41 | 50.61 | 55.69 | 55.28 | 55.56 | 55.23 | 55.57 | 55.85 | 55.12 |
| $TiO_2$ | 0.14 | 0.17 | 0.11 | 0.38 | 0.17 | 0.23 | 0.22 | 0.42 | 0.22 | 0.29 | 0.61 |
| $Al_2O_3$ | 8.40 | 7.13 | 10.79 | 3.86 | 6.56 | 9.25 | 11.00 | 8.30 | 12.61 | 10.25 | 8.03 |
| $Cr_2O_3$ | 0.04 | 0.02 | 0.04 | 0.06 | 0.04 | 0.04 | 0.09 | 0.03 | 0.11 | 0.08 | 0.04 |
| FeO | 3.34 | 6.15 | 2.40 | 8.82 | 6.77 | 4.15 | 2.94 | 4.46 | 1.89 | 3.29 | 6.23 |
| MgO | 11.59 | 10.29 | 9.70 | 12.79 | 10.49 | 10.34 | 9.86 | 10.85 | 9.23 | 9.25 | 10.49 |
| MnO | 0.06 | 0.08 | 0.02 | 0.05 | 0.02 | 0.03 | 0.03 | 0.02 | 0.04 | 0.01 | 0.05 |
| CaO | 18.33 | 15.50 | 14.13 | 19.03 | 15.73 | 14.43 | 14.89 | 14.41 | 13.90 | 13.48 | 15.27 |
| $Na_2O$ | 3.01 | 5.17 | 5.80 | 2.85 | 5.28 | 6.48 | 5.82 | 5.81 | 6.41 | 6.92 | 4.55 |
| $K_2O$ | 0.06 | 0.01 | 0.01 | 0.00 | 0.00 | 0.16 | – | – | – | – | 0.38 |
| Total | 98.87 | 99.95 | 99.41 | 98.45 | 100.75 | 100.39 | 100.41 | 99.53 | 99.98 | 99.42 | 100.77 |

| | Graphite-bearing eclogites | | Low-MgO pyroxenes from kyanite- and corundum-bearing eclogites | | | | | Granulites |
|---|---|---|---|---|---|---|---|---|
| | KEC-86-GB-12 | KEC-86-GB-70 | KEC-86-QB-1 | KEC-86-KB-3 | KEC-86-KB-4 | KEC-86-KB-74B | KEC-86-CB-68 | KGR-86-76 |
| $SiO_2$ | 56.45 | 55.44 | 54.58 | 56.09 | 55.88 | 54.88 | 57.58 | 50.07 |
| $TiO_2$ | 0.16 | 0.25 | 0.08 | 0.12 | 0.09 | 0.07 | 0.05 | 1.07 |
| $Al_2O_3$ | 9.44 | 5.85 | 9.78 | 12.84 | 13.48 | 13.03 | 17.55 | 8.48 |
| $Cr_2O_3$ | 0.08 | 0.12 | 0.13 | 0.03 | 0.13 | 0.02 | 0.07 | 0.08 |
| FeO | 4.30 | 5.89 | 0.88 | 2.12 | 2.15 | 2.25 | 0.82 | 5.53 |
| MgO | 9.70 | 12.33 | 12.51 | 8.23 | 8.20 | 8.53 | 5.86 | 12.40 |
| MnO | 0.04 | 0.05 | 0.01 | 0.00 | 0.00 | 0.05 | 0.02 | 0.04 |
| CaO | 15.17 | 15.61 | 18.50 | 13.73 | 13.17 | 13.56 | 7.79 | 22.16 |
| $Na_2O$ | 5.56 | 4.25 | 3.91 | 6.69 | 7.12 | 6.89 | 11.19 | 1.37 |
| $K_2O$ | 0.16 | 0.07 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 |
| Total | 101.06 | 99.86 | 100.40 | 99.86 | 100.24 | 99.29 | 100.94 | 101.21 |

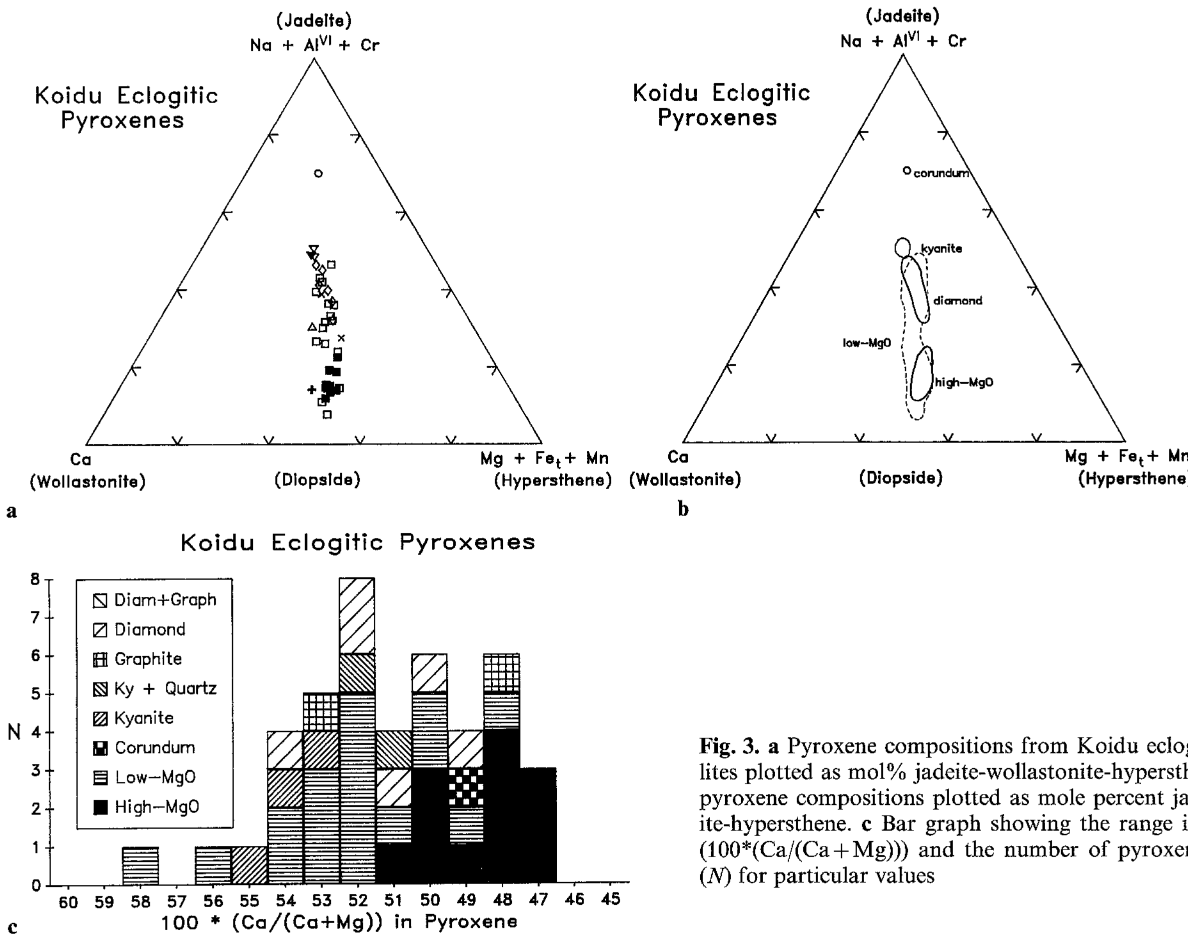



**Fig. 3.** **a** Pyroxene compositions from Koidu eclogites and granulites plotted as mol% jadeite-wollastonite-hypersthene. **b** Fields of pyroxene compositions plotted as mole percent jadeite-wollastonite-hypersthene. **c** Bar graph showing the range in calcium value (100*(Ca/(Ca+Mg))) and the number of pyroxene compositions (*N*) for particular values

(0.09–0.61 wt% $TiO_2$). The content of $Cr_2O_3$ is low, except for diopsides (0.02–0.42 wt% $Cr_2O_3$) coexisting with bimineralic eclogitic pyrope. Pyroxenes have low, but in some cases discernible contents of $K_2O$ (less than 0.38 wt% $K_2O$), shown in Table 3. Carbon-bearing eclogites KEC-86-DB-10, KEC-86-GB-12 and KEC-86-DB-9 have abnormally high $K_2O$-bearing clinopyroxenes (0.16, 0.16 and 0.38 wt%, respectively). An occluded omphacite in diamond in an eclogite from the Mir pipe (Sobolev 1977) contains 0.30 wt% $K_2O$; otherwise the phases in both diamond and host rock are very similar, including identical $Na_2O$ contents in both inclusion and host-rock garnets. Potassium-bearing clinopyroxenes are also reported in eclogites from South Africa (McCandless and Gurney 1989), and in glass (19.9 wt% $K_2O$) from omphacitic melting (Switzer and Melson 1969). Potassium contents in diopside from peridotite in the Argyle lamproite are typically 0.1–0.4 wt% $K_2O$, but reach up to 1.3 wt% $K_2O$ (Jaques et al. 1989). Because potassium is difficult to accommodate in the pyroxene structure (e.g. Harlow and Dowty 1982) it is possible that K is present in a discrete phase, introduced metasomatically or exsolved on decompression.

### *Primary accessory minerals*

Average chemical analyses for kyanite in two kyanite-bearing eclogites and one grospydite are listed in Table 4. Kyanite is relatively pure, containing 62.0–66.6 wt% $Al_2O_3$ and 34.0–37.1 wt% $SiO_2$, but detectable amounts of $Cr_2O_3$ (0.03–0.32 wt%), and lesser amounts of FeO (0.07–0.16 wt%) are present. Large corundum grains from the corundum-bearing eclogite (Table 4) are also relatively pure (99.5 wt% $Al_2O_3$), with only minor amounts of FeO (0.26 wt%) and lesser amounts of $Cr_2O_3$ (0.14 wt%).

**Table 4.** Kyanite, corundum, and pyroxene analyses from Koidu eclogites

| | Kyanite | | | Corundum | Altered pyroxene |
|---|---|---|---|---|---|
| | KEC-86-KB-1 | KEC-86-KB-3 | KEC-86-KB-4 | KEC-86-CB-68 | KEC-86-KB-74B |
| $SiO_2$ | 35.50 | 34.01 | 37.14 | 0.00 | 56.54 |
| $TiO_2$ | 0.03 | 0.00 | 0.03 | 0.02 | 0.10 |
| $Al_2O_3$ | 63.94 | 66.62 | 61.96 | 99.54 | 12.54 |
| $Cr_2O_3$ | 0.32 | 0.03 | 0.23 | 0.14 | 0.01 |
| FeO | 0.07 | 0.16 | 0.16 | 0.26 | 2.42 |
| MgO | 0.01 | 0.01 | 0.03 | 0.00 | 9.06 |
| MnO | 0.01 | 0.00 | 0.04 | 0.00 | 0.00 |
| CaO | 0.00 | 0.00 | 0.00 | 0.00 | 14.17 |
| $Na_2O$ | 0.01 | 0.01 | 0.04 | 0.00 | 5.17 |
| $K_2O$ | 0.00 | 0.00 | 0.03 | 0.00 | 0.52 |
| Total | 99.89 | 100.84 | 99.66 | 99.96 | 100.53 |

### *Secondary accessory minerals*

Numerous secondary minerals occur in veins within the eclogites. These minerals include phlogopite, amphibole, plagioclase, ilmenite, rutile, sulfide, spinel and carbonates. The chemistry of all but spinel and carbonate are discussed below.

**Table 5.** Secondary accessory minerals from Koidu eclogites

| | Phlogopites | | | | | | |
|---|---|---|---|---|---|---|---|
| | KEC-86-DB-10 | KEC-80-5 | KEC-86-19 | KEC-81-DB-1 | | | |
| | | | | (Core) | (Rim) | (Core) | |
| $SiO_2$ | 39.03 | 41.66 | 40.96 | 39.04 | 39.14 | 37.55 | 39.60 |
| $TiO_2$ | 2.72 | 2.58 | 1.58 | 3.92 | 4.00 | 3.91 | 3.89 |
| $Al_2O_3$ | 15.97 | 14.55 | 13.85 | 12.39 | 12.99 | 14.16 | 14.08 |
| $Cr_2O_3$ | 0.02 | 0.15 | – | 0.09 | 0.09 | 0.13 | 0.09 |
| FeO | 11.24 | 7.52 | 4.42 | 10.39 | 10.47 | 10.67 | 10.45 |
| MgO | 17.07 | 20.61 | 23.78 | 18.89 | 18.47 | 17.99 | 19.67 |
| MnO | 0.02 | 0.00 | 0.04 | 0.10 | 0.07 | 0.08 | 0.07 |
| CaO | 0.00 | 0.01 | – | 0.06 | 0.05 | 0.08 | 0.03 |
| $Na_2O$ | 0.08 | 0.42 | 0.15 | 0.26 | 0.37 | 0.66 | 0.30 |
| $K_2O$ | 8.90 | 8.83 | 10.29 | 9.37 | 9.36 | 8.95 | 9.12 |
| BaO | – | – | – | 0.26 | 0.26 | 0.41 | 0.39 |
| Total | 95.05 | 96.33 | 95.07 | 94.77 | 95.27 | 94.56 | 97.69 |

| | Amphiboles | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | KEC-80-5 | KEC-86-8 | KEC-86-19 | KEC-81-AB-11 | KEC-81-DB-1 | | | |
| | | | | | (Core) | (Rim) | (Core) | |
| $SiO_2$ | 42.53 | 44.59 | 39.50 | 47.71 | 39.68 | 40.15 | 38.77 | 38.20 |
| $TiO_2$ | 1.55 | 2.66 | 0.81 | 0.47 | 1.87 | 1.03 | 1.34 | 3.17 |
| $Al_2O_3$ | 13.58 | 11.88 | 15.50 | 10.44 | 15.03 | 14.75 | 15.07 | 15.89 |
| $Cr_2O_3$ | 0.09 | 0.42 | 0.31 | 0.22 | 0.05 | 0.07 | 0.04 | 0.12 |
| FeO | 9.97 | 4.46 | 6.98 | 3.16 | 12.09 | 12.99 | 13.43 | 10.89 |
| MgO | 15.66 | 17.62 | 17.01 | 20.23 | 13.07 | 12.69 | 12.25 | 13.37 |
| MnO | 0.21 | 0.09 | 0.22 | 0.05 | 0.14 | 0.15 | 0.19 | 0.09 |
| CaO | 10.15 | 9.01 | 10.37 | 9.44 | 10.95 | 11.24 | 11.36 | 10.14 |
| $Na_2O$ | 3.79 | 3.43 | 2.92 | 5.30 | 2.60 | 3.03 | 2.56 | 3.38 |
| $K_2O$ | 0.94 | 1.11 | 0.98 | 0.75 | 1.48 | 0.80 | 1.72 | 1.15 |
| BaO | – | – | – | – | 0.17 | 0.03 | 0.15 | 0.22 |
| Total | 98.47 | 95.27 | 94.60 | 97.77 | 97.13 | 96.93 | 96.85 | 96.62 |

| | Plagioclase | | |
|---|---|---|---|
| | KEC-86-KB-4 | KEC-86-11 | KEC-86-KB-74B |
| $SiO_2$ | 54.78 | 63.49 | 64.85 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 |
| $Al_2O_3$ | 28.14 | 25.67 | 18.64 |
| $Cr_2O_3$ | 0.02 | 0.00 | 0.00 |
| FeO | 0.29 | 0.00 | 0.10 |
| MgO | 0.01 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 |
| CaO | 11.30 | 0.35 | 1.00 |
| $Na_2O$ | 5.30 | 5.47 | 11.22 |
| $K_2O$ | 0.22 | 0.29 | 0.05 |
| Total | 100.06 | 95.27 | 95.86 |

Representative chemical data for secondary phlogopite grains are given in Table 5. Phlogopites from different eclogites contain a wide range in the oxides $Al_2O_3$ (12.9–16.0 wt%), MgO (10.1–23.8 wt%) and FeO (4.4–11.2 wt%). Titanium (1.6–3.5 wt% $TiO_2$) is relatively constant.

Representative chemical data for secondary amphibole (<2 modal %, Table 5), based on Leake's (1968) classification, show that these are pargasite, ferroan pargasite, pargasitic hornblende, and edenitic hornblende. This nomenclature is appropriate based on the calculated presence of octahedrally coordinated aluminum and substantial substitution of sodium and postassium in the A-sites of the somewhat subcalcic structure. Core compositions in eclogite KEC-81-DB-1 have slightly greater $TiO_2$ and MgO contents relative to rims, and lesser amounts of FeO and CaO. Compositions vary from grain to grain especially in the minor elements Ti, Cr, and Ba. Compared to the upper mantle amphibole compositional compilation of Dawson and Smith (1982), amphiboles analyzed in the present study most closely resemble pargasites occurring as secondary kelyphite rims replacing garnet, although the former are non-kelyphitic and are slightly richer in Al and Fe and poorer in Cr. Koidu amphiboles are also broadly similar to amphiboles in eclogites from Roberts Victor (Windom and

**Table 6.** Oxides from Koidu eclogites

| | Rutile | Ilmenite | |
|---|---|---|---|
| | KEC-80-DB-D1 | KEC-80-DB-D1 | KEC-80-B1 |
| $SiO_2$ | – | – | 0.00 |
| $TiO_2$ | 98.58 | 55.08 | 49.40 |
| $Zr_2O_3$ | 0.18 | 0.38 | – |
| $Al_2O_3$ | 0.38 | 0.09 | 0.35 |
| $Cr_2O_3$ | 0.14 | 0.11 | 0.20 |
| $Fe_2O_3$ | 0.30 | 0.72 | 11.77 |
| FeO | 0.00 | 33.56 | 29.12 |
| NiO | – | 0.33 | – |
| MgO | 0.00 | 8.68 | 8.27 |
| MnO | – | 0.55 | 0.41 |
| $Nb_2O_3$ | 0.57 | 0.14 | – |
| $Ta_2O_3$ | 0.02 | – | – |
| Total | 100.17 | 99.64 | 99.52 |

Boettcher 1980; Bishop et al. 1978), Orapa, (Tollo 1982) and the Stockdale Kimberlite (Meyer and Brookins 1971).

Plagioclase (KEC-86-KB-4, KEC-86-KB-74B and KEC-86-11, Table 5) is most abundant in kyanite-bearing eclogites and is andesine ($An_{47}$) to albite ($An_2$ and $An_{11}$) in composition.

Rutile is the most common accessory phase in the Koidu eclogites. Representative compositions of rutile and two ilmenites from 2 eclogites are presented in Table 6 (Tompkins 1983). Rutiles are essentially $TiO_2$ (98.6 wt%) with minor amounts of $Nb_2O_5$ (0.57 wt%) and $Al_2O_3$ (0.38 wt%). High quality data for rutiles are difficult to obtain because of abundant ilmenite lamellae which cause extreme variability in single point analyses. These intergrowths are similar morphologically to those described from eclogites in the Stockdale Kimberlite (Meyer and Boctor 1975), Orapa (Tollo 1982), and Jagersfontein, (Haggerty 1983). Ilmenite is identified in two eclogites (KEC-80-DB-D1 and KEC-80-B1) and is characterized by very low chrome contents and constant MgO (8.3–8.7 wt%).

Quantitative analyses (Table 7) of sulfides were obtained from two eclogites (KEC-80-DB-D1 has low-MgO garnets, and KEC-

**Table 7.** Sulfides from Koidu eclogites

Primary sulfide (KEC-80-DB-D1)

| | (PO) | (PY) | (PY) | (PY) | (CP) | ("KO") | Magnetite |
|---|---|---|---|---|---|---|---|
| S | 42.10 | 52.85 | 52.84 | 49.13 | 35.64 | 38.55 | 0.17 |
| Fe | 57.14 | 44.48 | 41.87 | 44.03 | 29.64 | 27.54 | 65.83 |
| Co | 0.12 | 0.36 | 0.36 | 1.40 | 0.14 | 0.39 | 0.12 |
| Ni | 0.89 | 1.27 | 5.01 | 5.40 | 0.44 | 18.39 | 0.47 |
| Cu | 0.05 | 0.07 | 0.11 | 0.08 | 34.18 | 14.68 | 0.00 |
| Total | 100.30 | 99.03 | 100.19 | 100.04 | 100.04 | 99.55 | 66.59 |
| FE/(FE+NI) | 0.98 | 0.97 | 0.89 | 0.89 | 0.99 | 0.60 | 0.99 |
| # analyses | 3 | 2 | 3 | 3 | 4 | 3 | 2 |

Secondary sulfide (KEC-80-DB-D1)

| | (CP) | (PY) | (PY) | Open beam | | | Magnetite |
|---|---|---|---|---|---|---|---|
| | | | | (CP) | (PY) | (PY) | |
| S | 35.72 | 48.45 | 54.93 | 35.99 | 47.83 | 53.08 | 0.06 |
| Fe | 29.94 | 46.76 | 40.79 | 30.12 | 46.56 | 44.18 | 64.11 |
| Co | 0.09 | 0.95 | 1.96 | 0.09 | 0.59 | 1.47 | 0.16 |
| Ni | 0.05 | 2.11 | 2.93 | 0.07 | 2.17 | 1.77 | 0.04 |
| Cu | 34.72 | 0.54 | 0.03 | 34.90 | 0.87 | 0.00 | 0.37 |
| Total | 100.52 | 98.81 | 100.64 | 101.17 | 98.02 | 100.50 | 64.74 |
| FE/(FE+NI) | 1.00 | 0.96 | 0.93 | 1.00 | 0.96 | 0.96 | – |
| # analyses | 3 | 3 | 2 | 3 | 3 | 3 | 1 |

Three sulfide grains (KEC-86-58)

| | Grain 1 | | | Grain 2 | | | Grain 3 | |
|---|---|---|---|---|---|---|---|---|
| | (PM) | (PY) | (CP) | (PM) | (PY) | (CP) | (PM) | (PY) |
| S | 42.65 | 54.01 | 38.06 | 44.42 | 54.98 | 38.51 | 44.63 | 54.45 |
| Fe | 4.53 | 41.42 | 23.95 | 2.27 | 41.09 | 26.44 | 4.14 | 38.74 |
| Co | 1.19 | 0.39 | 0.23 | 1.21 | 0.72 | 0.16 | 0.66 | 0.79 |
| Ni | 49.59 | 3.16 | 6.32 | 52.64 | 2.82 | 4.01 | 50.27 | 4.56 |
| Cu | 1.57 | 0.26 | 29.88 | 0.20 | 0.23 | 30.49 | 1.37 | 0.18 |
| Total | 99.53 | 99.24 | 98.44 | 100.74 | 99.84 | 99.61 | 101.07 | 98.72 |
| FE/(FE+NI) | | 0.93 | 0.79 | – | 0.94 | 0.87 | – | 0.89 |
| # analyses | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 |

86-58 has high-MgO garnets). Three sulfide globules in KEC-86-58 are comprised of polydymite, pyrite, and chalcopyrite. Iron-rich (2.27–4.14 wt% Fe) polydymite makes up approximately 70–80 modal % of the grains. Flare-shaped nickel-rich (2.82–4.56 wt% Ni) pyrite exsolution lamellae, several microns in width, are oriented in a single direction and are restricted to grain interiors. Chalcopyrite forms a narrow discontinuous rim around the major central phases in two of the three grains and contains 4.0–6.3 wt% Ni.

KEC-80-DB-D1 is of particular interest because it is diamond-bearing with two distinct sulfide assemblages present, neither of which resemble those described above. One grain is clearly secondary, because it is a dominant phase in a vein of calcite. The host, or central phase, is chalcopyrite ($\approx$60 modal %) with Co-bearing (0.98 wt% Co) rims and lamellae of pyrite. Magnetite is present, restricted to the pyrite rim. Sulfide Fe/(Fe + Ni) ratios are extremely high, ranging from 0.93–1.00. The assemblage in the second sulfide type is pyrrhotite + pyrite + chalcopyrite and an unidentified phase, similar to mineral "Ko" reported by Haggerty and Tompkins (1982) from Koidu in sulfide assemblages in ilmenite. This phase plots between pyrite and chalcopyrite in the Cu – Fe – S system, but contains substantial amounts of Ni (18.4 wt%). The central assemblage is polydymite with elongate blebs of pyrite, usually surrounded by magnetite and the unnamed phase ("Ko"). Two varieties of pyrrhotite are present. An interior composition is typically more S- and Ni-enriched relative to the pyrrhotite rim which is Fe-rich. Ratios of Fe/(Fe + Ni) for pyrite, chalcopyrite and pyrrhotite range from 0.9–1.0.

Pentlandite is absent in the Koidu sulfides analyzed, unlike sulfides described in eclogites from other localities (e.g. Tsai et al. 1979), where the most commonly observed assemblage is an intergrowth of pyrrhotite-pentlandite with minor chalcopyrite. The assemblages at Koidu are relatively Ni-poor and Fe-rich compared to those described by Tsai et al. (1979). The absence of pentlandite in the Koidu eclogites agrees well with the sulfide inclusion study by Efimova et al. (1983) who showed that sulfides in diamonds of eclogitic paragenesis have higher Fe/(Fe + Ni) ratios (0.89–0.99) than sulfides (0.59–0.64) in diamonds of ultramafic affinity; the latter is consistent with diamond genesis in depleted lithosphere (e.g. Haggerty 1986, 1989).

*Zoned garnets and clinopyroxenes*

In contrast to the general homogeneous nature of minerals from the upper mantle (Boyd and Finger 1975; Smith 1988), three of the Koidu eclogites are exceptional in that they exhibit zoning and mantling of garnets, and two generations of coexisting clinopyroxene.

Two types of garnet zoning are present, based on textural and chemical differences. Eclogite KEC-86-19 contains subhedral to rounded garnets concentrically and gradationally zoned in composition. The degree of zoning varies from grain to grain. The most extremely zoned garnets contain iron-rich cores (21.8 wt% FeO) and magnesium-rich rims (17.4 wt% MgO). Calcium remains relatively constant (7.0 wt% CaO). $Al_2O_3$ increases slightly (21.1–22.3 wt% $SiO_2$) from core to rim. Average analyses from this grain are listed in Table 8. In thin section, there is a marked change from the pale orange core to the clear rim. Cores of garnets are generally more altered and may contain highly altered inclusions which cause the garnets to be mildly anisotropic. These inclusions have not been analyzed but appear to be amphibole and phlogopite, based on color, habit, and the abundance of these silicates at grain boundaries. Two other eclogites, KEC-80-5 and KEC-81-DB-1, contain discontinuous, mantled garnets. The cores are pyrope-poor (34.3 and 33.7, respectively), and are surrounded by a veneer of amphibole and phlogopite, all of which is mantled by a second pyrope-rich garnet (58.5 and 47.9, respectively). Average garnet analyses for each eclogite are listed in Table 8. Calcium contents decrease by approximately 4.0 wt%, whereas in individual core and rim compositions Ca in homogeneous. Other elements analyzed show little variation.

**Table 8.** Zoned garnets and zoned pyroxenes from Koidu eclogites

| Garnets | KEC-80-5 | | KEC-81-DB-1 | | KEC-86-19 | |
|---|---|---|---|---|---|---|
| | Core | Rim | Core | Rim | Core | Rim |
| $SiO_2$ | 39.96 | 42.04 | 40.03 | 40.75 | 39.65 | 42.04 |
| $TiO_2$ | 0.13 | 0.50 | 0.36 | 0.63 | 0.30 | 0.25 |
| $Al_2O_3$ | 20.90 | 20.37 | 22.61 | 22.45 | 21.12 | 23.04 |
| $Cr_2O_3$ | 0.14 | 0.11 | 0.01 | 0.00 | 0.04 | 0.01 |
| FeO | 21.65 | 15.01 | 16.12 | 14.38 | 21.77 | 10.64 |
| MgO | 9.71 | 17.38 | 9.04 | 13.22 | 10.04 | 17.38 |
| MnO | 0.46 | 0.35 | 0.32 | 0.33 | 0.61 | 0.56 |
| CaO | 8.99 | 5.40 | 12.21 | 8.76 | 6.58 | 7.00 |
| $Na_2O$ | 0.00 | 0.00 | 0.10 | 0.16 | 0.00 | – |
| $K_2O$ | 0.01 | 0.00 | – | – | 0.00 | – |
| Total | 101.95 | 101.16 | 100.80 | 100.68 | 100.11 | 100.92 |

| Pyroxenes | KEC-80-5 | | KEC-81-DB-1 | KEC-86-19 | |
|---|---|---|---|---|---|
| | Core | Rim | | Core | Rim |
| $SiO_2$ | 52.39 | 54.74 | 55.26 | 55.03 | 55.09 |
| $TiO_2$ | 0.36 | 0.14 | 0.09 | 0.18 | 0.18 |
| $Al_2O_3$ | 4.17 | 6.19 | 5.69 | 1.11 | 2.69 |
| $Cr_2O_3$ | 0.02 | 0.09 | 0.04 | 0.04 | 0.06 |
| FeO | 5.62 | 5.97 | 5.34 | 3.01 | 3.18 |
| MgO | 14.09 | 11.64 | 11.58 | 17.22 | 15.81 |
| MnO | 0.08 | 0.02 | 0.03 | 0.11 | 0.09 |
| CaO | 18.64 | 17.19 | 18.65 | 22.42 | 20.70 |
| $Na_2O$ | 3.18 | 5.39 | 3.77 | 0.69 | 2.06 |
| $K_2O$ | 0.01 | 0.10 | 0.02 | – | – |
| Total | 98.56 | 101.47 | 100.47 | 99.81 | 99.86 |

Zoned clinopyroxenes coexist with zoned garnets (Table 8) in eclogites KEC-80-5 and KEC-86-19. Texturally blebby, rounded diopsides of $Jd_{17}Di_{83}$ and $Jd_5Di_{95}$, respectively, are overgrown by a pristine second generation, $Jd_{29}Di_{71}$ and $Jd_{13}Di_{87}$, respectively. The dominant chemical exchange in the M1 site is Al for Mg, and in the M2 site is Na for Ca. Ca:Mg:Fe ratios vary only slightly. Zoned clinopyroxenes behave in a manner similar to unzoned pyroxenes with a trend from diopside to jadeite (Fig. 3a). KEC-86-19 core and rim compositions and KEC-80-5 core composition fall in the field defined for low-MgO clinopyroxenes, with less than 23 mol% jadeite; rim compositions for KEC-80-5 fall in the diamond-bearing eclogite field (Fig. 3b).

Zoning of garnet and clinopyroxene in eclogite has been described in only one eclogite from Roberts Victor (Hatton and Gurney 1979). They describe smoothly zoned garnets with MgO-rich rims and cores enriched in CaO and $TiO_2$ and to a lesser extent FeO. This is similar to the Koidu garnets but zoning is subtle. Rim to core variations are 16.3–15.9 wt% MgO, compared to Koidu which has up to a 10 wt% enrichment from core to rim. Clinopyroxenes from the Roberts Victor eclogite are weakly zoned with CaO-, MgO-rich rims and $Na_2O$-, $Al_2O_3$-, $TiO_2$-rich cores (Hatton and Gurney 1979). This is the opposite to that observed in the Koidu eclogites.

## Bulk chemistry

Bulk-rock major element chemistry was determined for 25 Koidu eclogites (KEC) and two lower crustal granulites (KGR). Twenty-two are bimineralic eclogites, one is diamond-bearing (KEC-81-DB-1), one contains kyanite (KEC-86-KB-74B), and another contains 30 modal % amphibole (KEC-81-AB-11). Chemical analyses, together with

**Table 9.** Bulk chemistries of eclogites

| | High-MgO eclogites | | | | | | | | | Granulites | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-81 2 | KEC-81-AB-11 | KEC-86-15 | KEC-86-19 | KEC-86-58 | KEC-86-73A | KEC-86-73B | KEC-86-90 | KEC-86 107 | KGR-86-75 | KGR-86-76 |
| $SiO_2$ | 47.39 | 47.84 | 46.17 | 47.73 | 48.59 | 47.83 | 48.32 | 43.99 | 44.52 | 50.11 | 46.23 |
| $TiO_2$ | 1.00 | 0.39 | 0.68 | 0.32 | 0.34 | 0.44 | 0.33 | 0.62 | 0.37 | 0.97 | 0.93 |
| $Al_2O_3$ | 12.72 | 12.96 | 15.83 | 13.67 | 14.12 | 14.53 | 13.38 | 18.95 | 20.15 | 21.88 | 21.66 |
| FeO | 9.42 | 4.97 | 10.49 | 8.17 | 4.56 | 7.77 | 6.48 | 10.61 | 6.45 | 11.52 | 8.95 |
| MnO | 0.23 | 0.19 | 0.21 | 0.32 | 0.19 | 0.24 | 0.22 | 0.26 | 0.27 | 0.19 | 0.10 |
| MgO | 16.68 | 19.51 | 15.90 | 16.29 | 19.62 | 17.65 | 18.38 | 18.13 | 20.15 | 7.48 | 7.71 |
| CaO | 11.07 | 10.80 | 9.49 | 12.49 | 11.57 | 9.90 | 10.87 | 7.06 | 7.37 | 3.63 | 11.49 |
| $Na_2O$ | 1.18 | 2.55 | 0.91 | 0.88 | 1.04 | 1.33 | 1.30 | 0.42 | 0.36 | 3.20 | 1.60 |
| $K_2O$ | 0.57 | 0.42 | 0.47 | 0.48 | 0.17 | 0.33 | 0.68 | 0.28 | 0.44 | 1.20 | 1.59 |
| $P_2O_5$ | 0.18 | 0.06 | 0.07 | 0.05 | 0.03 | 0.04 | 0.04 | 0.04 | 0.07 | 0.04 | 0.03 |
| Total | 100.44 | 99.69 | 100.22 | 100.40 | 100.23 | 100.06 | 100.00 | 100.36 | 100.15 | 100.22 | 100.29 |
| Mg value | 77.81 | 88.61 | 75.01 | 79.79 | 89.50 | 81.81 | 84.89 | 77.19 | 86.09 | 56.27 | 63 |
| Trace elements (ppm) | | | | | | | | | | | |
| Y | 16.9 | 26.4 | 14.7 | 43.1 | 18.9 | 23.6 | 18.9 | 15.2 | 14.1 | 23.5 | 17.7 |
| Sr | 266 | 404 | 124 | 123 | 235 | 113 | 325 | 50 | 92 | 387 | 506 |
| U | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 |
| Rb | 15.6 | 3.1 | 11.1 | 15.0 | 3.3 | 7.6 | 10.5 | 8.4 | 8.5 | 24.3 | 56.1 |
| Th | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 |
| Pb | 4 | 6 | 5 | 6 | 6 | 3 | 4 | 4 | 2 | 7 | 3 |
| Ga | 11 | 11 | 13 | 12 | 10 | 11 | 8 | 12 | 10 | 16 | 19 |
| Nb | 48 | 45 | 13 | 12 | 11 | 10 | 30 | 8 | 18 | 48 | 8 |
| Zr | 44 | 95 | 32 | 73 | 17 | 38 | 38 | 23 | 33 | 290 | 33 |
| Zn | 35 | 19 | 55 | 20 | 13 | 26 | 16 | 26 | 15 | 68 | 24 |
| Ni | 221 | 861 | 416 | 265 | 259 | 162 | 305 | 299 | 210 | 133 | 87 |
| Cr | 392 | 2356 | 494 | 1079 | 1147 | 2271 | 1874 | 506 | 2242 | 527 | 364 |
| V | 316 | 232 | 200 | 209 | 333 | 251 | 250 | 206 | 183 | 188 | 245 |
| Ce | 64 | 77 | 28 | 27 | 50 | 27 | 49 | 19 | 33 | 35 | 14 |
| Ba | 435 | 240 | 272 | 242 | 178 | 258 | 656 | 89 | 143 | 664 | 770 |
| La | 24 | 27 | 2 | 4 | 17 | 6 | 10 | 2 | 6 | 16 | 4 |

| | Diamond-bearing and low-MgO eclogites | | | | | | | | | | | Low-MgO and kyanite-bearing eclogites | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-81-DB-1 | KEC-81-3 | KEC-81-4 | KEC-81-5 | KEC-81-7 | KEC-81-8 | KEC-81-10A | KEC-81-12 | KEC-81-18 | KEC-81-21 | KEC-86-13 | KEC-86-71A | KEC-86-71B | KEC-86-72A | KEC-86-72B | KEC-86-KB-74A |
| $SiO_2$ | 46.25 | 45.38 | 48.53 | 43.66 | 45.49 | 47.47 | 50.13 | 46.70 | 48.90 | 48.75 | 48.07 | 46.33 | 46.10 | 42.80 | 46.41 | 46.03 |
| $TiO_2$ | 0.86 | 0.77 | 0.70 | 0.72 | 0.90 | 0.89 | 0.46 | 1.41 | 0.78 | 0.56 | 0.74 | 0.59 | 0.56 | 0.84 | 0.76 | 0.45 |
| $Al_2O_3$ | 14.57 | 16.95 | 12.63 | 17.15 | 15.51 | 15.61 | 13.78 | 14.88 | 12.36 | 13.80 | 14.16 | 18.37 | 17.80 | 17.25 | 14.34 | 26.71 |
| FeO | 12.83 | 10.48 | 13.07 | 16.22 | 11.74 | 10.61 | 8.34 | 15.67 | 11.44 | 10.99 | 13.78 | 11.27 | 11.04 | 17.60 | 13.83 | 6.28 |
| MnO | 0.24 | 0.16 | 0.23 | 0.31 | 0.21 | 0.19 | 0.17 | 0.31 | 0.21 | 0.20 | 0.26 | 0.22 | 0.23 | 0.38 | 0.26 | 0.09 |
| MgO | 10.94 | 9.24 | 12.56 | 10.35 | 12.96 | 10.08 | 11.44 | 7.62 | 12.01 | 12.16 | 10.14 | 10.08 | 9.75 | 7.90 | 9.50 | 6.19 |
| CaO | 12.96 | 15.16 | 10.40 | 10.73 | 11.51 | 12.30 | 12.06 | 11.07 | 11.62 | 11.13 | 10.68 | 11.15 | 12.57 | 11.78 | 12.79 | 11.72 |
| $Na_2O$ | 1.12 | 1.80 | 1.59 | 0.87 | 1.42 | 2.17 | 3.24 | 1.85 | 1.48 | 2.57 | 2.02 | 1.21 | 1.32 | 1.14 | 2.11 | 2.40 |
| $K_2O$ | 0.40 | 0.19 | 0.23 | 0.37 | 0.38 | 0.84 | 0.73 | 0.73 | 1.04 | 0.29 | 0.59 | 0.58 | 0.86 | 0.45 | 0.23 | 0.47 |
| $P_2O_5$ | 0.04 | 0.10 | 0.04 | 0.03 | 0.08 | 0.04 | 0.06 | 0.16 | 0.04 | 0.05 | 0.07 | 0.08 | 0.05 | 0.04 | 0.04 | 0.03 |
| Total | 100.21 | 100.23 | 99.98 | 100.41 | 100.20 | 100.20 | 100.41 | 100.40 | 99.88 | 100.50 | 100.51 | 99.88 | 100.28 | 100.18 | 100.27 | 100.37 |
| Mg value | 62.90 | 63.60 | 65.56 | 55.83 | 78.63 | 65.29 | 73.10 | 49.06 | 67.52 | 68.65 | 59.32 | 63.91 | 63.63 | 47.08 | 57.63 | 66.13 |
| Trace elements (ppm) | | | | | | | | | | | | | | | | |
| Y | 16.9 | 13.0 | 22.0 | 24.4 | 23.1 | 17.0 | 9.3 | 39.5 | 15.7 | 13.6 | 26.4 | 22.1 | 20.8 | 37.2 | 21.6 | 4.2 |
| Sr | 94 | 479 | 76 | 56 | 117 | 165 | 220 | 153 | 120 | 107 | 150 | 117 | 170 | 195 | 117 | 380 |
| U | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 |

**Table 9** (continued)

| | Diamond-bearing and low-MgO eclogites | | | | | | | | | | | Low-MgO and kyanite-bearing eclogites | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-81-DB-1 | KEC-81-3 | KEC-81-4 | KEC-81-5 | KEC-81-7 | KEC-81-8 | KEC-81-10A | KEC-81-12 | KEC-81-18 | KEC-81-21 | KEC-86-13 | KEC-86-71A | KEC-86-71B | KEC-86-72A | KEC-86-72B | KEC-86-KB-74A |
| Rb | 13.1 | 5.8 | 4.0 | 14.0 | 10.5 | 27.0 | 22.8 | 13.8 | 29.3 | 8.8 | 12.6 | 14.8 | 15.3 | 17.9 | 8.5 | 21.4 |
| Th | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | | <2 | <2 | <2 |
| Pb | 5 | 5 | 6 | 5 | 6 | 4 | 4 | 4 | 5 | 5 | 5 | 3 | 3 | 7 | 5 | 2 |
| Ga | 13 | 17 | 14 | 14 | 14 | 15 | 12 | 18 | 12 | 12 | 12 | 14 | 13 | 15 | 15 | 18 |
| Nb | 12 | 19 | 7 | 10 | 29 | 17 | 16 | 6 | 16 | 44 | 186 | 17 | 20 | 23 | 44 | 8 |
| Zr | 46 | 32 | 29 | 18 | 81 | 32 | 46 | 63 | 55 | 28 | 45 | 38 | 50 | 55 | 35 | 36 |
| Zn | 100 | 76 | 104 | 98 | 64 | 81 | 51 | 127 | 82 | 74 | 75 | 71 | 69 | 88 | 88 | 70 |
| Ni | 229 | 248 | 387 | 110 | 324 | 204 | 170 | 143 | 147 | 259 | 117 | 131 | 156 | 268 | 104 | 159 |
| Cr | 437 | 328 | 584 | 830 | 975 | 363 | 353 | 211 | 386 | 544 | 208 | 494 | 294 | 247 | 332 | 147 |
| V | 305 | 334 | 254 | 275 | 241 | 346 | 252 | 454 | 295 | 250 | 360 | 207 | 191 | 299 | 310 | 102 |
| Ce | 14 | 15 | 17 | 18 | 33 | 24 | 23 | 22 | 19 | 22 | 19 | 18 | 22 | 11 | 18 | 8 |
| Ba | 215 | 1260 | 84 | 100 | 168 | 277 | 378 | 393 | 425 | 105 | 412 | 918 | 817 | 305 | 85 | 248 |
| La | 5 | 6 | 4 | <1 | 9 | <1 | 16 | 7 | 7 | 3 | 9 | 5 | 3 | 5 | 4 | 4 |

one bar C.I.P.W. norms and 30 kb normative mineralogy (Smyth 1981), are given in Tables 9–10. High pressure norm calculations were not always successful because of the extreme compositions of some xenoliths. Total iron is expressed as FeO, and chromium abundances are included in the trace element section.

*Major element chemistry*

Eclogites show significant variations in $SiO_2$ (42.8–50.1 wt%), $Al_2O_3$ (12.4–26.7 wt%), FeO (4.6–17.6 wt%), MgO (6.2–20.2 wt%), CaO (3.6–15.2 wt%), and $Na_2O$ (0.36–3.24 wt%). Two sub-populations of eclogites are present, distinguished according to MgO content, and reflected in garnet compositions. High-MgO eclogites (15.9–20.2 wt% MgO) approach picrites in average composition (Table 9). The remaining bimineralic eclogites, and the two lower crustal granulites, form the low-MgO group (7–13 wt% MgO), and have close chemical affinities to alkali basalts. Diamond-bearing eclogite KEC-81-DB-1 and kyanite-bearing eclogite KEC-86-KB-74B, fall in the low-MgO group.

The concentration of major elements in the Koidu eclogites is typical of other upper mantle eclogites (Dawson 1980), and the compositional range is similar to that of basalts. A comparison of the geochemistries of the Koidu eclogites and granulites with fields of average basalts and eclogites, peraluminous eclogites, and grospydites from other localities (Dawson 1980) are illustrated in Fig. 4a, b.

On the basis of CaO, MgO and FeO (Fig. 4a), the Koidu eclogites plot in the center of the ternary, divided into high- and low-MgO groups, similar to the main eclogite and basalt fields of Dawson (1980). The kyanite-bearing eclogite, corresponds to the peraluminous eclogite field, and the diamond-bearing eclogite is in the field of carbonaceous eclogites. High-MgO eclogites have a lower calcium content than those illustrated by Dawson (1980), a reflection possibly of the presence of pyrope-rich garnets. Low-MgO eclogites show slight enrichment towards CaO, and the CaO and FeO tie line.

On the basis of $CaO-Al_2O_3-(FeO+MgO)$ (Fig. 4b), Koidu eclogites form a tighter cluster than the eclogite compilation by Dawson (1980). As a whole, Koidu eclogites are relatively constant in CaO but are variable in $Al_2O_3$ contents. Kyanite eclogite, KEC-86-KB-74B, falls in the peraluminous field, and KEC-81-DB-1 in the carbonaceous field. High-MgO eclogites have a relatively constant FeO + MgO value and contain the least amount of CaO and $Al_2O_3$.

High-MgO eclogites, as a group, contain less CaO than low-MgO eclogites and show a strong positive correlation with increasing $SiO_2$. Calcium contents for the high-MgO group increase from 7.1–12.5 wt% CaO, whereas low-MgO eclogites are virtually constant at $\approx$12 wt% CaO. KEC-81-3 is unusually rich in calcium, containing 15.2 wt% CaO. Granulite KGR-86-75, contains only 3.2 wt% CaO for a silica content of 50.1 wt%. Both eclogite groups have positive correlations of total alkalies with increasing $SiO_2$, and all but 2 eclogites are subalkaline, plotting below the Macdonald and Katsura (1964) line that separates alkalic from tholeiitic suites. Granulites are alkaline, plotting just above the Macdonald and Katsura (1964) line.

*Normative calculations*

From 1 bar norms, all samples are olivine normative, 16 are hypersthene normative, and 11 samples are nepheline normative. Olivine and nepheline normative eclogites contain, on average 46.6 wt% $SiO_2$, and have close chemical affinities to alkali basalts, based on the basalt tetrahedron (Yoder and Tilley 1957), except that K, Na, and P contents are low, for a given MgO, for rocks generally termed alkali basalts. Nepheline in the norm ranges from 0.8–6.0%, and olivine from 19.3–32.7%. All xenoliths are diopside normative (7.9–31.2%) with the exception of a kyanite eclogite,

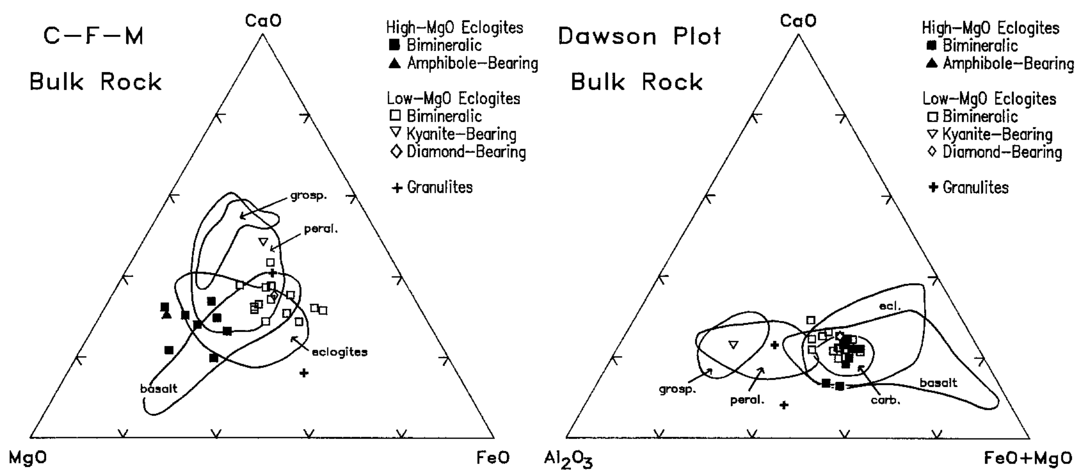
**Table 10.** Normative mineralogies

| | Olivine and hypersthene normative | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-81-2 | KEC-86-15 | KEC-86-19 | KEC-86-58 | KEC-86-73A | KEC-86-73B | KEC-86-90 | KEC-86-107 | KEC-81-DB-1 | KEC-81-4 | KEC-81-5 | KEC-81-12 | KEC-81-18 | KEC-86-13 | KEC-86-71A | KGR-86-75 |
| 1 bar normative mineralogy | | | | | | | | | | | | | | | | |
| OR | 3.37 | 2.78 | 2.84 | 1.00 | 1.95 | 4.02 | 1.65 | 2.60 | 2.36 | 1.36 | 2.19 | 4.31 | 6.15 | 3.49 | 3.43 | 7.09 |
| AB | 9.98 | 7.70 | 7.45 | 8.80 | 11.25 | 11.00 | 3.55 | 3.05 | 9.48 | 13.45 | 7.36 | 15.65 | 12.52 | 17.09 | 10.24 | 27.08 |
| AN | 27.73 | 37.72 | 31.93 | 33.36 | 32.70 | 28.67 | 34.76 | 36.11 | 33.55 | 26.65 | 41.80 | 30.14 | 24.01 | 27.83 | 42.98 | 17.75 |
| DI | 20.92 | 7.19 | 23.86 | 18.87 | 12.93 | 19.92 | – | – | 25.07 | 20.23 | 9.34 | 19.87 | 27.26 | 20.42 | 9.70 | – |
| HY | 6.62 | 13.86 | 6.38 | 11.33 | 11.12 | 4.56 | 27.46 | 26.11 | 2.03 | 15.75 | 4.33 | 2.35 | 5.90 | 3.37 | 9.66 | 34.81 |
| NE | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| OL | 29.50 | 29.51 | 27.22 | 26.15 | 29.18 | 31.11 | 26.45 | 25.58 | 26.00 | 21.12 | 33.96 | 25.02 | 22.46 | 26.75 | 22.57 | 2.75 |
| IL | 1.90 | 1.29 | 0.61 | 0.65 | 0.84 | 0.63 | 1.18 | 0.70 | 1.63 | 1.33 | 1.37 | 2.68 | 1.48 | 1.41 | 1.12 | 1.84 |
| AP | 0.42 | 0.16 | 0.12 | 0.07 | 0.09 | 0.09 | 0.09 | 0.16 | 0.09 | 0.09 | 0.07 | 0.37 | 0.09 | 0.16 | 0.19 | 0.09 |
| C | – | – | – | – | – | – | 5.22 | 5.85 | – | – | – | – | – | – | – | 8.81 |
| Total | 100.44 | 100.21 | 100.41 | 100.23 | 100.06 | 100.00 | 100.36 | 100.16 | 100.21 | 99.98 | 100.42 | 100.39 | 99.87 | 100.52 | 99.89 | 100.22 |
| 30 kbar normative mineralogy | | | | | | | | | | | | | | | | |
| ILM | 2.16 | 1.42 | 0.71 | | 0.96 | 0.74 | 1.27 | 0.79 | 1.74 | 1.42 | 1.39 | 2.62 | 1.60 | 1.44 | 1.19 | 1.84 |
| KALS | 5.15 | 4.10 | 4.44 | | 3.00 | 6.35 | 2.40 | 3.91 | 3.37 | 1.94 | 2.97 | 5.65 | 8.91 | 4.80 | 4.87 | 9.50 |
| JD | 8.77 | 6.54 | 6.71 | | 9.94 | 10.00 | 2.96 | 2.63 | 7.76 | 11.05 | 5.75 | 11.79 | 10.43 | 13.54 | 8.37 | 20.86 |
| DIOP | 38.39 | 30.33 | 44.95 | | 35.97 | 42.21 | 22.77 | 27.62 | 33.32 | 27.88 | 23.08 | 20.55 | 32.75 | 24.91 | 28.96 | 7.90 |
| HED | 12.44 | 11.95 | 13.79 | | 9.53 | 9.00 | 8.00 | 5.32 | 23.29 | 17.51 | 22.02 | 24.62 | 18.57 | 20.42 | 19.56 | 7.13 |
| PYROPE | 6.84 | 19.05 | 0.25 | | 14.24 | 2.49 | 33.27 | 30.43 | 8.58 | 19.47 | 16.88 | 12.23 | 8.79 | 14.84 | 13.65 | 20.08 |
| ALMAN | 2.42 | 8.20 | 0.08 | | 4.12 | 0.58 | 12.78 | 6.40 | 6.55 | 13.36 | 17.59 | 16.02 | 5.45 | 13.30 | 10.07 | 19.80 |
| KY | – | – | – | | – | – | – | – | – | – | – | 4.68 | – | – | – | 8.34 |
| COR | – | – | – | | – | – | – | – | – | – | 1.83 | 1.85 | – | – | 5.57 | – |
| COES | – | – | – | | – | – | – | – | – | – | – | – | – | – | – | 4.55 |
| SP | 9.61 | 8.62 | 14.45 | | 10.17 | 12.94 | 8.65 | 14.30 | 7.96 | 2.29 | 4.18 | – | 4.93 | 2.86 | 4.49 | – |
| HERC | 3.36 | 3.67 | 4.79 | | 2.91 | 2.98 | 3.29 | 2.98 | 6.01 | 1.56 | 4.31 | – | 3.02 | 2.54 | 3.28 | – |
| WUSTITE | 3.67 | 2.35 | 3.20 | | 2.70 | 3.20 | 1.64 | 1.31 | 0.75 | 1.75 | – | – | 2.62 | 0.76 | – | – |
| PERC | 7.19 | 3.78 | 6.62 | | 6.46 | 9.51 | 2.97 | 4.32 | 0.68 | 1.77 | – | – | 2.93 | 0.59 | – | – |
| Total | 100.00 | 100.01 | 99.99 | | 100.00 | 100.00 | 100.00 | 100.01 | 100.01 | 100.00 | 100.00 | 100.01 | 100.00 | 100.00 | 100.01 | 100.00 |

| | Olivine and nepheline normative | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-81-AB-11 | KEC-81-3 | KEC-81-7 | KEC-81-8 | KEC-81 10A | KEC-81-21 | KEC-86-71B | KEC-86-72A | KEC-86-72B | KEC-86-KB-74B | KGR-86-76 |
| 1 bar normative mineralogy | | | | | | | | | | | |
| OR | 2.48 | 1.12 | 2.25 | 4.96 | 4.31 | 1.71 | 5.08 | 2.66 | 1.36 | 2.78 | 9.40 |
| AB | 11.04 | 4.15 | 10.64 | 11.76 | 16.65 | 18.80 | 8.84 | 5.54 | 11.24 | 16.23 | 9.51 |
| AN | 22.68 | 37.61 | 34.83 | 30.37 | 20.90 | 25.26 | 40.11 | 40.62 | 28.98 | 57.95 | 47.23 |
| DI | 24.17 | 30.34 | 17.74 | 24.89 | 31.24 | 24.17 | 18.02 | 14.76 | 28.35 | – | 7.86 |
| HY | – | – | – | – | – | – | – | – | – | – | – |
| NE | 5.71 | 6.00 | 0.75 | 3.58 | 5.83 | 1.60 | 1.26 | 2.22 | 3.58 | 2.21 | 2.18 |
| OL | 32.74 | 19.31 | 32.12 | 22.86 | 20.46 | 27.78 | 25.79 | 32.69 | 25.23 | 19.26 | 22.28 |
| IL | 0.74 | 1.46 | 1.71 | 1.69 | 0.87 | 1.06 | 1.06 | 1.60 | 1.44 | 0.85 | 1.77 |
| AP | 0.14 | 0.23 | 0.19 | 0.09 | 0.14 | 0.12 | 0.12 | 0.09 | 0.09 | 0.07 | 0.07 |
| C | – | – | – | – | – | – | – | – | – | 1.02 | – |
| Total | 99.70 | 100.22 | 100.23 | 100.20 | 100.40 | 100.50 | 100.28 | 100.18 | 100.27 | 100.37 | 100.30 |
| 30 kbar normative mineralogy | | | | | | | | | | | |
| ILM | | | 1.86 | 1.81 | | 1.15 | 1.13 | 1.46 | 1.49 | 0.75 | |
| KALS | | | 3.28 | 7.14 | | 2.48 | 7.22 | 3.26 | 1.88 | 3.27 | |
| JD | | | 10.09 | 15.18 | | 18.11 | 9.12 | 6.80 | 14.18 | 13.76 | |
| DIOP | | | 33.33 | 33.40 | | 31.73 | 32.45 | 19.20 | 29.04 | 26.31 | |
| HED | | | 17.82 | 20.61 | | 17.35 | 22.23 | 25.96 | 25.48 | 15.84 | |
| PYROPE | | | 8.01 | 2.01 | | 8.75 | 5.44 | 12.33 | 8.26 | 2.03 | |
| ALMAN | | | 4.68 | 1.35 | | 5.23 | 4.08 | 18.21 | 7.92 | 1.33 | |

**Table 10** (continued)

| | Olivine and nepheline normative | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | KEC-81-AB-11 | KEC-81-3 | KEC-81-7 | KEC-81-8 | KEC-81 10A | KEC-81-21 | KEC-86-71B | KEC-86-72A | KEC-86-72B | KEC-86-KB-74B | KGR-86-76 |
| KY | | | – | – | | – | – | 0.47 | – | 0.75 | |
| COR | | | – | – | | – | 1.55 | 12.31 | – | 35.96 | |
| COES | | | – | – | | – | – | – | – | – | |
| SP | | | 10.04 | 9.44 | | 6.09 | 9.65 | – | 5.54 | – | |
| HERC | | | 5.81 | 6.30 | | 3.60 | 7.14 | – | 5.25 | – | |
| WUSTITE | | | 2.32 | 1.36 | | 2.55 | – | – | 0.56 | – | |
| PERC | | | 2.75 | 1.40 | | 2.96 | – | – | 0.41 | – | |
| Total | | | 99.99 | 100.00 | | 100.00 | 100.01 | 100.00 | 100.01 | 100.00 | |

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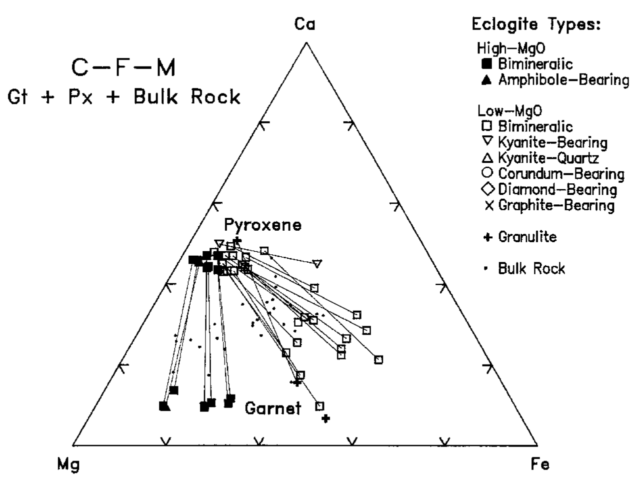


c

**Fig. 4. a** Plot of CaO, MgO, and total FeO in Koidu bulk-rock eclogites and granulites. Fields outlined and labeled are from Dawson (1980). Abbreviations are: grospydites, (*grosp*); peraluminous eclogites, (*peral*). **b** Plot of CaO, $Al_2O_3$, and total FeO+MgO in bulk-rock eclogites and granulites. Fields outlined and labeled are from Dawson (1980). Abbreviations are: bimineralic eclogites, (*ecl*); carbonaceous eclogites, (*carb*); grospydites, (*grosp*); peraluminous eclogites, (*peral*). **c** Garnet with coexisting pyroxene, and bulk-rock compositions for Koidu eclogites and granulites plotted as Ca–Fe–Mg. *Tie lines* connect coexisting garnet and pyroxene

KEC-86-KB-74B, which is the only xenolith containing 1.02% corundum in the norm. Olivine (3–34 norm %) and hypersthene (2–35 norm %) normative eclogites are undersaturated, have high MgO garnets and as defined by the basalt tetrahedron (Yoder and Tilley 1957) are olivine tholeiites. Eclogites with low-MgO garnets may be either hypersthene or nepheline normative. The bulk rock geochemistry of the Koidu eclogites reflects the mineral chemistry of garnet and clinopyroxene present. Figure 4c summarizes clinopyroxene, garnet, and bulk rock compositions in the Ca–Mg–Fe ternary. Bulk rock compositions lie along garnet-clinopyroxene tie lines, but are slightly skewed to the magnesium end member. This is due in part to the differences in $Fe_2O_3$ and FeO calculations used respectively for bulk rock compositions and mineral analyses, and in part to the presence of minor phases and intergranular assemblages. Using the lever-rule, bulk rock analyses agree well with the garnet to clinopyroxene ratios from Table 1. From the observations noted above, it is now possible to estimate, from garnet compositions, low-MgO and high-MgO groups for which rock analyses were not obtained. High-MgO eclogites are strictly bimineralic; the exception is KEC-81-AB-11 which contains 30 modal % amphibole. Eclogites with primary accessory minerals (diamond, graphite, quartz, kyanite, and corundum) are restricted to the low-MgO group.

## Trace element variations and isotope data

The 27 samples analyzed for major elements were also analyzed for the trace elements Rb, Sr, U, Rb, Th, Pb, Ga, Nb, Zr, Zn, Ni, Cr, V, Ce, Ba, and La, by XRF. For 5 of these samples, and 3 others, garnet and clinopyroxene mineral separates were analyzed for Rb, Sr, Nb, and Sm by Mass Spectrometry at the Max Planck Institute in Mainz. Trace element data for low- and high-MgO eclogites and 2 representative lower crustal granulites are presented in Table 9. Isotope data are presented in Table 11. Apart from this study, only sparse and incomplete data are available for bulk-rock eclogite xenoliths from other localities (Philpotts and Schnetzler 1970; Dawson 1980; MacGregor and Manton 1986).

Although variable, Cr, Ba, Ni, Sr, Nb, Zr, V, and Zn are the more abundant trace elements, with Y, Rb, Ce, La, Ga, Th, U, Pb among the less abundant. Interpretation of incompatible elements (Rb, Ba, Nb, K, and Sr) is equivocal because of the metasomatized nature of some of the Koidu eclogites, as shown by the strong correlation between $K_2O$ and Rb. These large-radius cations are located in secondary phlogopite, small-scale intergrowths of secondary amphibole (Erlank 1970), or in submicroscopic alteration products in clinopyroxene (Berg 1968). These locals correlate well with modal % amphibole and phlogopite (Table 1) identified petrographically. High-MgO eclogites contain less Rb and $K_2O$ than low-MgO eclogites, reflecting a less metasomatized state than some low-MgO eclogites. The two granulites contain the highest concentrations of Rb and $K_2O$, consistent with the presence of plagioclase and phlogopite in the modal mineralogy. Barium in the eclogites ranges from 84–1260 ppm, and Sr is from 50–506 ppm, comparable to highly metasomatized upper mantle peridotites (Erlank et al. 1987; Hawkesworth et al. 1983). Secondary amphibole and phlogopite are present but kimberlitic magma contamination is also a possible cause for high Ba and Sr concentrations. This is especially true for eclogite KEC-81-3, where in thin section, 1 mm wide kimberlite veins are present. There are no obvious distinctions in Ba and Sr between high- and low-MgO eclogites.

Variation in the compatible element Cr, reflects the concentration of Cr in the constituent minerals, insofar as high-MgO garnets and clinopyroxenes contain higher concentrations of Cr. Some high-MgO eclogites contain large concentrations of Cr (1,079–2,356 ppm), but others overlap with the low-MgO eclogite group (147–975 ppm). There is, however, a strong positive correlation with increasing MgO as a function of Cr content.

Zr/Y ratios (Table 9) are low, ranging from <1 to 12, with most values clustering between 1–3. These values correspond well with those of Island Arc low-K tholeiites and calc-alkaline basalts (Pearce and Cann 1973). Rb/Sr ratios (Table 9) are 0.01–0.25, and Sr ranges from 50–506 ppm. There is a rough negative correlation between Sr and Rb/Sr but neither a distinction nor a continuum of these trace concentrations is present in terms of high- and low-MgO groups.

It appears from most plots, that the Koidu high- and low-MgO eclogites are not due to simple fractionation. Various elemental log-log combinations were attempted but none show reasonable results. High-MgO eclogites have high Ni (>500 ppm) contents but are not simply picritic equivalents of low-MgO eclogites (162–417 ppm Ni) judging from the weak correlation of Mg vs Ni. Amphibole eclogite KEC-81-AB-11 contains anomalously high Ni contents (861 ppm), and is MgO-enriched making this sample

**Table 11.** Sm, Nd, and Sr concentrations for garnet and pyroxene mineral separates

| | Sm (ppm) | Nd (ppm) | Sr (ppm) | $\frac{^{147}Sm}{^{144}Nd}$ | $\frac{^{143}Nd}{^{144}Nd}$ | $\frac{^{87}Sr}{^{86}Sr}$ |
|---|---|---|---|---|---|---|
| KEC-81-DB-1 | | | | | | |
| (Cpx) | 1.928±6 | 1.400±1 | 0.530±5 | 0.8330 | 0.51559±2 | 0.70395± 3 |
| KEC-81-11 | | | | | | |
| (Gnt) | 8.620±5 | 2.183±9 | 0.367±1 | 2.3880 | 0.51414±2 | 0.70480± 2 |
| (GntFe) | 0.822±4 | 0.682±1 | 0.855±5 | 0.7289 | 0.51351±2 | 0.70413± 6 |
| (Amph) | 6.723±5 | 49.81 ±1 | 639.9 ±1 | 0.0816 | 0.51257±2 | 0.70300± 2 |
| KEC-86-9 | | | | | | |
| (Gnt) | 1.603±6 | 2.353±4 | 2.701±3 | 0.4120 | 0.51298±2 | 0.70403± 2 |
| (Cpx) | 0.993±1 | 4.080±1 | 147.0 ±3 | 0.1472 | 0.51282±2 | 0.70328± 2 |
| KEC-86-19 | | | | | | |
| (Gnt) | 1.041±2 | 0.978±3 | <2 | 0.6437 | 0.51334±2 | 0.70618± 6 |
| (GntFe) | 0.992±1 | 0.925±1 | 1.171±2 | 0.6480 | 0.51333±2 | 0.70494± 4 |
| (GntFeX) | 0.656±5 | 0.733±5 | 0.935±6 | 0.5410 | 0.51347±2 | 0.7060 ±10 |
| (Cpx) | 3.521±3 | 14.06 ±1 | 210.4 ±8 | 0.1510 | 0.51284±2 | 0.70333± 4 |
| (CpxFe) | 3.510±2 | 14.24 ±5 | 212.1 ±6 | 0.1490 | 0.51282±2 | 0.70314± 3 |

*Cpx*=Iron-poor clinopyroxene; *CpxFe*=Iron-rich clinopyroxene; *Gnt*=Iron-poor garnet; *GntFe*=Intermediate iron-rich garnet; *GntFeX*=Iron-rich garnet; *Amph*=Amphibole

Analyses from Max Planck Institute für Chemie, Mainz

**Table 12.** $K_D$ values for Koidu eclogites

| | KEC-80-80-B1 | KEC-81-81-2 | KEC-81-81-11 | KEC-86-86-2 | KEC-86-86-8 | KEC-86-86-15 | KEC-86-86-58 | KEC-86-86-73A | KEC-86-86-73B | KEC-86-86-90 | KEC-86-86-107 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| High-MgO eclogites | | | | | | | | | | | |
| Gt Ca | 0.294 | 0.353 | 0.297 | 0.307 | 0.325 | 0.323 | 0.302 | 0.291 | 0.301 | 0.328 | 0.417 |
| Gt Fe | 0.814 | 0.845 | 0.461 | 0.755 | 0.546 | 0.865 | 0.445 | 0.712 | 0.712 | 0.753 | 0.451 |
| Gt Mg | 1.912 | 1.815 | 2.297 | 1.964 | 2.124 | 1.886 | 2.322 | 2.036 | 2.042 | 2.000 | 2.165 |
| Mole Gt Ca | 0.097 | 0.117 | 0.097 | 0.101 | 0.109 | 0.105 | 0.098 | 0.096 | 0.099 | 0.106 | 0.137 |
| Px Mg | 0.793 | 0.783 | 0.819 | 0.818 | 0.876 | 0.773 | 0.888 | 0.802 | 0.811 | 0.847 | 0.816 |
| Px Fe | 0.136 | 0.129 | 0.073 | 0.106 | 0.053 | 0.146 | 0.047 | 0.110 | 0.089 | 0.121 | 0.063 |
| $K_D$ | 2.482 | 2.826 | 2.252 | 2.967 | 4.249 | 2.428 | 3.621 | 2.550 | 3.177 | 2.636 | 2.698 |

| | KEC-80-A2 | KEC-81-3 | KEC-81-4 | KEC-81-5 | KEC-81-7 | KEC-81-8 | KEC-81-10A | KEC-81-12 | KEC-81-18 | KEC-81-21 | KEC-86-6 | KEC-86-11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low-MgO eclogites | | | | | | | | | | | | |
| Gt Ca | 0.907 | 1.190 | 0.299 | 0.729 | 0.779 | 0.948 | 0.704 | 0.665 | 0.984 | 0.528 | 0.971 | 1.259 |
| Gt Fe | 1.213 | 0.986 | 1.466 | 1.385 | 1.078 | 1.098 | 1.047 | 1.691 | 1.358 | 1.210 | 1.221 | 0.995 |
| Gt Mg | 0.833 | 0.872 | 1.281 | 0.922 | 1.191 | 1.000 | 1.305 | 0.729 | 0.693 | 1.279 | 0.821 | 0.764 |
| Mole Gt Ca | 0.307 | 0.390 | 0.098 | 0.240 | 0.256 | 0.311 | 0.230 | 0.216 | 0.324 | 0.175 | 0.322 | 0.417 |
| Px Mg | 0.584 | 0.506 | 0.691 | 0.777 | 0.582 | 0.504 | 0.495 | 0.623 | 0.548 | 0.562 | 0.630 | 0.626 |
| Px Fe | 0.162 | 0.112 | 0.175 | 0.200 | 0.123 | 0.106 | 0.116 | 0.305 | 0.191 | 0.165 | 0.152 | 0.101 |
| $K_D$ | 5.249 | 5.108 | 4.519 | 5.836 | 4.283 | 5.221 | 3.424 | 4.738 | 5.622 | 3.222 | 6.164 | 8.072 |

| | KEC-86-13 | KEC-86-71B | KEC-86-72A | KEC-86-72B | KEC-80-DB-D1 | KEC-80-DB-2 | KEC-80-DB-3 | KEC-80-DB-40 | KEC-86-DB-9 |
|---|---|---|---|---|---|---|---|---|---|
| Low-MgO eclogites | | | | | | | | | |
| Gt Ca | 0.681 | 0.978 | 0.873 | 0.821 | 0.930 | 0.613 | 0.887 | 0.880 | 0.900 |
| Gt Fe | 1.408 | 1.037 | 1.490 | 1.403 | 0.825 | 1.008 | 0.580 | 0.872 | 0.942 |
| Gt Mg | 0.945 | 1.054 | 0.692 | 0.867 | 1.195 | 1.275 | 1.450 | 1.196 | 1.224 |
| Mole Gt Ca | 0.224 | 0.319 | 0.286 | 0.266 | 0.315 | 0.212 | 0.304 | 0.299 | 0.294 |
| Px Mg | 0.575 | 0.513 | 0.722 | 0.563 | 0.519 | 0.582 | 0.484 | 0.492 | 0.561 |
| Px Fe | 0.187 | 0.071 | 0.280 | 0.204 | 0.087 | 0.134 | 0.056 | 0.098 | 0.187 |
| $K_D$ | 4.581 | 7.109 | 5.552 | 4.466 | 4.118 | 3.434 | 3.457 | 3.660 | 2.309 |

| | KEC-86-DB-10 | KEC-86-GB-12 | KEC-86-GB-70 | KEC-86-CB-68 | KEC-86-KB-1 | KEC-86-KB-3 | KEC-86-KB-4 | KEC-86-KB-74B | (Granulite) KGR-86-76 |
|---|---|---|---|---|---|---|---|---|---|
| Low-MgO eclogites | | | | | | | | | |
| Gt Ca | 0.750 | 0.833 | 0.378 | 1.396 | 1.022 | 1.719 | 1.275 | 1.376 | 0.483 |
| Gt Fe | 1.096 | 1.327 | 1.326 | 0.425 | 0.450 | 0.745 | 0.930 | 0.915 | 1.240 |
| Gt Mg | 1.232 | 0.924 | 1.301 | 1.302 | 1.558 | 0.628 | 0.800 | 0.769 | 1.353 |
| Mole Gt Ca | 0.244 | 0.270 | 0.126 | 0.447 | 0.337 | 0.556 | 0.424 | 0.450 | 0.157 |
| Px Mg | 0.551 | 0.511 | 0.664 | 0.299 | 0.659 | 0.432 | 0.429 | 0.452 | 0.672 |
| Px Fe | 0.124 | 0.127 | 0.178 | 0.024 | 0.026 | 0.062 | 0.063 | 0.067 | 0.168 |
| $K_D$ | 3.953 | 5.779 | 3.802 | 4.067 | 7.321 | 8.266 | 7.916 | 8.027 | 3.666 |

highly distinctive. Substantial overlap is noted in most cases for the high- and low-MgO eclogite groups in terms of trace element concentrations; the exceptions are Ga and Zn. These two trace elements along with Cr and Ni are compatible in spinel, yet petrographically, spinel is very rare in the Koidu eclogites, and is unlikely to have been a precursor phase. The granulites are enriched in incompatible elements (e.g. Sr, Ba, Ti, Rb, Zr, K) but depleted in Nb relative to the eclogites.

Isotope data for the Koidu xenolith suite are incomplete and therefore only preliminary results are presented. Present day $^{87}Sr/^{86}Sr$, $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios on garnet and clinopyroxene separates from 2 samples (KEC-86-DB-9 and KEC-86-19), and garnet and amphibole ratios from another 2 samples (KEC-81-DB-1 and KEC-81-AB-11), are presented in Table 11. Sr in clinopyroxene from KEC-86-19 is 211 ppm and is 147 ppm for KEC-86-DB-9. Amphibole from KEC-81-AB-11 contains 637.9 ppm Sr. In KEC-86-19, Sm in clinopyroxene is 3.5 ppm, and is 0.656–1.041 ppm in garnet. The concentration of Sm in KEC-86-DB-9 is reversed, with 0.993 ppm in clinopyroxene, and 1.603 ppm in garnet. Nd ranges from 4.080 to 14.325 ppm in clinopyroxene, and 0.733 to 2.353 ppm in garnet.

Isotopic variations are present in different generations of the same mineral, shown especially in KEC-81-AB-11.

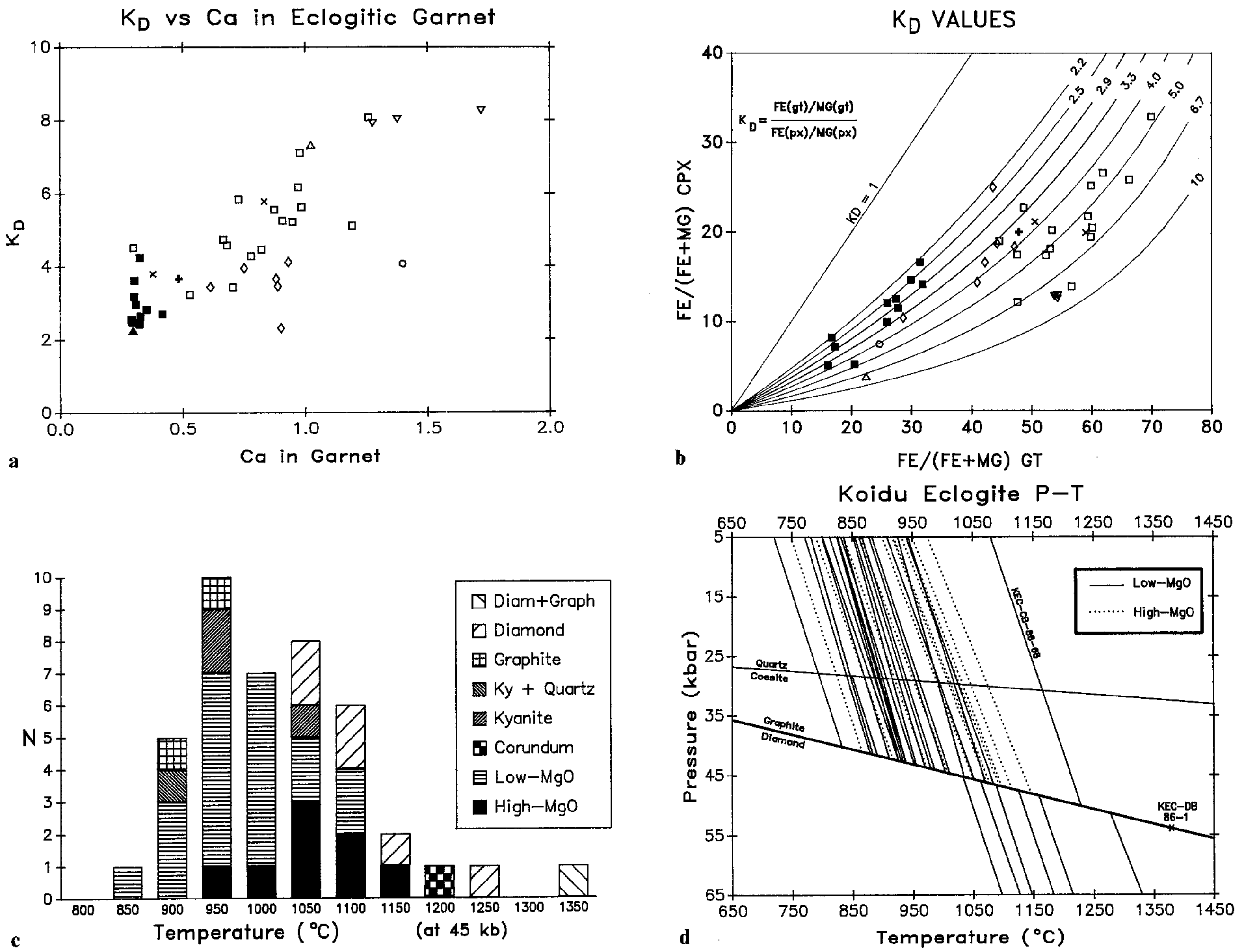


**Fig. 5. a** Plot of Ca in garnet versus $K_D$ for Koidu eclogites and granulites. **b** The distribution diagram of $K_D$ for the ratio Fe/(Fe+Mg) in eclogite garnets and clinopyroxenes from Koidu. **c** Bar graph of temperatures of equilibration for Koidu eclogites. **d** Temperature (Ellis and Green 1979) – pressure plot of individual eclogite xenoliths from Koidu. The diamond-graphite stability curve is plotted from Kennedy and Kennedy (1976); the quartz-coesite stability curve is plotted from Bohlen and Boettcher (1982). KEC-DB-86-1 is a diamond- and graphite-bearing xenolith, and KEC-CB-86-1 is a corundum-bearing xenolith

Iron-rich garnet contains substantially smaller amounts of Sm and Nd relative to Fe-poor garnet. This results in extremely high $^{147}Sm/^{144}Nd$ ratios (2.38) vs (0.7289) relative to the rest of the garnet separates (0.412–0.648). $^{147}Sm/^{144}Nd$ values for 3 garnet compositions from KEC-86-19 range from 0.541 to 0.648. Clinopyroxene $^{143}Nd/^{144}Nd$ ratios for garnet separates are all quite similar (average = 0.5130), with the exception of KEC-81-DB-1 which gives a $^{143}Nd/^{144}Nd$ value of 0.51559. Ages estimated from Sm–Nd mineral isochrons range from 92–247 Ma. Amphibole from KEC-81-AB-11 contains the highest concentrations of Nd (49.81 ppm) and Sr (639.9 ppm).

## Geobarometry and geothermometry

Coexisting garnet and pyroxene geothermometry (Ellis and Green 1979) are applied and temperature is calculated assuming a range of pressures. Estimates of P are determined from the accessory phases, diamond, graphite, quartz after coesite, kyanite, and plagioclase.

### *$K_D$ values*

$K_D$ values, calculated for coexisting garnet and clinopyroxene pairs for 43 eclogites and two granulites using total iron as $Fe^{2+}$, are listed in Table 12, in order of high- and low-MgO eclogite and associated accessory minerals. $K_D$ values range from 2.25 for KEC-81-AB-11, the amphibole-bearing eclogite, to 8.27 for KEC-86-KB-3, a kyanite-bearing eclogite; sample KEC-86-19, an eclogite with concentrically zoned garnets, gives a much higher value with a core $K_D$ of 12.18. High-MgO eclogites ($n=9$) contain the lowest $K_D$ values, ranging from 2.0 to 3.5. Diamond-bearing eclogites ($n=6$) range from 3.4–4.0, and low-MgO bimineralic eclogites ($n=15$) range from 3.3–6.7. Kyanite-bearing eclogites ($n=4$), with the exception of KEC-86-QB-1, which contains quartz, gives the highest $K_D$ values that cluster at 7.5. The corundum-bearing eclogite has a $K_D$ of 3.0, and the two graphite-bearing eclogites are 3.8 and 5.8.

There is a strong positive correlation between mole percent calcium in garnet versus $K_D$ for the entire suite (Fig. 5a). Even more interesting is that high-MgO eclogites,

**Table 13.** $K_D$ values for eclogites with zoned garnets and pyroxenes

| | Core 81-1A | Rim 81-1B | Core 80-5 | Rim 80-5 | Core 86-19 | Rim 86-19 |
|---|---|---|---|---|---|---|
| Gt Ca | 0.975 | 0.688 | 0.723 | 0.419 | 0.536 | 0.536 |
| Gt Fe | 1.005 | 0.881 | 1.359 | 0.910 | 1.384 | 0.635 |
| Gt Mg | 1.005 | 1.444 | 1.087 | 1.879 | 1.138 | 1.851 |
| Mole Gt Ca | 0.327 | 0.220 | 0.228 | 0.131 | 0.175 | 0.177 |
| Px Mg | 0.458 | 0.458 | 0.780 | 0.624 | 0.932 | 0.853 |
| Px Fe | 0.103 | 0.103 | 0.175 | 0.180 | 0.091 | 0.098 |
| LN $K_D$ | 1.492 | 0.998 | 1.718 | 0.518 | 2.522 | 1.094 |
| $K_D$ | 4.45 | 2.71 | 5.57 | 1.68 | 12.46 | 2.99 |
| Kbars | Temperature in °C | | | | | |
| 5 | 934 | 1034 | 774 | 1168 | 547 | 940 |
| 10 | 950 | 1053 | 789 | 1190 | 559 | 958 |
| 15 | 966 | 1076 | 804 | 1213 | 571 | 976 |
| 20 | 982 | 1090 | 819 | 1235 | 584 | 994 |
| 25 | 998 | 1109 | 834 | 1258 | 596 | 1012 |
| 30 | 1014 | 1128 | 849 | 1280 | 608 | 1030 |
| 35 | 1030 | 1147 | 864 | 1302 | 620 | 1048 |
| 40 | 1046 | 1166 | 879 | 1325 | 633 | 1066 |
| 45 | 1062 | 1184 | 894 | 1347 | 645 | 1084 |
| 50 | 1078 | 1203 | 909 | 1370 | 657 | 1103 |
| 55 | 1094 | 1221 | 924 | 1392 | 669 | 1121 |
| 60 | 1110 | 1240 | 939 | 1415 | 682 | 1139 |
| 65 | 1126 | 1259 | 954 | 1437 | 694 | 1157 |
| 70 | 1142 | 1277 | 969 | 1460 | 706 | 1175 |

with the lowest $K_D$ values, contain the lowest mole % Ca in garnet. In addition, kyanite-bearing eclogites, with the highest $K_D$s, have the largest grossular components. Diamond-bearing eclogites are intermediate between these two extremes. Figure 5b, shows the distribution of Mg and Fe between coexisting garnet and clinopyroxene, and a large range in temperatures of equilibration. Sobolev (1970) has shown that high jadeite components in the clinopyroxene are correlated with high $K_D$ values, which is also the case for the Koidu eclogites.

### *Temperature range*

Eclogites exhibit a large range in equilibrium temperatures, extending from approximately 845–1345° C at 45 kb; there is one exception for the core of KEC-86-19, which gives a temperature of 645° C. High-MgO eclogites range from 950° to 1150° C, with an average at 1052° C (Fig. 5c). Twenty of the low-MgO bimineralic eclogites have a temperature range of 850–1100° C at 45 kb, averaging at approximately 978° C. Therefore, on average, high-MgO eclogites are 75° C hotter than bimineralic low-MgO eclogites. Two kyanite-bearing eclogites have temperatures of 950° C, one is at slightly higher temperatures (1100° C), and the kyanite + quartz eclogite has a slightly lower temperature of 900° C. Corundum-bearing eclogite KEC-86-CB-68 has a very high temperature of 1200° C. Diamond-bearing eclogites give the highest temperatures of equilibration, ranging from 1050° to 1250° C. The diamond + graphite-bearing eclogite is at an even higher temperature (1350° C). The two graphite only eclogites have much lower temperatures at 900° and 950° C. There is a negative correlation between the distribution coefficient and temperature: the high-MgO eclogites are the hottest and low-MgO kyanite eclogites are the coolest.

Core and rim temperature estimates for the three eclogites with zoned garnets and clinopyroxenes are given separately in Table 13. KEC-81-DB-1 and KEC-80-5, with discontinuously zoned garnets, have core-rim temperatures of 1062–1183° C and 894–1347° C at 45 kb, respectively. For KEC-86-19, which has continuously zoned garnets, the most iron-rich core composition and the most magnesium-rich rim composition from one garnet grain, were used for the calculation. Blebby, resorbed diopside-rich clinopyroxene compositions were used as the coexisting core composition. Similarly, overgrown, secondary, jadeite-rich rim compositions were used as the coexisting rim compositions. The temperature for the core and rim of KEC-86-19 is 645° C and 1085° C, respectively, at 45 kb.

### *Pressure estimates*

Theoretical and experimental diamond-graphite reaction curves are in reasonable agreement (Bundy et al. 1961; Kennedy and Kennedy 1976), and coexisting diamond and graphite are recorded in eight diamond-graphite eclogites from Roberts Victor (e.g. Reid et al. 1976); one from Orapa (Shee 1978); and one from Koidu. It is noted, however, that neither graphite nor diamond are pseudomorphs of the other.

The coexistence of diamond and graphite in the Koidu eclogites suggests that the eclogites formed under $P-T$ conditions close to the diamond-graphite reaction curve. By combining the Ellis and Green (1979) equation with the equation defining the graphite-diamond stability curve (Kennedy and Kennedy 1976) conditions of equilibration are determined as illustrated in Fig. 5d. Seven other diamond-bearing xenoliths with high jadeite components in pyroxene form a band about 227° C wide at lower temperatures (1030°–1277° C at 45–50 kb) than the diamond + graphite-bearing sample. Results obtained for other eclogites and the granulites are also shown in Fig. 5d, in which $P$ (5–65 kb) is varied to obtain $T$, and in which the accessory minerals are used to define $P-T$ limits. The quartz-coesite transition curve (Bohlen and Boettcher 1982), is also plotted on Fig. 5d. The breakdown of kyanite at extreme $P-T$ conditions is not known, and pressures of formation for kyanite eclogites and grospydites can only be constrained by their lower stability limits defined by the experimentally determined stability fields for the polymorphs of $Al_2SiO_5$. There is, however, an interesting spatial relation among quartz, kyanite, and corundum, with the possibility that kyanite has formed from $Al_2O_3$ and $SiO_2$. The 30 modal % amphibole in KEC-81-AB-11, is secondary and neither absolute upper nor lower pressure stability limits can resonably be determined for the formation of this eclogite. Granulites at Koidu contain plagioclase which constrains their $P$ and $T$ conditions to the lower crust.

### *Specific gravity*

Specific gravity values for the eclogites and two granulites are listed in Table 14, along with temperatures of equilibration at 45 kb, garnet to clinopyroxene ratios, and garnet, clinopyroxene, and bulk rock magnesium and calcium oxide values. Values of specific gravity for the eclogites range from 3.06 to 3.60 g/cc. The two granulites have values of 3.02 and 3.08 g/cc. Kyanite-bearing, low-MgO eclogites as a group, have the lowest specific gravities ranging from

**Table 14.** Specific gravity, temperatures, and mineral ratios for Koidu eclogites

| Xenolith | g/cc | °C (45 kb) | GT:PX | RX MG′ | PX CA′ | PX MG′ | GT CA′ | GT MG′ |
|---|---|---|---|---|---|---|---|---|
| KEC-80-A2 | 3.21 | 983 | 1.1 | | 53.39 | 78.28 | 52.13 | 40.71 |
| KEC-80-B1 | 3.33 | 1085 | 1.0 | | 49.87 | 85.36 | 13.33 | 70.14 |
| KEC-80-DB-D1 | 3.10 | 1082 | 1.1 | | 52.08 | 85.64 | 43.76 | 59.16 |
| KEC-80-DB-2 | 3.36 | 1058 | 1.4 | | 48.81 | 81.28 | 32.47 | 55.85 |
| KEC-80-DB-3 | 3.21 | 1146 | 0.8 | | 51.98 | 89.63 | 37.95 | 71.43 |
| KEC-80-DB-40 | ? | 1116 | 1.3 | | 51.19 | 83.39 | 42.39 | 57.83 |
| KEC-81-DB-1 | 3.45 | 1257 | 1.1 | 62.90 | 53.68 | 79.46 | 49.24 | 50.00 |
| KEC-81-2 | 3.20 | 1046 | 1.0 | 77.81 | 50.79 | 85.86 | 16.28 | 68.23 |
| KEC-81-3 | 3.45 | 1065 | 1.1 | 63.60 | 54.29 | 81.88 | 57.71 | 46.93 |
| KEC-81-4 | 3.41 | 848 | 0.8 | 65.56 | 48.78 | 79.79 | 18.92 | 46.63 |
| KEC-81-5 | 3.60 | 890 | 1.4 | 55.83 | 52.65 | 79.53 | 44.16 | 39.97 |
| KEC-81-7 | 3.32 | 1011 | 1.4 | 68.63 | 49.83 | 82.55 | 39.54 | 52.49 |
| KEC-81-8 | 3.30 | 988 | 1.0 | 65.29 | 51.77 | 82.62 | 48.67 | 47.66 |
| KEC-81-10A | 3.12 | 1078 | 1.0 | 73.10 | 48.22 | 81.01 | 35.04 | 55.48 |
| KEC-81-AB-11 | 3.14 | 1134 | 1.0 | 88.61 | 47.47 | 91.82 | 11.45 | 83.28 |
| KEC-81-12 | 3.18 | 938 | 1.0 | 49.06 | 58.05 | 67.13 | 47.33 | 30.12 |
| KEC-81-18 | 3.10 | 973 | 0.9 | 67.52 | 54.03 | 74.15 | 58.68 | 33.79 |
| KEC-81-21 | 3.21 | 1048 | 1.0 | 68.65 | 49.64 | 77.30 | 29.22 | 51.39 |
| KEC-86-QB-1 | 3.15 | 889 | 2.3 | | 51.54 | 96.20 | 39.61 | 77.59 |
| KEC-86-2 | 3.40 | 1009 | 1.5 | | 49.69 | 88.53 | 13.52 | 72.23 |
| KEC-86-KB-3 | 3.12 | 1033 | 1.0 | | 54.53 | 87.45 | 73.24 | 45.74 |
| KEC-86-KB-4 | 3.24 | 944 | 1.0 | | 53.57 | 87.20 | 61.45 | 46.24 |
| KEC-86-6 | 3.29 | 941 | 0.7 | | 52.20 | 80.56 | 54.19 | 40.21 |
| KEC-86-8 | 3.40 | 878 | 1.0 | | 48.65 | 94.29 | 13.27 | 79.55 |
| KEC-86-DB-9 | 3.41 | 1344 | 1.0 | | 51.13 | 75.00 | 42.37 | 56.51 |
| KEC-86-DB-10 | 3.38 | 1031 | 1.2 | | 50.05 | 81.63 | 37.84 | 52.92 |
| KEC-86-11 | 3.06 | 933 | 1.1 | | 53.18 | 86.11 | 62.23 | 43.43 |
| KEC-86-GB-12 | 3.12 | 918 | 1.0 | | 52.95 | 80.09 | 47.41 | 41.05 |
| KEC-86-13 | 3.23 | 958 | 0.6 | 59.32 | 51.99 | 74.80 | 41.88 | 40.16 |
| KEC-86-15 | 3.45 | 1105 | 1.1 | 75.01 | 47.94 | 83.39 | 14.62 | 68.56 |
| KEC-86-19 | 3.36 | 653 | 1.0 | 79.79 | 47.74 | 90.82 | 32.90 | 44.82 |
| KEC-86-58 | 3.32 | 926 | 1.0 | 89.50 | 47.24 | 94.97 | 11.51 | 83.92 |
| KEC-86-CB-68 | 3.31 | 1211 | 1.0 | | 48.89 | 92.57 | 51.74 | 75.39 |
| KEC-86-GB-70 | 3.36 | 934 | 0.8 | | 47.68 | 78.86 | 22.51 | 49.52 |
| KEC-86-71A | 3.30 | | 1.2 | 63.91 | | | 45.65 | 52.45 |
| KEC-86-71B | 3.26 | 893 | 1.1 | 63.63 | 51.10 | 87.84 | 48.13 | 50.41 |
| KEC-86-72A | 3.53 | 945 | 0.9 | 47.08 | 51.71 | 72.06 | 55.78 | 31.71 |
| KEC-86-72B | 3.48 | 1004 | 0.7 | 57.63 | 51.88 | 73.40 | 48.64 | 38.19 |
| KEC-86-73A | 3.40 | 1071 | 1.0 | 81.81 | 47.20 | 87.94 | 12.51 | 74.09 |
| KEC-86-73B | 3.34 | 977 | 1.1 | 84.89 | 49.56 | 90.11 | 12.85 | 74.15 |
| KEC-86-KB-74B | 3.24 | 960 | 1.0 | 66.13 | 53.31 | 87.09 | 64.15 | 45.67 |
| KGR-86-75 | 3.02 | | 1.0 | 56.27 | | | 13.82 | 45.33 |
| KGR-86-76 | 3.08 | 978 | 1.0 | 63.04 | 56.22 | 80.00 | 26.31 | 52.18 |
| KEC-86-90 | 3.58 | 1067 | 1.4 | 77.19 | 47.62 | 87.50 | 14.09 | 72.65 |
| KEC-86-107 | 3.41 | 1089 | 2.0 | 86.09 | 47.69 | 92.83 | 16.15 | 82.76 |

3.12 to 3.24 g/cc. Diamond-bearing, low-MgO eclogites have on average a higher specific gravity, ranging from 3.10–3.45 g/cc. Bimineralic low- and high-MgO eclogites show no clustering, and both groups of eclogites have a wide range in specific gravity. The calculated range of seismic $V_p$ wave velocities for the entire group is 7.4–8.7 km/s.

## Summary and conclusions

1. A variety of upper mantle eclogites and two lower crustal granulites from the Koidu Kimberlite Complex, Sierra Leone, West Africa consist of bimineralic garnet and clinopyroxene eclogites, and eclogites containing one or more of the following primary accessory minerals: diamond, graphite, kyanite, quartz after coesite, and corundum. This is now the fifth kimberlite locality in which eclogite xenoliths are solely present but in which peridotitic (ultramafic) diamonds are also reported (Harris and Gurney 1979; Meyer and Boyd 1972).

2. Koidu eclogites range from apparent cumulates to rocks with strong mineral fabrics and cross-cutting lineations. Most eclogites have intermediate textures, and cannot be classified as Group I or Group II (MacGregor and Carter 1970) as defined at Roberts Victor. Most Koidu eclogites contain minor amounts of secondary amphibole (pargasite and edenite), phlogopite, calcite, rutile, sulfide, and spinel, attributed to upper mantle metasomatism. One eclogite contains ≈30 modal % amphibole and this sample, in company with other minerals, is the first evidence for upper mantle metasomatism in the lithospheric Archean West African Craton. Near surface or entrainment contamination by kimberlite is distinctive. Oriented inclusions of rutile in both garnet and clinopyroxene are present. Banding or layering of minerals and a fine-grained matrix, suggestive

of partial melting, is restricted to kyanite and corundum-bearing eclogites. Most eclogites contain a 50:50 garnet to clinopyroxene ratio. Petrographically, lower crustal granulites are very similar in texture, fabric, alteration and/or preservation of minerals to eclogites, except for the presence of plagioclase.

3. Garnets show a wide range in chemical composition and distinct groupings based on MgO contents. Garnets from bimineralic eclogites are pyropic, whereas garnets in bimineralic eclogites with kyanite, corundum, diamond, or graphite are grossular and almandine-rich. Coexisting clinopyroxenes show a continuum from diopside to jadeite. High-MgO garnets coexist with diopside-rich clinopyroxene; low-MgO garnets from diamond-bearing eclogites, coexist with omphacitic clinopyroxene; and low-MgO garnets, from kyanite-bearing eclogites, coexist with jadeite-rich clinopyroxene. In contrast to the general homogeneous nature of minerals from the upper mantle, the Koidu eclogites are exceptional in that three eclogites of the 47 xenoliths in this study exhibit extensive zoning or mantling of both garnet and clinopyroxene. Two texturally and chemically distinct types of garnet zoning are present. Gradational zoning is characterized by the exchange of Fe for Mg. Cores are Fe-rich and rims are Mg-rich. Mantled garnets from two eclogites have almandine-rich cores, surrounded by a veneer of amphibole and phlogopite, all of which is mantled by a second, more pyropic garnet. Coexisting clinopyroxenes have resorbed, blebby diopsides, overgrown by a pristine second generation of more jadeite-rich clinopyroxene. Accessory primary phases of kyanite and corundum have almost pure compositions. Secondary accessory phases in all eclogites have similar compositions and consist of pargasite/edenite, phlogopite, three varieties of sulfide, spinel and rutile.

4. Bulk rock major element compositions show a wide range in composition which is similar to that of basalts. Based on MgO content, there are two populations. These are high-MgO (16–20 wt% MgO), and low-MgO (7–13 wt% MgO) eclogites. High-MgO eclogites contain high-MgO garnets and clinopyroxenes, and have close chemical affinities to picrites. Low-MgO eclogites contain low-MgO garnets and low-MgO clinopyroxenes and are compositionally similar to alkali basalts. High-MgO eclogites are strictly bimineralic, low-MgO eclogites are also bimineralic, but are accompanied by primary accessory minerals of diamond, graphite, kyanite, quartz, or corundum; the latter are peraluminous. Based on 1 bar normative mineralogy, eclogites are olivine-hypersthene normative and nepheline normative. High-MgO eclogites are olivine and hypersthene normative and suggest a possible link to olivine tholeiites. Olivine and nepheline normative eclogites suggest a possible link to alkali basalts.

5. Incompatible trace element variations (K, Rb, Ba, and Sr) are difficult to interpret due to superimposed metasomatism that has significantly modified pristine variations. Compatible trace element variations are neither a function of modal mineralogy and nor can high and low-MgO eclogites be separated isotopically. The absence of linear trends in incompatible elements suggests that the Koidu eclogites may not related by simple fractionation. From Ni vs MgO, it appears that high-MgO eclogites are not simply picritic equivalents of low-MgO eclogites. Lower crustal garnet granulites are enriched in Sr, Ba, Ti, Rb, K, and Zr and depleted in Nb relative to upper mantle eclogites.

6. Sm – Nd isochrons on selected garnet and clinopyroxene mineral separates give preliminary ages ranging from 92 Ma (for mineral separates from KEC-86-DB-9) to 247 Ma (core data for KEC-86-19). Diamonds are considered to be cogenetic with garnet and clinopyroxene, and based on the Proterozoic ages of eclogitic diamonds elsewhere, the relatively young ages for these eclogites must be apparent ages. $\varepsilon_{Nd}$ values range from +4.05 to +5.23, and are similar to oceanic island basalts, suggesting a source with a high Sm/Nd ratio, and a possibly depleted upper mantle.

7. Temperatures of equilibration at 45 kb range from 850°–1350° C. High-MgO eclogites have, on average, a higher temperature of equilibration (peaking at 1050° C), than bimineralic low-MgO eclogites, which peak at 950° C. Diamond-bearing, low-MgO eclogites have the highest temperatures of equilibration, 1050–1350° C at 45 kb. Accessory minerals of diamond, graphite, quartz after coesite, kyanite, plagioclase and amphibole provide markers in $P-T$ space from experimental transition curves. The Koidu Kimberlite sampled a deep vertical column of the West African Craton, ranging from depths of ≈130–170 km, (45–55 kb), up to and including the lower crust. Specific gravities for eclogites range from 3.06 to 3.60 g/cc, and the range of calculated $V_p$ seismic velocities is 7.5–8.7 km/sec.

8. Geochemistry and geothermometry suggest that there are possibly two origins for the Koidu eclogites. The high pressure and high temperatures of equilibration for the high-MgO eclogites, coupled with the absence of diamond, suggests an origin in the deeper and more oxidized, fertile asthenosphere, or possibly at the thermal boundary layer between the lithosphere and the asthenosphere (Haggerty 1986); this is supported by the similarity in eclogite garnet compositions and discrete garnet megacrysts. Low-MgO eclogites, with accessory diamond, graphite, kyanite, quartz, and corundum, have a lower temperature of equilibration for a given pressure, implying equilibration in the cooler, shallower, and less oxidizing lithosphere. Some diamond-bearing eclogites, however, may have originated at the lithosphere-asthenosphere boundary (Haggerty 1986). Diamond growth and contrasts in diamond morphology and color correlate with zoned garnet and clinopyroxene and metasomatic amphibole and phlogopite, implying metasomatic, secondary diamond growth (Navon et al. 1988). The relatively young ages for the eclogites may be the result of metasomatism or indicative of a thermal event of protokimberlite, possibly related to the onset of continental fragmentation. At present we have insufficient evidence to unequivocally relate the eclogites from Koidu in the West African Craton to a specific mechanism or process of formation although the data imply a $P-T$ and geochemical telescoping of eclogites sampled by the Complex. The most reasonable explanation for the absence of peridotites is pervasive metasomatism of the subcontinental lithosphere, which is supported by more advanced metasomatism of the lithospherically-derived low-MgO eclogitic suite.

## Appendix 1

### *Analytical techniques*

All eclogites were cleaned in an ultrasonic bath and cataloged in handspecimen. A second cataloging, by stereomicroscopy made special note of accessory minerals, overall texture, color, and general appearance. Koidu eclogites and granulites are labeled with the prefix 'KEC' and 'KGR', respectively. Bimineralic samples (garnet and clinopyroxene) are followed by a number uniquely assigned to each xenolith for identification (e.g. KEC-86-8). Samples with accessory minerals are designated by the following abbreviations (e.g. KEC-86-DB-10): where, diamond-bearing = DB, graphite-bearing = GB, amphibole-bearing = AB, kyanite-bearing = KB, corundum-bearing = CB, and quartz (after coesite)-bearing = QB. Forty-six, relatively unaltered xenoliths were selected for further detailed examination and analysis. These included representatives of each xenolith type catalogued during a second classification of the entire suite. Specific gravities of the selected suite were determined prior to cutting the xenoliths in half. One portion was used for polished-thin section preparation, crushed for making pellets and discs for major and trace element analyses, and/or for isotopic studies, and the remaining half catalogued for reference. Twenty-seven of the 46 samples were selected for geochemical analysis. Although sample size and kimberlite contamination were constraints, an effort was made to select xenoliths representative of the entire suite. Diamonds from the Koidu kimberlite fluoresce blue under short wave UV light (Granthem and Allen 1960). By contrast, diamonds in eclogites from Koidu do not fluoresce and from this we infer that there are at least two distinct populations, eclogitic and ultramafic. Specific gravities were determined according to methods by Judd and Shakoor (1981) with water temperature correction factors outlined by Sinkankas (1972). Repetitive measurements on quartz and topaz were equal to Handbook values $\pm 0.02$ gm/cc. Petrographic studies were undertaken on doubly polished-thin sections and mineral grain mounts by reflected and transmitted light microscopy. Chemical analyses of individual minerals of selected xenoliths were performed using the an ETEC Autoprobe. Operating conditions generally included an accelerating voltage of 15 kilovolts, an aperture current of 0.3 microamperes, 15 second counting intervals for each element, and an average beam diameter of approximately 5 microns. For all elements, $K\alpha$ radiation was used with 3 wavelength-disperisve spectrometers and LIF, KAP and PET analyzing crystals. Matrix correction factors followed those of Bence and Albee (1968), and Albee and Ray (1970). Geochemical standards used for analyses included a variety of both natural and synthetic silicates and oxides. Results are expressed as weight per cent of the oxides and atomic proportions were calculated to fit structural formulae, with $Fe^{2+}/Fe^{3+}$ calculated according to the method by Finger (1972). Precision of the electron microprobe data was estimated by replicate analyses of standards. Calculated end members for garnet analyses are expressed as grossular ($Ca_3Al_2Si_3O_{12}$), pyrope ($Mg_3Al_2Si_3O_{12}$), and almandine ($Fe_3Al_2Si_3O_{12}$), with Gross = Grossular 100*(Ca/(Ca + Mg + Fe)); Pyr = Pyrope 100*(Mg/(Ca + Mg + Fe)); Alm = Almandine 100*(Fe/(Ca + Mg + Fe)). Pyroxene quadrilateral components are wollastonite ($CaSiO_3$), enstatite ($MgSiO_3$) and ferrosilite ($FeSiO_3$), with Wo = Wollastonite 100*(Ca/(Ca + Mg + Fe)); En = Enstatite 100*(Mg/(Ca + Mg + Fe)); Fs = Ferrosilite 100*(Fe/(Ca + Mg + Fe)). Calculated pyroxene end members for jadeite, diopside, and hedenbergite are mole %:

$$Jd = \text{Jadeite } 100 \times ((Na + Al^{VI} + Cr)/(Na + Al^{VI} + Cr + Ca + Mg + Fe + Mn));$$

$$Wo = \text{Wollastonite } 100 \times (Ca/(Na + Al^{VI} + Cr + Ca + Mg + Fe + Mn));$$

$$Hy = \text{Hypersthene } 100 \times ((Mg + Fe + Mn)/(Na + Al^{VI} + Cr + Ca + Mg + Fe + Mn)).$$

All bulk chemical analyses were determined on a Siemens automated X-ray Fluorescence (XRF) Spectrograph following the procedures and matrix corrections by Norrish and Hutton (1969), and Norrish and Chappell (1967). Cr-tube radiation was used for major elements and Mo-tube (Rb, Sr, Y, U, Th, Pb, and Ga) and Au-tube (Nb, Zr, Zn, V, Cr, Ni, Ce, Ba, and La) radiations for trace element analyses. Both synthetic and natural standards were used for calibration. USGS standard BHVO was analyzed as an internal standard. Total iron was determined as $Fe_2O_3$. All ferric iron was converted to ferrous iron using the CIPW.BAS program. CIPW norms were calculated for hypothetical assemblages at 1 bar and at 30 kb, using the CIPW.BAS norm program, and the MANTLE.FOR program by Smyth (1981), respectively.

Niodymium, Sm, Rb, and Sr isotopes were determined for coexisting garnet and clinopyroxene separates from 8 Koidu xenoliths. All sample preparation was done at the Max-Planck-Institut für Chemie at Mainz under the supervision of Dr. Emil Jagoutz, following the procedures and instrumentation outlined by Jagoutz (1988).

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