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# THE ALLEGED KIMBERLITE–CARBONATITE RELATIONSHIP: ADDITIONAL CONTRARY MINERALOGICAL EVIDENCE

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ABSTRACT. This paper seeks to refute the commonly held view that kimberlites and carbonatites are genetically related. The view is based on two assumptions: (A) that they must be genetically related because both contain primary magmatic carbonate; (B) that kimberlites are found associated with nepheline syenite–ijolite–carbonatite complexes. In order to examine these assumptions, mineralogical definitions are presented for both carbonatite and kimberlite. These mineralogical criteria are then compared to the mineralogy of the carbonate-rich residua of kimberlites, using Canadian and South African examples, and to the supposed kimberlites of carbonatite complexes.

It is concluded that the carbonate-rich residuum of kimberlite lacks the mineralogical characteristics of carbonatite in that it contains primary serpentine and calcite, exhibits liquid immiscibility features, lacks NaFe silicates and Nb minerals. Spinel is rare but when present is magnetite, whereas carbonatites contain titaniferous magnesioferrite–magnetites associated with manganoan ilmenites.

The supposed kimberlites of carbonatite complexes, commonly termed "central complex kimberlites" or "kimberlitic dikes" are shown to be lamprophyres and to differ markedly from the mineralogy of true kimberlite. For example, kimberlites contain Mg–ilmenite, titaniferous–magnesian–aluminous chromite, magnesian ulvöspinel–magnetite solid solutions, and rare, $Al_2O_3$-poor pyroxenes. In contrast, the lamprophyres from the Fen alkaline complex (Norway) and the Ile Bizard diatreme (Quebec) contain andradite–grossular garnet, manganoan ilmenites, titaniferous–aluminous–magnesian chromites, ulvöspinel–magnetites, $Al_2O_3$-rich pyroxenes, nepheline, and melilite.

It is concluded that kimberlite and carbonatite are not genetically related. Kimberlites do not occur in alkaline complexes, do not differentiate to carbonatites, and are not associated with rift tectonics. The terms "central complex kimberlite" and "kimberlitic dike" should be abandoned. Kimberlites that differentiate to carbonate-rich residua should be called calcite kimberlites to distinguish them from true carbonatites.

## INTRODUCTION

The First and Second International Kimberlite Conferences (1973, 1977) and the International Symposium on Carbonatites (1976) did little to clarify to the non-specialist in alkaline rock petrology the petrogenetic relationships between kimberlite and carbonatite. It is widely believed that these two rocks are genetically related. This belief rests upon two assumptions:

1. Because kimberlites and carbonatites both contain primary magmatic carbonatite, they must be related petrogenetically.
2. Kimberlites are associated with miascitic nepheline syenite–ijolite–carbonatite complexes.

Belief in the kimberlite–carbonatite relationship has important petrological and economic consequences. It can lead to confused petrogenetic speculation, for example, the linking together of such diverse magmas as kimberlite, carbonatite, and anorthosite in mantle plume models (Anderson, 1975) or to the erection of overly complex petrogenetic schemes in an effort to relate such rocks as nepheline syenite or ijolite to kimberlite (Ernst, 1975). In economic terms the belief can lead to misdirected exploration efforts, such as carbonate-rich kimberlite for niobium, alnöite for diamond, or rift structures for kimberlites.

Some aspects of the kimberlite–carbonatite relationship are due to problems of terminology. Usage of the terms kimberlite and carbonatite is exceedingly lax and leads to the introduction of such ill-defined and imprecise terms as "kimberlitic," "near kimberlite," "kimberlitic–carbonatite," and "carbonatite–kimberlite."

In this paper kimberlites are defined as "inequigranular alkalic peridotites containing rounded and corroded megacrysts of olivine, phlogopite, magnesian ilmenite, and pyrope set in a fine grained groundmass of second generation euhedral olivine and phlogopite together with primary and secondary (after olivine) serpentine, perovskite, carbonate (calcite and/or dolomite), and spinels. The spinels range in composition from titaniferous–magnesian–aluminous–chromite to magnesian ulvöspinel–ulvöspinel–magnetite. Accessory minerals include diopside, monticellite, apatite, rutile, and nickeliferous sulphides. Some kimberlites can contain major modal amounts of diopside or monticellite."

Kimberlites rich in monticellite, for example, De Beers, Elwin Bay, appear to lack diopside (Skinner and Clement, 1977; Mitchell, 1978a).

Pyroxenes are relatively rare in kimberlites. Many are high pressure megacrysts of uncertain origin, for example, the discrete nodule assemblage of Boyd and Nixon (1975), or are produced by the fragmentation of lherzolite xenoliths. Euhedral post-fluidization liquidus clinopyroxene has been described in kimberlites from West Greenland, Arkansas, and Southern Africa (Dawson, Smith, and Hervig, 1977; Emeleus and Andrews, 1975; Meyer and others, 1977; Skinner and Clement, 1977). No equivalent of pyroxene sövites or alnöites are known as late differentiates of kimberlite magmas.

A definition applicable to all varieties of carbonatites is difficult to formulate because of the great mineralogical diversity of carbonatitic rocks. It is customary to consider a carbonatite to be "any carbonate-rich rock of apparent magmatic derivation or descent" (Heinrich, 1966). Such an approach is simplistic and petrologically unsound, as no attention is paid to the other minerals present or to consanguineous rocks. Rigid petrographic pidgeonholing based upon the dominance of a single mineral leads to two rocks of in part similar mineralogy but of different origins having the same descriptive names. This usually results in unwarranted speculation concerning the petrogenetic relationships between the rocks. Analogous problems have occurred in studies of anorthosites and eclogites.

Intrusive and extrusive carbonatites are known, and a single definition will not encompass both types as the extrusive varieties are mineralogically different to the intrusive types and are not merely their fine grained equivalents. The extrusive carbonatites are pyroclastic rocks, commonly termed natro–carbonatites as these rocks are rich in the rare mineral nyerereite, $4(CaCO_3Na_2CO_3)$. This paper is concerned essentially with intrusive carbonatites, as it is these rocks that are commonly compared with carbonate-rich kimberlites.

Intrusive carbonatites are here defined to be "igneous rocks rich in primary magmatic carbonate (calcite, dolomite, ankerite), with the associated major minerals being apatite, magnetite, and phlogopite (and/or tetraferriphlogopite). Minor amounts of sodic pyroxenes and amphiboles are typical and in some cases can be present in major amounts, as in pyroxene–sövites. Characteristic accessory minerals include niobium and rare-earth bearing minerals, for example, pyrochlore (koppite, pandaite), perovskite (knopite, dysanalyte, leushite), bastnaesite, synchisite, and monazite".

It is important to note that the mineralogy of carbonatites that lack associated alkaline rocks is similar to those that are accompanied by such rocks. Olivine is not a common or characteristic mineral of carbonatites. When present it is either as a cumulate phase together with apatite and magnetite (for example, Jacupiranga, Loolekop) or as phenocrysts in association with clinopyroxene and/or melilite in carbonate-rich dike rocks such as alnöites.

### KIMBERLITES THAT DIFFERENTIATE TO CARBONATE-RICH RESIDUA

Carbonate-rich kimberlites can contain over 50 percent carbonate as calcite and/or dolomite, either as a groundmass phase or as segregations, crosscutting veins, and dikes. The occurrence of such rocks has in part led to the concept of a kimberlite–carbonatite relationship (assumption 1.) Three examples of carbonate-rich kimberlites are described below to illustrate the characteristic features of these rocks.

1. *Benfontein Sills, South Africa.*—The Benfontein kimberlite is an intrusion consisting of three major sills each of which results from multiple intrusion. (Dawson and Hawthorne, 1973). The sills show evidence of magmatic sedimentation of mafic phases, and cumulus textures are common. Differentiation of the magma occurred in situ and prior to injection. Transporting liquids were carbonate-rich and have differentiated to form carbonate rocks with intercumulus carbonates. In one of the sills, carbonate-rich liquids have migrated diapirically toward the upper portions of the sill. Rooted and detached diapirs and ocelli of of carbonate are attributed by Dawson and Hawthorne (1973) to be the result of liquid immiscibility. The carbonate-rich liquids have crystallized calcite, dolomite, magnetite, and minor serpentine, chlorite, and quartz.

2. *Somerset Island, Arctic Canada.*—The Somerset Island kimberlites represent structurally low levels of typical kimberlite diatremes. Tuffaceous and highly brecciated kimberlites characteristic of the upper levels of Southern African kimberlites are absent.

The Peuyuk diatreme contains three phases of kimberlite, defined by the groundmass oxide mineral assemblage and the presence or absence of carbonate segregations (Mitchell and Clarke, 1976). Phases A and B lack carbonate segregations, and the groundmass consists of an intimate mixture of second generation olivine, perovskite, spinel, apatite, serpentine, and carbonate. This groundmass is termed the silicate–oxide groundmass. In phase C, the most evolved phase of the diatreme, the silicate–oxide groundmass is veined by irregular lobate discontinuous patches of carbonate. Patches of silicate–oxide groundmass can be completely enveloped by amoeboid patches of carbonate and vice versa. Such textures have been found also in the Finsch pipe, South Africa, where they are termed emulsion textures (Clement, 1975). Within the Peuyuk C and Korvik-Selatiavak kimberlites can be found ocelli of carbonate set in a silicate–oxide groundmass and ocelli of silicate–oxide set in a carbonate groundmass. Such textures are interpreted to indicate the presence of two immiscible liquids during the final stages of crystallization (Clarke and Mitchell, 1975; Mitchell, 1975).

The Elwin Bay monticellite kimberlite (Mitchell, 1978a) contains emulsion textures involving silicate–oxide and carbonate groundmasses and ocelli that contain calcite and apparently primary serpentine.

Carbonate and serpentine are the only phases common to both the silicate and carbonate groundmasses. Olivine, spinel, apatite, monticellite, perovskite, and phlogopite *never* crystallize from the immiscible carbonate liquids.

3. *Premier carbonate dikes.*—Carbonate-rich rocks represent the final phase of igneous activity at the Premier Pipe, South Africa, where they occur as isolated dikes and as anastomozing veins that are gradational into kimberlite (Robinson, 1975). The dikes are composed of calcite, perovskite, magnetite ($MgO = 1.9\text{-}2.8$ percent; $TiO_2 = 0.6\text{-}1.1$ percent; $Al_2O_3 = 0.1\text{-}0.2$ percent; $Cr_2O_3 = 0.1$ percent; $MnO = 0.3\text{-}0.5$ percent; $FeO_T = 88.0\text{-}89.5$ percent; this work) and serpentine with traces of apatite and sulphides. Perovskites are mantled by the magnetite which is itself extensively resorbed. The rocks are regarded by Robinson (1975) as an intercumulus phase of kimberlite that has segregated from kimberlite and intruded already-consolidated portions of the diatreme as dikes.

### FEATURES COMMON TO CARBONATE-RICH KIMBERLITE

Carbonate dikes, ocelli, and emulsion textured groundmasses similar to those described above are common features of many other kimberlites, for example, western Greenland dikes (Emeleus and Andrews, 1975), the Finsch, Montelo, Mullersvei, and Andresfontein pipes (Clement, 1975) and many Yakutian diatremes (Mal'kov, 1975).

Features common to all kimberlites that develop carbonate-rich phases are:

1. Carbonate-rich rocks represent the final stages of activity or ultimate differentiation products.
2. Carbonate-rich segregations are not associated with the highly brecciated portions of diatremes except as crosscutting dikes and veins.
3. Carbonate-rich segregations are composed essentially of calcite with much lesser amounts of serpentine (primary) and magnetite. Apatite is not a major phase. Sodic pyroxenes, niobium, and rare-earth minerals are absent.

4. Many of the carbonate-rich segregations present textural evidence that liquid immiscibility has played a role in their development.

## EXPERIMENTAL STUDIES RELEVANT TO THE FORMATION OF CARBONATE-RICH KIMBERLITE

*Low pressure experimental studies.*—Franz and Wyllie (1967) and Franz (ms) have studied the "synthetic kimberlite" system CaO–MgO–$SiO_2$–$CO_2$–$H_2O$(CMSCH) and have concluded:

1. Liquids initially poor in $CO_2$ cannot fractionate by the precipitation of olivine and pyroxenes to residua that crystallize carbonated and hydrated phases because of a pronounced thermal barrier in this system.
2. Liquids can exist at temperatures as low as 605°C at a eutectic involving portlandite, calcite, monticellite, and brucite.
3. Olivine can crystallize from liquids on the low temperature side of the thermal barrier, when univariant curves for decarbonation reactions involving high temperature phases (spurrite) intersect the vapor-saturated liquidus surface. Therefore olivine and calcite can crystallize together at low (600°-800°C) temperatures (Wyllie, 1966).

Comparing the CMSCH study with the known crystallization history of kimberlite and the observations described above on kimberlites that differentiate to carbonate-rich residua, the following points emerge:

1. No liquid immiscibility is evident in CMSCH.
2. No eutectic (as evidenced by lack of eutectic textures or constant proportions of coexisting groundmass minerals) appears to be involved in natural kimberlite.
3. Most of the minerals crystallizing on the low temperature side of the CMSCH thermal barrier are never found in kimberlite, for example, larnite, calciochondrite, portlandite, spurrite. This is surprising as for these minerals the CMSCH system provides a good analogy to natural kimberlite compositions.
4. Danchin and others (1975) consider that the composition of nucleated autoliths gives a close approximation to relatively late stage kimberlite liquids. Analyses of nucleated autoliths contain low $CO_2$ and plot in CMSCH on the high temperature side of the thermal barrier — yet they crystallize calcite as a residual phase. Danchin and others (1975) believe that the composition of kimberlite liquids is controlled by olivine precipitation for much of their crystallization history.

In summary the CMSCH data are *not* compatible with observations of natural kimberlites. This, of course, may reflect compositional differences between CMSCH and kimberlites. For example, kimberlites contain much titanium and iron, as evidenced by the crystallization of abundant perovskite and spinel prior to the onset of calcite crystallization.

Liquid immiscibility, involving carbonate and silicate liquids, has been demonstrated in experimental studies of a wide variety of bulk compositions, for example, granites, syenites, ijolites, lamprophyres (Koster van Groos, 1975; Ferguson and Currie, 1971), but the compositions and liquidus phases are very different from those observed in kimberlite. Addition of such components as $Al_2O_3$ and $Na_2O$ to CMSCH, in an effort to either bypass the thermal barrier or to induce immiscibility renders the system inapplicable to kimberlite studies, because feldspar or melilite appear as liquidus phases.

The importance of Franz's (ms) work is that it demonstrates that low temperature carbonate-rich silicate liquids are capable of crystallizing calcite and olivine and that carbonate-rich residua might be generated. Wyllie (1966) refers to such residua as carbonatites, but it should be clearly realized that they are not carbonatites as defined in this paper.

Studies of the system $CaO–MgO–SiO_2–TiO_2–CO_2–H_2O$ and the iron bearing analogues of this and CMSCH are desirable in attempting to reproduce the crystallization of kimberlite.

*High pressure experimental studies.*—Concentration of $CO_2$ during the final stages of kimberlite crystallization requires that the initial magma at its source in the upper mantle contains $CO_2$. Wyllie and Huang (1976) and Eggler (1976) have determined experimentally that $CO_2$ in the mantle is probably fixed as carbonates rather than as fluid $CO_2$. The existence of a stable subsolidus mantle carbonate is supported by the presence of carbonate inclusions in mantle-derived pyrope (McGetchin and Besancon, 1973). Wyllie and Huang (1976) have shown that partial melting of carbonated mantle can occur at temperatures as low as 1250°C at 50 kb and that the initial liquid is very rich in normative carbonate. This liquid is termed a haplocarbonatite, with the implication that it will ultimately crystallize to a carbonatite. Wyllie and Huang (1975a,b) also demonstrate that progressive melting of carbonated mantle will give rise to a continuum of liquid compositions which will change from haplocarbonatite to haplokimberlite to haplobasalt as the degree of partial melting increases. Haplokimberlites are considered to be liquids containing normative larnite, olivine, and carbonate.

Wyllie and Huang (1976) and Eggler (1976) have shown therefore that the initial partial melting of carbonated model mantle compositions ($CaO–MgO–SiO_2–CO_2$ and olivine–orthopyroxene–clinopyroxene–$CO_2$) will give rise to liquids that are silica-undersaturated and rich in $CO_2$. The studies do not, however, demonstrate any relationship between carbonatite and kimberlite, as advocated by Wyllie and Huang (1975a,b), for two reasons:

First, the haplocarbonatites are simply carbonate-rich liquids and will not crystallize to carbonatites as defined in this paper. The liquids are, however, similar to the carbonate-rich residua of kimberlites described above.

Secondly, the composition of the haplokimberlitic liquid is uncertain (Wyllie, 1977; Eggler, 1976) and might be melilitic or nephelinitic. This liquid will fractionate by and crystallize to assemblages containing abundant pyroxene. The high pressure differentiation of kimberlite appears to be controlled by the crystallization of olivine, pyroxenes of the discrete nodule assemblage (Boyd and Nixon, 1975), garnet, and ilmenite rather than by an olivine–pyroxene cotectic. Unfortunately as yet little is known of the proportions of these minerals involved in any fractionation event, and although discrete pyroxenes are common in some kimberlites they appear to be rare or absent in others. It is unwise, however, to consider any of these experimental liquids as being the equivalent of a high pressure unfractionated kimberlitic magma, because the composition of such a magma is unknown, as kimberlite lavas do not exist. The closest approximation appears to be the Igwisi Hills extrusive (Reid and others, 1975), but even this lava has undergone extensive crystallization. Importantly, with regard to the haplokimberlitic liquid, the dominant phenocryst is olivine, and pyroxenes are rare.

Wyllie and Huang's (1976) data are applicable in a general manner to kimberlite, if kimberlites are produced by very small amounts of partial melting of carbonated mantle, as the abundant volatiles can be derived by carbonate decomposition. The initial stages of melting of a carbonated garnet lherzolite therefore might be envisaged to produce a sequence of liquids that would range from carbonate-liquid to carbonate-rich kimberlite to kimberlite, as the degree of melting increased. Further melting might generate a wide variety of undersaturated basaltic liquids, depending upon the local pressure-temperature regime (Green, 1972). Significantly all these melts would be able to reconcentrate $CO_2$ in their differentiates.

## CENTRAL COMPLEX KIMBERLITES

Dawson (1967) introduced the term "central complex kimberlite" to describe the micaceous basic to ultrabasic dikes and plugs found in or near some alkaline rock-carbonatite complexes, for example, Ngualla, (Tanzania), Rangwa (Kenya), Arbarastakh (Yakutia), Fen (Norway).

Dawson (1967, 1971) originally emphasized that these rocks were not true kimberlites of the type found as the products of regional kimberlite magmatism, but this distinction has been largely ignored by many geologists. Designation of such rocks as kimberlite also stems from Von Eckermann's (1967) study of the dikes associated with the Alnö complex, Sweden. Von Eckermann relies upon Shand's (1934) definition of kimberlite, which implies that melilite (now altered to carbonate) was an essential mineral of kimberlite, a conclusion at variance with all petrographic studies of kimberlite, and arising from Shand's inability to accept a magmatic origin for calcite.

Central complex kimberlites lack such characteristic minerals of true kimberlites as pyrope, magnesian ilmenite, magnesian ulvöspinel, and diamond or garnet lherzolite xenoliths, and application of the term kimberlite to these rocks has resulted in a broadening of the usage of the term to include any rock that contains the assemblage phlogopite–spinel–olivine–calcite and/or clinopyroxene. This usage is especially prevalent in North America where numerous calcite-rich ultrabasic dikes of small size and limited exposure are referred to as "kimberlitic dikes" for example, Coral Rapids (Brown, Bennett, and George, 1967), Arvida (Gittins, Hewins, and Laurin, 1975), Bachelor Lake (Watson, 1955), Keith Township (Watson, Bruce, and Holiday, 1978), with the implication that the sample sizes available are too limited to find any of the characteristic minerals of kimberlite (Watson, Bruce, and Holiday, 1978). This practice is petrographically unsound, as dikes are named on the absence of minerals. In terms of their mode the dikes are better referred to as lamprophyres, a term that does not carry the petrogenetic implications of kimberlite, until further work demonstrates whether or not they are true kimberlites. Some of the "kimberlitic dikes" that have high modal calcite contents are termed "kimberlitic–carbonatitic" dikes (Gittins, Hewins, and Laurin, 1975) or "carbonatite–kimberlite" (Zhabin, 1967).

Three central complex kimberlites are described below and compared with typical true kimberlites.

### THE FEN COMPLEX, NORWAY

The diatreme occupying the core of the Fen alkaline complex is commonly considered to be the type example of a central complex kimberlite. Saether (1957) has considered it to be the residual product of a kimberlite magma. The rock, termed damtjernite, consists of rounded to euhedral phenocrysts of titanian phlogopite, titanian pargasite, Na–Al diopsides and Ti–Al salite set in a matrix of Mg-rich biotite, Ti–Al salite ferropargasite, spinel (see below), Mn-bearing ilmenite (see below), calcite, and rarely nepheline and feldspars (Saether, 1957; Griffin and Taylor, 1975; Mitchell, 1979b). Olivine is considered by Saether (1957) to be a phenocryst, but the majority are probably derived by the fragmentation of spinel lherzolite nodules (Griffin, 1973). Petrographically the damtjernite is unlike any known variant of kimberlite. Even though it is mantle derived, shows fluidization effects, and liquid immiscibility features (Griffin and Taylor, 1975), it should not be regarded as kimberlite, because it contains none of the characteristic minerals of kimberlite. Damtjernite appears to be a hybrid rock formed by the crystallization of several batches of nephelinite or alkali basalt over a wide pressure range at high temperatures under high $H_2O$ and $CO_2$ pressures (Mitchell, 1979b; Mitchell and Brunfelt, 1975).

### ILE BIZARD, MONTREAL, CANADA

The intrusive breccias that occur at Ile Bizard are all considered to be kimberlite (Clark, 1972). The breccias are of particular interest, in that several microscopic diamonds are reputed to have originated in these rocks, although it has never been conclusively shown that the diamonds were not contaminants in the milling system.

New mineralogical data obtained during this study show that the matrix of the igneous breccia found on the north side of Ile Bizard contains phenocrysts of phlogopite (3 percent FeO, 0.1 percent $TiO_2$) serpentinized olivine (?), spinels (see below), and pyroxene. The pyroxenes (table 1) are aluminous and similar in composition to megacryst pyroxenes of high pressure origin found in alkali basalts and nephelinites. The cores of many of the pyroxenes have undergone melting and have formed a glass of a composition very similar to that of the original pyroxene. All the pyroxenes are corroded and exhibit reaction rims toward the groundmass which is composed of garnet, phlogopite (3 percent FeO), perovskite, calcite, and serpentine together with very fine grained optically unresolvable material. Portions of the groundmass are enriched in CaFeAl silicates that Marchand (ms) considered to be due to immiscibility; these areas may, however, represent areas where residual fluids are concentrated. Portions of the unresolvable groundmass contain very small orange spherical structures which may represent devitrified glass. Garnets formed as reaction rims about pyroxenes and spinels and as discrete euhedral crystals. Garnets occurring around spinels are strongly zoned with respect to $TiO_2$ and can contain up to 10 percent $TiO_2$ (schorlomite$_{39}$–andradite$_{54}$grossular$_7$). The majority of garnets are strongly zoned also from $Sch_6And_{75}Gross_{19}$ to $Sch_6And_{42}Gross_{51}$. Low analytical totals for some garnets indicate the presence of hydrogrossular (Marchand, ms). The perovskite is very close in composition to pure $CaTiO_3$ and contains 1.7 to 2.0 FeO, with low analytical totals indicating 0 to 5 percent REE and Sr. Marchand (ms) described mantle-derived lherzolite xenoliths from this locality.

The matrix of the south shore breccia consists of phenocrysts of phlogopite (5-6 percent FeO; 2-3 percent $TiO_2$) set in a groundmass of melilite (akermanite-rich), nepheline, spinel, perovskite, and calcite. The olivine are richer in FeO (11-24 percent) than are kimberlitic olivines (6-12 percent FeO). Perovskite is identical to that found in the north shore breccia.

Spinel compositions in rocks from both localities at Ile Bizard are described below.

The Ile Bizard rocks are clearly not kimberlites as defined in this paper but are lamprophyres (alnöites, polzenites) similar to those found in other diatremes in this region, for example, Ile Cadieux, and are a part of the activity associated with the Oka carbonatite complex.

TABLE 1

Compositional range of pyroxenes in kimberlites, lamprophyres, and pyroxene-sovites

| | $Al_2O_3$ | $TiO_2$ | FeO* | $Na_2O$ |
|---|---|---|---|---|
| Prairie Creek kimberlite (40) | 0- 2.1 | 0.1-1.9 | 1.6- 4.0 | 0.2-2.5 |
| Roberts Victor kimberlite (6) | 0.1- 0.4 | 0.3-0.8 | 2.5- 4.9 | 0.1-1.1 |
| Fen, lamprophyre (25) | 1.2-13.0 | 1.0-5.6 | 3.4- 6.8 | 0.1-1.5 |
| Ile Bizard lamprophyre (10) | 0.5- 6.6 | 0.5-2.3 | 2.6- 6.9 | 0.4-1.3 |
| Claylick Creek, lamprophyre (5) | 2.5- 4.8 | 1.5-2.8 | 4.4- 7.4 | 0.3-0.5 |
| Keith Township, lamprophyre (8) | 1.8- 3.1 | 1.6-2.8 | 6.7-16.5 | 6.5-0.7 |
| Fen, pyroxene sovite (10) | 1.0- 1.2 | 0.2-0.5 | 15.5-16.5 | 2.3-3.4 |
| Alno, pyroxene sovite (7) | 2.2- 9.4 | 0.8-2.7 | 8.5-18.6 | 0.6-3.1 |

* Total Fe expressed as FeO. Data for Prairie Creek, Roberts Victor Keith Township, and Alno from Lewis (ms), Dawson, Smith, and Hervig (1977), Watson, Bruce, and Holiday (1978), and Von Eckermann (1974) respectively. All other data, this work. Number of analyses given in parentheses.

### ALNÖ, SWEDEN

Review papers by Von Eckermann (1966, 1967) summarize his numerous studies of the dike rocks associated with the Alnö alkaline complex. These dikes include such disparate types as ouachitite, alvikite, beforsite, kimberlite, alnöite, and melilite basalt. The profusion of dike types is probably unwarranted as many of the dikes are simply modal variants of the alnöitic assemblage of olivine–clinopyroxene–phlogopite–melilite and carbonates. Von Eckermann considers that kimberlites are one of the dominant types of dike, but as noted above, he used the term in the very broadest sense. Thus a typical Alnö "kimberlite," for example, the Sundsvall dike (Von Eckermann, 1966) consists of phenocrysts of phlogopite and serpentinized olivine set in a groundmass of carbonate, serpentine, perovskite, apatite, and opaque oxide minerals. Included in the kimberlite group also are dikes containing aegerine–augite and polzenites in which the melilite has been replaced by melanite and carbonate. All gradations between alnöites and such "kimberlites" can be found. Primary garnet in a number of the "kimberlites" is considered to be melanite.

Little mineralogical data is available for the dikes. Three observations are, however, of interest.

1. Von Eckermann (1974) described large corroded megacrysts of magnesian ilmenite (7.3 percent MgO) from a kimberlite dike.
2. Kresten (1976) has described chrome–pyrope xenocrysts (?) in a beforsitic alnöite.
3. Kresten and Persson (1975) have found diopside megacrysts in an alnöite breccia similar in composition to the discrete nodule megacrysts found in South African kimberlites.

The above minerals appear to be not characteristic of the dikes in general. Their presence suggests that mantle derived material may be present as inclusions in some of the dikes but does not indicate the presence of kimberlite.

In summary modern mineralogical studies of the Alnö dikes are required. From Von Eckermann's description it seems unlikely that any of the dikes in the complex are true kimberlites, as the bulk of the micaceous ultrabasic rocks are alnöites and related rocks.

### MINERALOGICAL DISTINCTIONS BETWEEN KIMBERLITE LAMPROPHYRE, MICA PERIDOTITE, AND CARBONATITE

A primary contention of this paper is that kimberlites, mica peridotites, and lamprophyres (central complex kimberlite, kimberlitic rocks) have different origins. If true, this should be reflected in variation in the chemical composition of the constituent minerals, with the proviso that some mineralogical convergence can be expected as minerals of similar composition will form wherever the correct physico-chemical conditions for stability are met in magmas of diverse origins. Spinels, ilmenites, and pyroxenes are important in this context, as they can form over a wide range of pressures and temperatures and take part in extensive solid solution series. The introduction of the term "kimberlitic rock" is in part due to the fact that reflected and transmitted light petrography of micaceous ultrabasic rocks cannot be used to determine whether or not a given rock is a true kimberlite, as these methods cannot accurately indicate mineral compositional variation. Many such rocks in addition are highly altered by deuteric carbonatization and serpentinization processes, and the original mafic mineralogy is difficult to discern. Oxide mineral studies are particularly important in this regard, as they are in general exceedingly abundant and unaffected by the alteration processes.

## SPINEL

Spinel compositions illustrate well some of the mineralogical differences between kimberlites, lamprophyres (central complex kimberlites), mica peridotites, and carbonatites. Figures 1 and 2 show the compositional fields of spinels from these rocks plotted as end member "spinel molecules" in the reduced (total iron as FeO) and oxidized spinel prisms (Mitchell and Clark, 1976; Haggerty, 1976).

*Kimberlite.*—Kimberlite spinel compositions have been summarized by Haggerty (1975, 1976), Mitchell (1979a), and Mitchell and Clarke (1976) and are characterized by extensive compositional variation, high MgO and high $TiO_2$ contents compared to spinels from common basic igneous rocks.

Figure 1 indicates that early spinels in the Peuyuk kimberlite are $TiO_2$ poor (<1 percent) aluminous magnesian chromites which evolve to titaniferous magnesian aluminous chromite (1-12 percent $TiO_2$) and ultimately to members of the magnesian ulvöspinel–ulvöspinel–magnetite series. Trends of compositional evolution are across the spinel prism from the base near the $MgCr_2O_4$–$FeCr_2O_4$ join toward the $Mg_2TiO_4$–$Fe_2TiO_4$ apex. Spinels in micaceous kimberlites (fig. 1; Tunraq, Kirkland Lake) are poorer in alumina than kimberlite spinels but have similar evolutionary trends toward titanium enrichment at relatively constant Fe/Fe+Mg ratios.

*Lamprophyres (central complex kimberlites).*—Figures 1 and 2 illustrate the compositions of spinels from the Ile Bizard northern and southern breccias and the Fen damtjernite. In these occurrences three groups of spinels are present: I — pleonaste (Fen) or hercynitic pleonaste (Bizard), II — titaniferous–aluminous–magnesian chromite, III — ulvöspinel–magnetite.

Group I is made up of low $TiO_2$ transparent green spinels. At Fen they are undoubtedly xenocrystal, as Griffin (1973) has described spinels of identical composition in lherzolite xenoliths in these rocks. A similar origin can be postulated for the Ile Bizard group I spinels.

Group II spinels (minor abundance) occur rarely as cores to group III spinels. They are low Ti aluminous–magnesian–chromites which show little compositional variation. These spinels are the only lamprophyric spinels that are at all similar to kimberlite spinels as they overlap the composition of the earliest prefluidization aluminous–magnesian–chromites in the Peuyuk kimberlite.

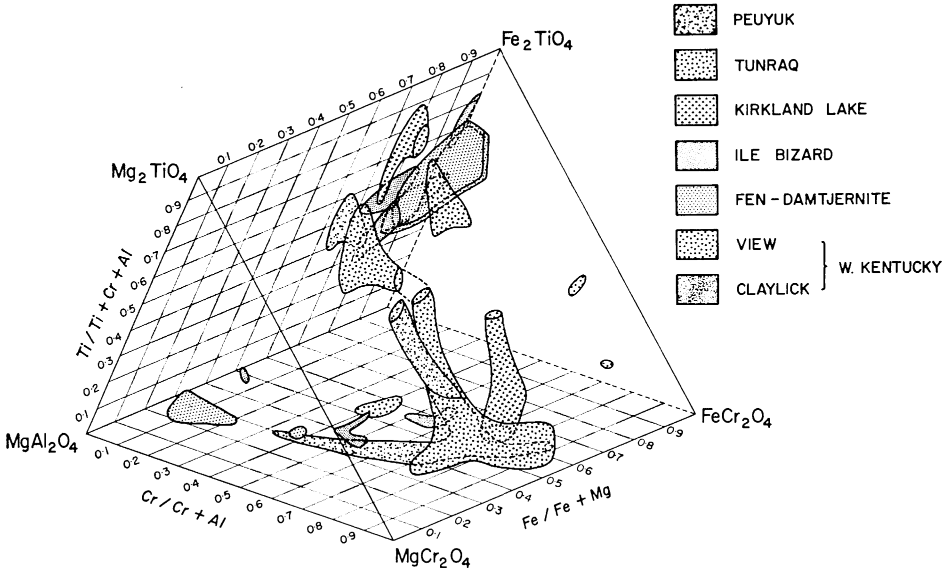

Fig. 1. Compositional fields of spinels from kimberlites and lamprophyres plotted in a reduced spinel prism. Data are from Mitchell (1979a), Mitchell and Clarke (1976), and this work.

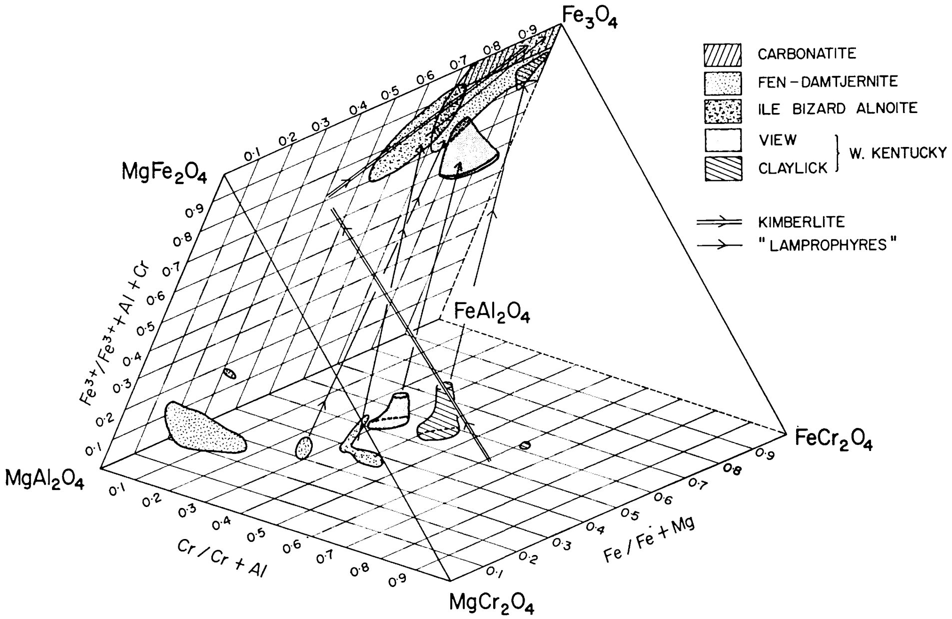

Fig. 2. Compositional fields of spinels from kimberlites, lamprophyres, and carbonatites plotted in an oxidized spinel prism. Data are from Mitchell (1979a), Mitchell and Clarke (1976), Prins, (1972), Haggerty (1976), and this work.

Group III spinels are euhedral small groundmass spinels which comprise the bulk of the spinel populations, except in Ile Bizard northern breccia where they occur as large resorbed "phenocrysts." They are members of the ulvöspinel–magnetite solid solution series and range in $TiO_2$ from 5 to 12 percent at Fen and from 7 to 15 percent at Ile Bizard. At each locality these spinels are zoned toward margins poorer in $TiO_2$. Spinels from these rocks are in general more aluminous and richer in iron than kimberlite spinels.

*Mica peridotites.*—Dike rocks occurring in Western Kentucky and Southern Illinois have been described at various times as mica peridotites, kimberlites, or lamprophyres (see Meyer, 1976, for a summary of previous studies). No previous data exist on the composition of spinel in these dikes. Two intrusions were examined in this study.

A. Claylick Creek.—A highly altered mica-poor dike consisting of serpentinized and carbonatized olivine (?) set in a fine-grained groundmass of biotite (8-9 percent FeO; 2-5 percent $TiO_2$), chlorite, serpentine, calcite, euhedral aluminous clinopyroxene (table 1), and spinel. The spinel assemblage consists of euhedral crystals and titaniferous–aluminous–magnesian–chromite ($<4$ percent $TiO_2$) mantled by anhedral ulvöspinel–magnetite (figs. 1 and 2). This latter spinel also occurs as discrete crystals. Ulvöspinel–magnetites are zoned toward $TiO_2$ poor margins and are extremely corroded due to resorption of spinel by the fluid which eventually crystallized as the carbonate–silicate groundmass. Resorption of ulvöspinel–magnetite has also been accompanied by the crystallization of rutile as irregular discrete crystals and as partial mantles intergrown with serpentine and carbonate about spinel. Perovskite and ilmenite appear to be absent.

B. View.—A mica rich dike consisting of serpentinized and carbonatized phenocrysts set in a groundmass of phlogopite (6-7 percent FeO; 4-6 percent $TiO_2$), chlorite, serpentine, calcite, and spinel. The spinel assemblage is similar to that of the Claylick Creek dike (see above). Ulvöspinel–magnetites have undergone extensive resorption. Perovskite, rutile, and pyroxene are absent. Ilmenite containing 1 to 3 percent MnO and less than 0.2 percent MgO is present as irregular crystals which have been formed by the resorption of euhedral laths.

The spinel assemblages and crystallization trends (fig. 1 and 2) are essentially identical to those observed in the Ile Bizard and Fen lamprophyres excepting that the xenocrystal group I hercynites are absent. The presence of manganoan ilmenite, absence of pyrope, and absence of titaniferous–magnesian–aluminous–chromites and magnesian ulvöspinels indicates that these mica peridotites are best considered to be lamprophyres with no kimberlitic affinities.

*Lamprophyre spinel characteristics.*—Lamprophyre spinels differ from kimberlite spinels in that the former are:

1. Lower in Ti and Mg reflecting a lack of solid solution toward magnesian ulvöspinel.
2. Richer in iron (and $Fe^{3+}$) reflecting their higher magnetite contents. This distinction is clearly seen in figure 2.
3. Lack spinels with Cr/Cr+Al ratios greater than 0.8, that is, a more aluminous spinel assemblage lacking in titaniferous–magnesian–aluminous chromite, the characteristic earliest post-fluidization kimberlite spinel.
4. Have a different evolutionary trend. The kimberlite trend is across the spinel prisms from low to high $TiO_2$ at relatively constant Fe/Fe+Mg. The lamprophyre trends (fig. 2) are of increasing $TiO_2$ with increasing Fe/Fe+Mg, that is, diagonally upward along the axis of the spinel prism.
5. Lamprophyre spinels commonly are richer in MnO (1.0-2.5 percent) than kimberlite spinels which typically contain less than 1 percent MnO.

*Carbonatites.*—In carbonatites, spinel commonly occurs as large (up to 5 cm) euhedral crystals which are compositionally very close to pure magnetite. High levels of MnO (2-12 percent) are common (McMahon and Haggerty, 1977; Haggerty, 1976) but should not be regarded as being characteristic (Prins, 1972). MgO contents are very variable but are not as high as found in kimberlite spinels. Carbonatite spinels with appreciable MgO are easily distinguishable from kimberlite spinels, as the MgO content reflects solid solution toward magnesioferrite rather than magnesian ulvöspinel, and therefore such spinels lack appreciable $TiO_2$. Von Eckermann (1974) has described titaniferous magnetites from Alnö containing 3.9 to 7.6 percent $TiO_2$, with low MgO (1.6-3.8) contents that indicate solid solution toward ulvöspinels. These spinels are also rich in MnO (1.3-2.9 percent).

The compositional field of carbonatite spinel compared with those of lamprophyre and kimberlite is shown in figure 2. Most carbonatite spinels plot at the $Fe_3O_4$ apex.

The principal characteristics of carbonatite spinels are lack of $Cr_2O_3$, low $TiO_2$ and MgO relative to kimberlite spinel, and commonly high MnO. Most are members of the magnesioferrite–ulvöspinel–magnetite series, and spinels characteristic of kimberlite do not occur in any carbonatite so far examined.

It should be noted that spinel compositions in kimberlites, carbonatites, and lamprophyres all converge upon $Fe_3O_4$. Kimberlite magnetite can, however, be easily distinguished by its paragenesis as mantles on titanium chromites, as olivine pseudomorphs, and in being poor in MnO. The magnetite–apatite cumulates so common in carbonatites do not occur in kimberlites.

*Arvida and Keith Township kimberlitic dikes.*—Data presented for the Arvida and Keith Township "kimberlitic dikes" by Gittins, Hewins, and Laurin (1975) and Watson, Bruce, and Holiday (1978) illustrate the use of spinel compositions to distinguish between lamprophyre and kimberlite.

The Arvida spinels are ulvöspinel–magnetites containing up to 8 percent MgO and 5 percent MnO and are similar to the Ile Bizard-Fen group III spinels. The high MnO and low MgO and $TiO_2$ relative to kimberlite spinels indicate that the rock has no kimberlite affinities and should be termed a lamprophyre.

Spinels in the Keith Township dike are similar to the Ile Bizard-Fen group II spinels with Cr/Cr+Al ratios of 0.3 to 0.7, Fe/Fe+Mg ratios of 0.3 to 0.5, and with low $TiO_2$ (0.1-6 percent) relative to kimberlite spinels. Zonation is along the axis of the reduced spinel prism at constant Cr/Cr+Al ratios toward increasing Fe/Fe+Mg and the $Fe_2TiO_4$ apex. Magnesian ulvöspinel is absent. The spinels and their compositional trends are similar to those of lamprophyres not kimberlites.

### ILMENITE

Ilmenite occurs in kimberlites as discrete monomineralic nodules and as lamellar intergrowths with pyroxenes. Kimberlite ilmenites are chemically characterized by high MgO (5-22 percent), high $Cr_2O_3$ (0.1-2.5 percent), and low Mn (<1.0 percent) contents (Mitchell, 1977).

The Fen damtjernite (lamprophyre) contains ilmenite as primary skeletal crystals and as exsolution lamellae in magnetite. The ilmenites are characterized by low MgO (<5 percent), low $Cr_2O_3$ (<0.1 percent), and high MnO (4.7-9.8 percent) contents (Griffin and Taylor, 1975; Mitchell, unpub. data). Ilmenite in the View lamprophyre contains 1 to 3 percent MnO.

Ilmenite in carbonatite occurs principally as exsolution lamellae in magnetite. Typically the ilmenites are poor in MgO (<5 percent) and $Cr_2O_3$ (<0.1 percent) with variable MnO contents (Prins, 1972; Haggerty, 1976; Mitchell, unpub. data). Oxidation exsolution ilmenite with high (15-24 percent) MgO has been found at the Jacupiranga carbonatite, but this ilmenite can be easily distinguished from kimberlite ilmenite of similar MgO content on the basis of the MnO content (Mitchell, 1978b).

Ilmenites that contain appreciable MnO can be found in kimberlites (Mitchell, Carswell, and Brunfelt, 1973); however, these appear in general to be secondary ilmenites distinct in paragenesis to the discrete nodule ilmenite discussed above. Mn-rich ilmenite appears to form in many carbonated ultrabasic magmas as a late stage primary or secondary mineral.

Figure 3 compares the compositions of ilmenites from kimberlites, lamprophyres, and carbonatites and demonstrates that ilmenite composition is an effective means of discriminating between these rocks, providing the paragenesis is also considered.

### PYROXENE

Groundmass pyroxenes are not common in kimberlites, and little information is available regarding their composition. Table 1 indicates that kimberlite pyroxenes appear to be in general different in composition to pyroxenes from lamprophyres (central complex kimberlites and kimberlitic dikes) and carbonatites being relatively poor in Ti, Al, Fe, and Na. Kimberlite pyroxenes are thus diopsides, lamprophyre pyroxenes are Ti–Al salites and augites similar to pyroxenes found in undersaturated basic rocks, and carbonatite pyroxenes are aegerine augite and acmites.

## CONCLUSIONS

The experimental, field and petrographic observations cited above demonstrate conclusively that kimberlite magmas differentiate to carbonate-rich silica-poor residua. The differentiation process results in the formation of a spectrum of rocks that might be regarded as a kimberlite clan. It is possible to recognize at least three members of such a suite:

1. Kimberlite as defined in the introduction and which contains the characteristic suite of heavy minerals (Cr–pyrope, Mg–ilmenite) and discrete megacrysts, for example, Monastery, Thaba Putsoa, Wesselton, Tunraq.
2. Kimberlite as defined in the introduction but poor in or lacking the heavy mineral and megacryst assemblages, these minerals having been lost during differentiation, for example, Peuyuk, Jos, Benfontein.

Petrographically these rocks are similar to micaceous ultrabasic rocks related to alnöites and their differentiates. Only when one takes into account the composition and paragenesis of spinels, ilmenite, and pyroxene, et cetera and possible comagmatic rocks is it possible to determine whether or not they are true kimberlites.

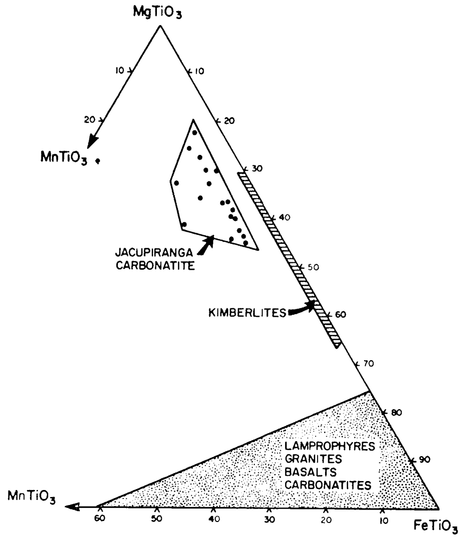

Fig. 3. Composition of ilmenites in kimberlites, carbonatites, and lamprophyres expressed as ternary molecular percentages of $MnTiO_3$, $MgTiO_3$, and $FeTiO_3$. Data are from Mitchell (1977, 1978b), Haggerty (1975, 1976), and this work.

3. Carbonate-rich residua poor in silicates, oxides, and the heavy mineral and discrete megacrysts suites, for example, the Premier carbonate dikes, carbonate ocelli.

These rocks would be termed carbonatites using the petrographic classification of Heinrich (1966). As shown above, they have, however, very different mineralogies, antecedents, and cogmatic rocks to the carbonatites of alkaline complexes and are better termed *calcite–kimberlite* or *calcareous kimberlites* (Mitchell, 1970) to emphasize this petrogenetic difference.

Many "Central complex kimberlites" and "kimberlitic dikes" are characterized by the presence of aluminous clinopyroxenes, amphiboles, melilite, and its decomposition products. They lack Cr–pyrope and Mg–ilmenite; garnet when present is melanite, and ilmenites are commonly Mn-rich. Spinels are different in composition and evolutionary trend to kimberlite spinels. As these rocks are mineralogically different to petrographically similar kimberlite suite rocks, it is proposed that the terms "central complex kimberlite" and "kimberlitic dike" be abandoned, and the rocks be referred to as lamprophyres (alnöites, polzenites, bergalites, mica peridotites, et cetera).

Dawson (1970) and Verwoerd (1970) have discussed the relation of kimberlite and carbonatite magmatism to tectonics and have noted that whilst carbonatites are closely related to rift structures, kimberlites are typically found in inter-rift areas. Only "central complex kimberlites" are associated with rifts. Considering these rocks not to be kimberlites emphasizes the different tectonic conditions required for kimberlite and carbonatite formation.

Mitchell (1970) has discussed the similar geochemistry of kimberlites and carbonatites and concluded that this is not evidence for a genetic relationship between the two rocks because similar trace element assemblages can be produced by various processes such as partial fusion, fractional crystallization, and volatile enrichment, acting together or independently on a variety of unrelated magmas or source rocks.

In conclusion I consider that tectonic, geochemical, and mineralogical evidence does not support the hypothesis of a close petrogenetic relationship between kimberlites and carbonatites.

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