

AN HYPOTHESIS FOR THE ORIGIN OF KIMBERLITE

IAN D. MACGREGOR

Department of Geology, University of California, Davis, California 95616

ABSTRACT

Kimberlites are characteristically associated with a suite of mafic and ultramafic xenoliths whose mineralogy indicates an origin within the upper mantle. The phase chemistry of the xenoliths may be reconciled with known experimental data at high pressures, as suites of crystal cumulates, or residual phases, that have formed during the high-pressure fractional crystallization of a mafic magma. The geological association of kimberlites with specific suites of xenoliths, and the comparison with experimental data, give support to this cognate hypothesis previously proposed by a number of other authors.

Models of the Earth's thermal history indicate that the upper mantle heated up for the first few billions of years after which time it has slowly cooled to its present state. It is postulated that the kimberlites are formed by the closed system fractional crystallization of mafic magmas which have formed by fractional fusion during the early heating of the upper mantle. During the cooling cycle in the last few billions of years, the mafic liquids have cooled through fractional crystallization to the ambient mantle temperatures, and changed composition towards a kimberlite. Sequential primary phase assemblages are represented by harzburgite, garnet harzburgite, garnet lherzolite, hypersthene eclogite, eclogite, kyanite eclogite to an olivine-diopside-perovskite rock. Parallel changes in the liquid composition are through picrite, tholeiite, alkali basalt, a diopside-ilmenite composition to kimberlite.

INTRODUCTION

Although kimberlites occupy only a very small proportion by volume of the igneous rocks, they are of special interest for they are the sole natural source of diamonds, and they give us the opportunity of examining petrological processes that occur deep within the upper mantle. The characteristic association in kimberlites of high-pressure phase assemblages (MacGregor, 1968) with a postulated high-pressure liquid matrix (O'Hara, 1968) indicates that they can contribute to the deciphering of upper mantle processes. Furthermore, the rapid accumulation of new geophysical evidence on the nature of the upper mantle has stimulated our studies of high-pressure magmas, and pointed to the importance of interrelating geophysical and petrologic evidence.

Three general types of hypotheses have long been considered for the genesis of kimberlites. First, they are a mechanical mixture of a H₂O-rich ankeritic magma and a granitic lower crust (Dawson, 1967). Second, they result directly from the partial melting, at high pressures, of a mafic to ultramafic mantle (Wagner, 1928; Holmes, 1936). Third, they are formed by high pressure differentiation of a mafic magma by a process of continued fractional crystallization (Williams, 1932; O'Hara, 1968). This paper attempts to evaluate the origin of kimberlite magmas in the light of new data, and attempts a synthesis of the new data in terms of the geophysical evolution of the upper mantle. It will be seen that the main prejudice of this paper is that the geophysical environment has a direct effect on the petrological associations of kimberlites and their genesis. No new mechanisms are introduced, but rather an attempt is made to analyze the whole context of their origin.

In this paper the term kimberlite is used in a more general sense and extends beyond the definition given by Dawson (1967). It includes the alkali-rich basaltic rocks and their rock associations which are found to have geo-

logical and geophysical characteristics common to the general description included in the following section.

GENERAL DESCRIPTION OF THE GEOLOGY OF KIMBERLITE

Kimberlites may be categorized by a number of common factors that place limitations on theories of their genesis. Considering their world-wide distribution, the geological similarities of the kimberlites and their associations would point to certain common factors governing their origin. The common description of these rocks, therefore, places a first-order restriction on theories of their genesis.

Kimberlites occur as intrusive igneous rocks, generally as dikes, fissures and pipes (Williams, 1932) and some form small diatremes or volcanic vents (Hearn, 1968). The pipes are generally irregular structures resulting from the intersection of dikes or fissures and have not been found to exceed 1 mile in diameter. Compared with other igneous rocks they only occur in bodies of very small volume. No plutonic equivalents of kimberlite have been found and their record remains only in the hypabyssal and volcanic realm.

Kimberlites are widely distributed throughout the earth, but their known occurrences are restricted to the stable cratonic areas (Bardet, 1964). Because of poor sampling of the oceans, this latter observation is difficult to evaluate although other arguments, presented later, would indicate that it is a valid one. They are not directly associated with large mountain building orogenies, but rather related to regional epirogenic events, following deep fracture patterns to the surface (Crockett and Mason, 1968; Dawson, 1962).

Kimberlites are also widely distributed in time. The earliest kimberlites that have been found are approximately 2 b.y. old (Allsop *et al.*, 1967) and kimberlitic diatremes as young as Eocene have also been recorded (Hearn, 1968). The distribution of kimberlitic magmas in time (Fig. 1) indicates that there have been increasing volumes of kim-

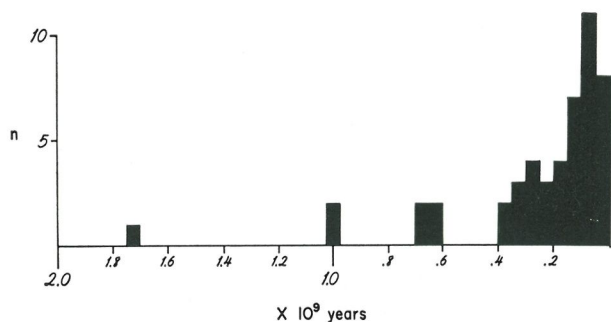


FIG. 1. Distribution of kimberlite magmas in time (Allsop *et al.*, 1967; Du Toit, 1954; Grantham and Allen, 1960; Hearn, 1968; Holmes and Paneth, 1936; Lebedev, 1961; Makhlayev and Surina, 1965; Mikheyenko and Nenashev, 1968; Pollard *et al.*, 1957; Shoemaker *et al.*, 1962; Sibirtsev and Prokopchuk, 1964; Stadelhoffen, 1963; Ukhanov, 1963; Wade and Prider, 1940; White and Pierson, 1961; Zartman *et al.*, 1967).

berlitic intrusion with increasing time, and as the sample arises primarily from Shield areas older than 800 m.y. the age distribution is probably real and not simply an artifact of erosion. In addition it may be noted that there is a time-spatial distribution of kimberlitic magmatism that roughly follows the development of continental crust. As an example, Figure 2 shows the age distribution of North American kimberlitic magmas. The contour lines limit areas outside of which no kimberlites of greater age are known to occur, although younger kimberlites may occur within areas of older kimberlitic intrusion. Figure 2 shows the parallel development of kimberlitic intrusion with the evolution of continental crust (Goldich *et al.*, 1966), although one should note that the kimberlites always post-date the crustal development by at least 0.5 b.y. The latter restriction is unique to kimberlite magmas and may be a significant factor related to their genesis.

Petrologically, the kimberlites are a complex and variable mixture of transported rocks and minerals mixed together in varying and erratic proportions with a transporting fluid. The transporting igneous fluid varies in composition from a mafic to an ultramafic and probably to a carbonatitic composition. Its chemistry, mineralogy and texture is entirely dependent on the proportions of the phases that form an individual mixture. The ubiquitous presence of hydrous phases such as serpentine and phlogopite and interstitial carbonates in the matrix is also indicative of a vapor-rich magma.

The kimberlitic matrix is composed primarily of serpentine and phlogopite, with lesser amounts of other hydrous phases such as amphiboles, chlorite and zeolites. Apatite, monticellite, magnetite, perovskite and carbonates may also be found. In addition xenocrysts derived from the inclusions are commonly found distributed throughout the matrix; of these olivine, clinopyroxenes (chrome diopside, omphacite, diopside-hedenbergite), enstatite, garnet and ilmenite are by far the most common.

The inclusions characteristically comprise two suites of

samples. First, inclusions of accidental origin include rounded and angular fragments of rocks that are obviously derived from the stratigraphic section through which the kimberlite has traversed; these include metamorphosed basement rocks and sedimentary and volcanic rocks that come from horizons that are stratigraphically higher and lower than the present erosional levels. In the second group are xenoliths with phase assemblages that indicate a high pressure origin, from depths within the upper mantle. These xenoliths are characteristically ultramafic rocks such as harzburgites, garnet harzburgites and garnet lherzolites, mafic rocks such as eclogites and kyanite eclogites and occasionally xenoliths with intergrown diopside and ilmenite. The origin of the mantle derived xenoliths is still a matter for debate with opinions varying as to whether they are of accidental or cognate origin.

Independent of their origin, the mafic and ultramafic xenoliths indicate the minimum depth of kimberlite genesis. For example, xenoliths of mafic composition all occur as eclogites, some of which are kyanite-bearing. This allows the use of the basalt to eclogite transition (Green and Ringwood, 1967a, 1967b, 1967c) to place a minimum depth of origin (Fig. 3). In addition ultramafic rocks are characteristically garnet-bearing and this places them on the high-pressure side of the spinel-peridotite to garnet-peridotite transition (MacGregor, 1969) (Fig. 3). A further restriction on the minimum depth of origin is the presence of diamond in the kimberlite matrix and as an accessory mineral in eclogite and lherzolite xenoliths. The diamond to



FIG. 2. Age distribution of North American kimberlites. Contours outline areas outside of which no older kimberlites have been reported (Hearn, 1968; Ross, 1926; Heinrich, 1966; Shoemaker *et al.*, 1962; Zartman *et al.*, 1967).

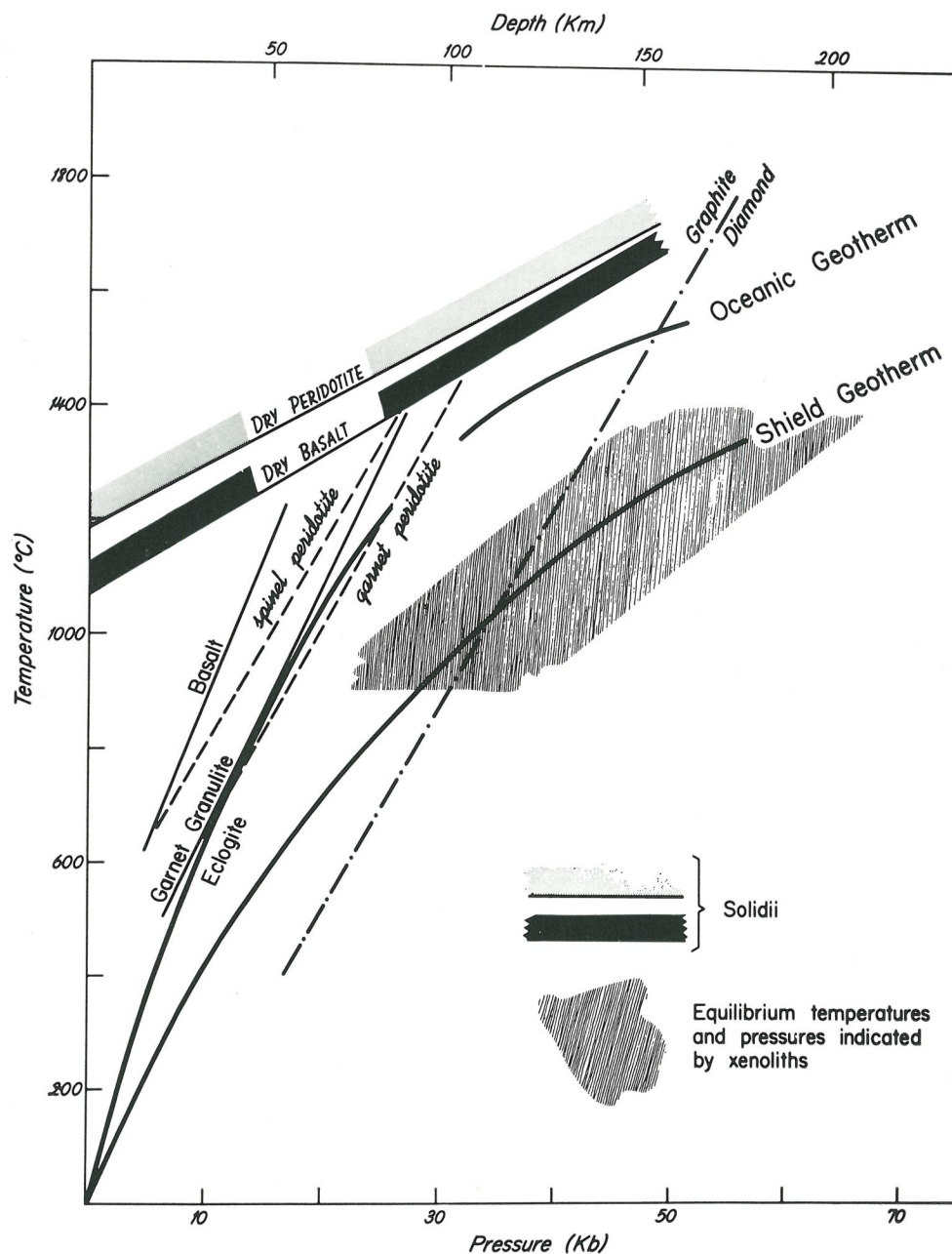


FIG. 3. Temperature-pressure section showing general area of kimberlite genesis as indicated by included high pressure xenoliths. Also included are the diamond-graphite stability curve (Bundy *et al.*, 1961) and a Shield and Oceanic geotherm (Clark and Ringwood, 1964).

graphite stability curve (Bundy *et al.*, 1961) (Fig. 3) restricts the kimberlite origin to even greater depths. It is possible to define more closely the environment at which the xenoliths equilibrated by using reactions which describe the Ca solid solution between coexisting pyroxenes (Davis and Boyd, 1965) and the Al-solubility in pyroxenes in equilibrium with garnet (Ringwood *et al.*, 1964; Boyd and England, 1964; MacGregor and Ringwood, 1964; O'Hara, 1967; Green and Ringwood, 1967a, 1967b, 1967c). Com-

paring the analytical data (O'Hara and Mercy, 1963; Nixon *et al.*, 1963; MacGregor and Ringwood, 1964; Boyd, 1968, 1969a; and Boyd and Nixon, 1969) with the experimental data (MacGregor and Ringwood, 1964; Green and Ringwood, 1967a, 1967b, 1967c; Boyd and England, 1964; Boyd, 1969b; MacGregor, 1964 and Ito and Kennedy, 1967) and theoretical analysis (O'Hara, 1967), it is possible to outline the range of temperatures and pressures within which the ultramafic xenoliths finally equilibrated (Fig. 3).

A further useful indication is obtained by comparing the chemistry of coexisting garnet and clinopyroxene from kyanite-bearing grosspyrites with experimental work by Green (1967) on similar compositions. In the case of a grosspyrite from the Roberts Victor pipe (MacGregor and Carter, 1969) a pressure of approximately 36 kbar and 1100°C is indicated. The combined data indicate a pressure range greater than 35 kbar and a temperature range of 900 to 1400°C for the final, pre-intrusion environmental conditions. Additional data on silicate and oxide phases included in diamonds (Meyer, 1968; Meyer and Boyd, 1968 and 1969) show significant differences in chemistry from those found in the xenoliths. In general the compositions are characterized by high Cr contents. Meyer and Boyd (1969) suggest that the inclusions are relics of igneous events, and being armored by the diamond failed to react in response to new equilibria at lower temperatures. The inclusions in the diamonds thus point to the possibility that the xenoliths themselves were originally formed at magmatic temperatures but have reequilibrated to the temperatures defined by the ambient geothermal gradient.

Another factor of interest is the final temperature of intrusion. There is a characteristic absence of any metamorphism other than minor baking around kimberlitic intrusions. Watson (1967) has summarized the instances where kimberlites have intruded coal seams and oil-bearing sands. In these cases maximum temperatures of approximately 600°C are indicated. The presence of phlogopite coexisting with primary carbonates further suggests temperatures in excess of 300°C (Bailey, 1964). The low temperatures would suggest that the kimberlitic matrix is composed of a volatile-rich magma. This is supported by the explosive nature of some kimberlites (Williams, 1932; Dawson, 1962; Dawson, 1967; Hearn, 1968) and the large proportion of volatiles in the kimberlite matrix. The widespread distribution of kimberlitic material through a narrow network of pipes and fissures, and the abundant, rounded and polished boulders of xenolithic material suggestive of mechanical abrasion also attest to a highly fluid magma of low viscosity.

The geochemistry of kimberlites has recently been summarized by Dawson (1967) who describes them as under-saturated basic rocks with unusually high amounts of K₂O, Al₂O₃, TiO₂, CaO, P₂O₅, H₂O and SO₃. However, their chemistry is highly variable, and may show systematic variations towards the chemistry of carbonated kimberlites and carbonatites that are often associated with kimberlites and are found in similar tectonic environments. The carbon isotopes in the carbonates (Conway and Taylor, 1969; Deines, 1968, 1969) are similar to those found in diamonds, again suggesting a mantle origin.

Radiometric age determinations of kimberlitic material indicate that the kimberlites and their xenoliths have had a complex history. In a number of cases the radiometric ages on the kimberlitic matrix indicate an age consistent with the stratigraphic age assigned to the pipe. For example the lead ages on galena in the kimberlite from the

Premier-pipe give a Precambrian age (1750 m.y.) consistent with paleomagnetic and stratigraphic evidence (Allsop *et al.*, 1967). In addition, K/Ar ages on phlogopite and amphiboles in the matrix often agree with the stratigraphic age (Lovering and Richards, 1964; Zartman *et al.*, 1967; Davidson, 1967). Rb/Sr ages on matrix material have also yielded consistent ages (Allsop and Nicolaysen, 1969; Zartman *et al.*, 1967). However, in many cases the K/Ar ages of phlogopite separated from kimberlites is much greater than the age of the intrusion (Milnheyenko and Nenashev, 1968; Davidson, 1967; Brookins, 1969). The crystallization of these minerals in an Ar-rich environment (Zartman *et al.*, 1967) is one possible interpretation of this anomaly, although the presence of several consistent K/Ar dates suggests that some of the xenocrysts may have crystallized prior to extrusion.

Additional radiometric data have been collected on mafic and ultramafic xenoliths and their associated minerals. Manton and Tatsumoto (prs. commun.) and Allsop and Nicolaysen (1969) illustrate that at least some of the mafic xenoliths are very old (from 1 to 3.5 b.y.). However, the isotopic data do not uniquely define the history of these xenoliths, and, in fact represent a fairly complex picture, the whole question of the uncertainty evolving around the question of the genesis of the alteration products. At least three interpretations are still possible:

1. The alteration products result from contamination by the kimberlitic fluid during its transit to the surface.
2. The primary garnets contained higher proportions of K and Rb in solid solution (Kushiro *et al.*, 1967). Later reaction resulted in the expulsion of the alkalis to grain boundaries.
3. If the xenoliths are cognate cumulates, it is possible that there has been a trapped interstitial liquid which has been, to a varying degree, in chemical communication with the evolving kimberlitic fluid. Reaction of the interstitial fluid with cumulate phases at different times would produce a complex isotopic history.

Since kimberlites apparently came from the upper mantle beneath continental shields, it is useful to look at the geophysical evidence of the nature of this region in contrast to orogenic zones or oceanic areas. Seismological studies indicate that the shields are characterized by a 30- to 40-km thick crust, high seismic velocities at the top of the upper mantle, and a low velocity zone, which is better defined by the shear wave than the compressional wave distribution. The top of the low velocity zone is at approximately 110 km (Brune, 1969; Vanek, 1969) and extends to depths varying from 150 (Vanek, 1969) to 320 (Dorman, 1969) km. In contrast, orogenic regions and ocean basins have lower upper mantle seismic velocities and low velocity zones that are more pronounced and extend from depths of approximately 60 to 240 km (Dorman, 1969). Studies of the earth's heat flow (Lee and Uyeda, 1965; Horai and Uyeda, 1969; Lubimova and Polyak, 1969; Simmons and Roy, 1969; von Herzen and Lee, 1969) indicate that shield areas (0.7 to 0.9 $\mu\text{m cal/cm}^2 \text{ sec}$) have about half the heat

flow of orogenic (1.7 to 2.5 $\mu\text{m cal/cm}^2 \text{ sec}$) and oceanic regions (1.3 to max. of 8.0 $\mu\text{m cal/cm}^2 \text{ sec}$) leading to estimates of thermal gradients beneath shields and orogenic regions or ocean basins as indicated in Figures 3 and 4 (Clark and Ringwood, 1964). Gravity studies (Brune, 1969) show small negative Bouguer anomalies over shield areas whereas orogenic areas are characterized by large negative and ocean basins by large positive anomalies. The differences in the gravity anomalies correlate well with the difference in the degree of tectonic stability of the different regions as indicated by their geology.

DISCUSSION

In the previous section, an attempt has been made to show that the kimberlites have an identity which is characterized by a similarity of structure, texture, mineralogy, mafic and ultramafic xenoliths, depth of origin and final temperature of intrusion. In addition the tectonic framework of their intrusion and their late age with respect to the shield areas they intrude are similar. These characteristics and their well-defined set of associations point to an orderly and unified mechanism of genesis, and stimulate the search for an hypothesis that incorporates all the descriptive aspects into a unified theory.

One of the most significant and debated aspects of the kimberlite pipes is the geological association of magmas of kimberlitic composition with phase assemblages, or xenocrysts from the xenoliths, that are characteristic of a high-pressure origin. This feature is observed independent of the other accidental inclusions that are characteristic of the local crustal or sedimentary sections through which the pipe has intruded. The question of the accidental or cognate origin of the high-pressure phase assemblages is a matter of continuing debate. Workers who favor an accidental origin (Holmes, 1936; Wagner, 1928; Davidson, 1967; Lebedev, 1964; McGetchin, 1969) point to the similarity of the high-pressure mafic and ultramafic assemblages with the rocks in high-grade regionally metamorphosed terrains. In addition the seismic data and subsolidus experimental (Fig. 3) data are consistent with an upper mantle containing the observed phase assemblages. Empirical data (McGetchin, 1969) on the size distribution of xenoliths also point to an accidental origin, and although the final interpretation is not clear, recent radiometric dating indicates that at least some xenoliths are significantly older than the kimberlite intrusion and therefore reasoned to be accidental.

Investigators who favor a cognate origin are impressed by the association of kimberlites with a unique suite of mantle derived xenoliths. In the same way different basic magmas are associated with specific xenolith suites (MacGregor, 1968). Although it can be argued that this is a function of the depth of origin of a specific magma, it is surprising that in kimberlites there are relatively few representatives of mafic and ultramafic phase assemblages from shallower parts of the mantle. Just as the narrow range of chemistry of granitic rocks, or characteristic asso-

ciation of phase assemblages in layered cumulate sequences is indicative of a specific governing process, it seems plausible to interpret the unique kimberlitic association as being genetically related to a specific physico-chemical process. The latter argument is supported by the experimental determination of crystal-liquid equilibria at high pressures (Davis, 1963; Ito and Kennedy, 1967; O'Hara, 1968), which indicates that the high-pressure xenoliths may be interpreted as a suite of crystal assemblages separating from a cooling, differentiating basic magma. The xenoliths may be arranged in a sequence of primary phase assemblages that are reasoned, from experimental data (Davis, 1963; O'Hara, 1968), to be the sequential sets of crystals in equilibrium with a mafic magma that is undergoing fractional crystallization at high pressure. The phase assemblages characteristic of harzburgite, garnet harzburgite, garnet lherzolite, hypersthene-eclogite, eclogite, and kyanite-eclogite thus may be interpreted as a successive sequence of crystal assemblages separating from a magma undergoing differentiation through fractional crystallization.

Theoretical analysis of the processes of fractional crystallization versus fractional fusion shows that the discontinuous series of cumulate phase assemblages, indicated by the cognate interpretation, is consistent with a fractional crystallization rather than fractional fusion origin (Prennall, 1969). A fractional crystallization hypothesis also requires a continuous series of differentiating liquids. In addition, systematic variations of the mineral chemistry within each cumulate phase assemblage is required. A series of continuous liquids is difficult to obtain, but it is possible that the group of Roberts Victor eclogites, previously interpreted as a series of successive liquids (MacGregor and Carter, 1969), represent part of the liquid differentiation trend. Examination of variations in mineral chemistry within each interpreted primary phase assemblage has yielded positive results. Chen (1969) shows that there is a continuous variation of the chemistry of lherzolites within each of three South African kimberlite pipes. The garnets and clinopyroxenes of eclogites also show systematic chemical variations (Rickwood *et al.*, 1968; MacGregor and Carter, 1969), and in the kyanite-eclogites a similar feature is noted (Sobolev *et al.*, 1968). In addition there are modal discontinuities between phase assemblages as would be expected from the theoretical analysis. The consistent agreement of the kimberlite rock associations with the experimentally derived high-pressure fractional crystallization sequence warrants further examination of the cognate hypothesis.

Several criticisms may be levelled at the cognate interpretation. First, the temperatures of equilibrium indicated by the "cumulate" phases are not compatible with experimentally indicated temperatures for crystal-liquid equilibria in dry basaltic liquids at high pressure. Second, the radiometric ages of some xenoliths are commonly significantly different from the time of intrusion. In addition initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of kimberlites and the associated

xenoliths (Zartman *et al.*, 1967; Allsop and Nicolaysen, 1969; Mitchell *et al.*, 1969; Manton and Tatsumoto, in press) do not show a clear relationship. Third, the textures of many of the ultramafic xenoliths are not characteristic of simple cumulate rocks with which we are familiar.

To answer these criticisms it is necessary to examine the whole environment of kimberlite genesis in terms of the crustal evolution of continental shields. Such an analysis represents the main thrust of the present contribution and the basis for a modified hypothesis of kimberlite genesis.

The thermal history of the earth is probably the single most fundamental factor affecting the genesis of basic magmas. A number of models have been proposed for the thermal evolution of the earth (Lubimova, 1958; MacDonald, 1959; Birch, 1965; Reynolds *et al.*, 1966; Lee, 1968; Hanks and Anderson, 1969). Although there is considerable uncertainty in the knowledge of many critical variables (*e.g.*, K, U and Th content and distribution in the earth, opacity, thermal conductivities, initial boundary conditions, *etc.*), certain major features are apparent. The most critical point for this discussion is that the upper mantle heated up in the first few billion years and has been cooling down ever since. As an example, the thermal curves calculated by Reynolds *et al.* (1966) are shown in Figure 4. Reynolds *et al.* (1966) consider a uniform chondritic earth in which partial melting and convection are important processes. Superimposed on the same figure are a number of melting curves for probable mantle materials.

For a discussion of melting phenomena in the upper mantle it is necessary to examine a number of limiting conditions which are defined by the melting curves of possible mantle compositions. Estimates of the average composition of the upper mantle (Ringwood, 1966; Carter, 1968; Nicholls, 1967; Harris *et al.*, 1967) indicate that it is essentially peridotitic. The melting curves of a dry (Ito and Kennedy, 1967; Green and Ringwood, 1967b) and wet peridotite (Kushiro *et al.*, 1968) are shown in Figure 4. In addition the melting curves of a dry (Cohen *et al.*, 1967) and water-saturated basalt (Yoder and Tilley, 1962; Lambert and Wyllie, 1968; Hill and Boettcher, 1970) (Fig. 4) allow the examination of the partially molten products of a peridotitic mantle. The melting curve of a hydrous kimberlitic magma has not been defined, although it probably lies between the water-saturated peridotite and water-saturated basalt curve (O'Hara, 1968). In this regard the beginning of melting of a basalt+H₂O+CO₂ mixture (H₂O:CO₂=1:1 mole percent) (Hill and Boettcher, 1970) may serve as a useful approximation of kimberlitic melting.

The different thermal models indicate that for the first few billion years the geotherms will rise through the upper mantle and melting will occur along or in between the beginning of melting curves in Figure 4 (depending on the water content and ambient compositions of the upper mantle). In the initial period melting will proceed to shallower depths with time. Considering the strong partition of H₂O in the liquid phase, especially at high pressures (Yoder 1965), it is apparent that if volcanism is an important pro-

cess at this stage, the mantle will be rapidly dehydrated, and the mean mantle melting curve will move towards that for a dry basalt or peridotite (Fig. 4). The rise of the melting curves will stem the rise of the geotherms, and somewhat suppress the rate at which the melting interface moves to the surface. During the stage of the heating of the upper mantle, magmas will be formed primarily by a process of fractional fusion. Fractional crystallization may well occur in pockets of magma which are intruded and structurally trapped at higher and cooler levels in the crust and upper mantle, but fractional fusion will be the dominant process.

After the first two to three billion years the upper mantle will begin to cool down. The intersection of the geothermal gradient with the mantle melting curve will move to greater depths and magmas formed by fractional fusion will similarly be formed at greater depths. However, magmas formed during the heating stage still exist and during cooling will be subject to the process of fractional crystallization which will become an increasingly important process in magma generation. Some magmas may be structurally trapped and isolated in magma chambers above the intersection of the geothermal gradient with the mantle melting curve. Cooling in these perched magma chambers, or for magma distributed through the upper mantle, will only be in response to the depression of the geothermal gradient. Up to the present time this implies cooling to temperatures down to the present geothermal gradients which will vary significantly from one tectonic region to another. Fractional crystallization during this period will result in a lowering of the magma's solidus temperature, and allow the existence of a liquid phase for long periods of time. Such is especially the case for closed system fractionation, where increasing volumes of H₂O and other volatile components will be dissolved in the magma, resulting in a significant and continuous depression of the melting curve. If the melting curve depression keeps pace with the lowering of the geothermal gradient, it will be possible to maintain a liquid phase for a long period of time. Examination of Figure 4 indicates that the estimated present day geothermal gradients for shield areas intersect the water saturated basalt and water saturated peridotite melting curves at depths of 50 and 110 km. Thus it is possible for water saturated magmas of these compositions to exist at depths in the mantle beneath the shields; and in this way it is also possible that the lower temperature, volatile-rich kimberlite magmas may have been formed through a process of fractional crystallization which has taken place over a long period of time. Support for a two stage process in the major evolution of the upper mantle is given by isotopic evidence (Fenton and Faure, 1969) which indicates that in the first few billion years the crust and upper mantle have evolved as a single homogeneously mixed system. After this time the upper mantle and crust started to evolve as two separate systems. In this interpretation, the first stage is correlated with the heating up of the upper mantle, and the second stage related to the subsequent cooling.

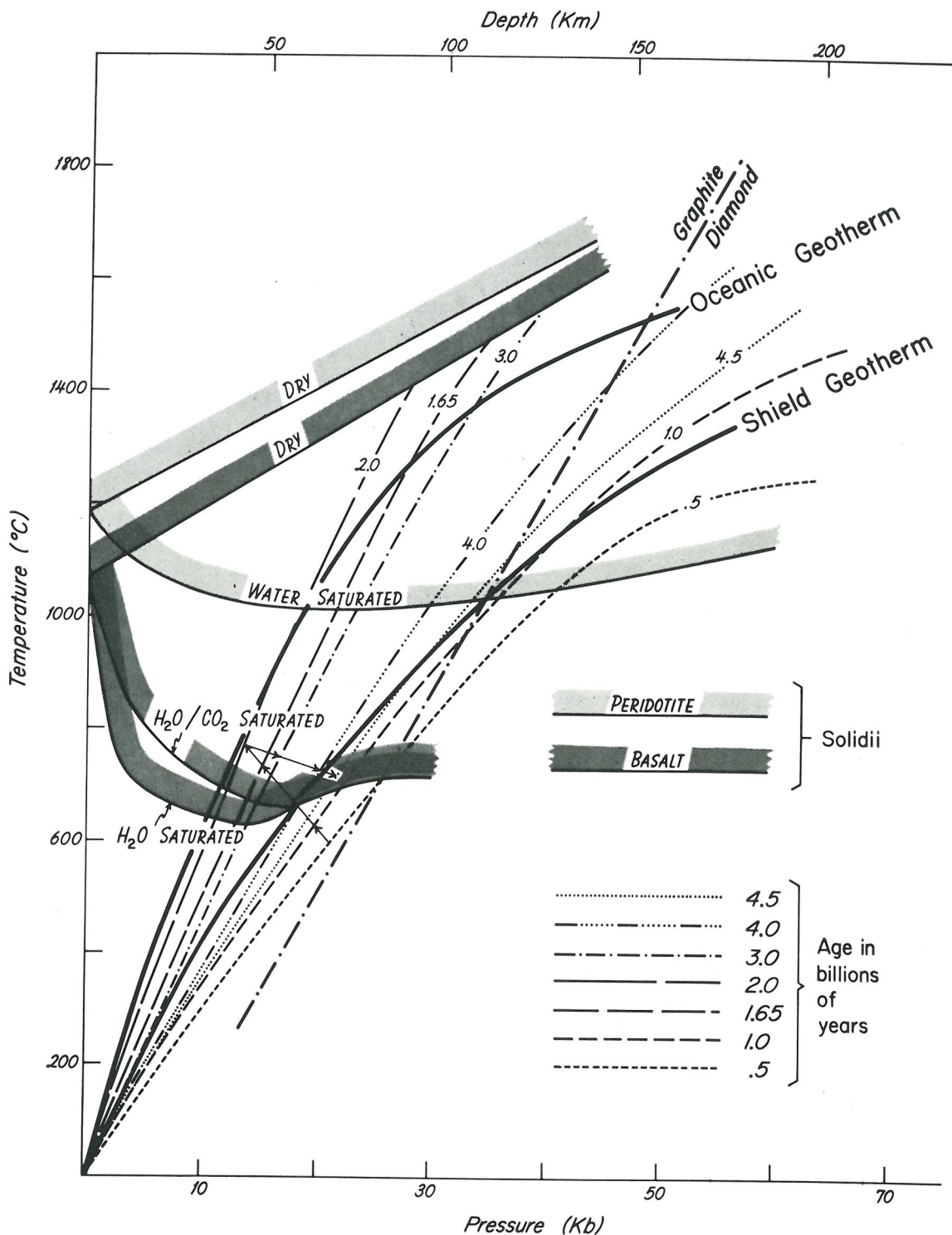


FIG. 4. Temperature-pressure section showing model for thermal evolution of earth (Reynolds *et al.*, 1966) superimposed on solidus curves for dry peridotite (Ito and Kennedy, 1967), water saturated peridotite (Kushiro *et al.*, 1968) dry basalt (Cohen *et al.*, 1967), water saturated basalt (Hill and Boettcher, 1970) and vapor saturated basalt where vapor phase is composed of 1:1 mole per cent of H₂O and CO₂ (Hill and Boettcher, 1970). Also included are the diamond-graphite stability curve (Bundy *et al.*, 1961) and a Shield and Oceanic geotherm (Clark and Ringwood, 1964). For the water saturated peridotite and vapor saturated basalt $P_{TOTAL} = P_{VAPOR}$. The arrows show the progression of the geothermal gradient with time.

The above model envisages a static evolution of the upper mantle although there is ample evidence that such is not the case. It is thus implied that if continental drift is an important process in continental development then the depth at which relative motion has taken place must lie beneath the zone of kimberlite genesis. It is thus considered that the general scheme is probably applicable to the stable shield areas which have not been involved in orogenic movements for long periods of time. In this sense it is interesting to recall that kimberlites are only found to intrude continental crust at periods in excess of 0.5 b.y. after its formation, and they are restricted to intrusion into areas of continental crust. Further, the increased frequency of kimberlitic intrusion with time may be correlated with the increasing area of continental crust and shields (Goldich *et al.*, 1966).

Examination of estimated, present-day geothermal gradients (Clark and Ringwood, 1964) beneath oceans and continents indicates that the oceanic geotherm falls above the zone of kimberlite genesis, as indicated by the equilibrium temperatures and pressures of the kimberlite xenoliths, while the continental or shield geotherm passes through this region. Within the framework of the model it is thus implied that oceanic regions have not cooled sufficiently to reach the zone of kimberlite genesis, while in the more stable continents and shields this zone has been reached. It is also of interest to note that the intersection of the shield geotherm with the water saturated peridotite melting curve and the graphite-diamond stability curve indicates a depth of origin in excess of 110 km. The correlation of this depth with the top of the low-velocity zone raises the possibility that under continents the low-velocity zone has resulted from slow cooling of a region that once intersected the mantle melting curve at shallower depths and at higher temperatures. During cooling fractional crystallization would have been the dominant process and it is hypothesized that the interstitial liquid phase has changed composition progressively towards a kimberlitic magma. In this regard it is therefore interesting to consider the low-velocity zone beneath the shields as a partially molten zone with a liquid composition of kimberlitic affinity that has formed by the process of fractional crystallization rather than direct partial fusion. This partially molten portion of the mantle beneath the shields may act as a long-term reservoir of magmatic material, which may remain dispersed or concentrated depending on the structural features of its environment.

The above model of kimberlite genesis would answer a number of the objections raised to the proposal that the high-pressure xenoliths are a cognate suite of samples. First, it would be possible to have crystal cumulates which have formed at a very early stage in the history of the basaltic magma as part of the whole kimberlite system, and the apparent old ages of some xenoliths may thus be explained. Second, the lack of igneous textures and the apparently low equilibrium temperatures are consistent with the hypothesis that they have formed as cumulates at

higher temperatures but undergone subsolidus and possibly later crystal-liquid reactions during slow cooling to give final temperatures approximating those of kimberlite genesis (Meyer and Boyd, 1969). These later reactions would also result in a redistribution of the radioactive isotopes and lead to a complex isotopic history. Third, the long term coexistence of a liquid phase in equilibrium, or possible chemical communication, with a solid assemblage allows the opportunity for continued reaction in the mantle and could result in a complex geochemical and isotopic history with attendant complexities in the final chemistry.

The above model raises the question of what are the limits of a cognate system. In the case of a layered intrusion, the sequences of cumulates are obviously related to each other by the process of fractional crystallization and hence are "cognate." However, even in this closed situation there is the possibility that different portions of the cumulate assemblage are related to different batches of magma. In the case of a partially molten volume, such as that which may exist throughout a varying zone in the upper mantle which is undergoing subsequent fractional crystallization, the limits of cognate association are difficult to define. Indeed, if the process of their formation involves periods of time as long as that envisaged in this model, the "cognate" relationship becomes increasingly obscure. It would seem, then, that in this context the term cognate implies primarily the association of rocks formed through a common geological process, which have in general come from the same geological and geographical environment. The degree of direct lineage is difficult to determine, and as in a complex intrusion, may imply some repetitive or cyclic phases involving the mixing of volumes that have had different histories but have been formed by the same general process. In the natural case strict adherence to a "cognate" or "accidental" origin may tend to confuse the interpretation of the several processes that are involved.

As a model it is useful to examine an example of a cognate association *sensu stricto*. In this hypothetical situation we can consider a closed, high-pressure magma chamber subject to the fractional crystallization of a mafic magma. An attempt to organize the rock associations characteristic of a kimberlite pipe in an orderly sequence of crystal cumulate assemblages precipitating from a basic magma of changing composition is shown in Figure 5. The following features should be noted:

1. Harzburgite, garnet harzburgite, garnet lherzolite, hypersthene eclogite, eclogite and an olivine-diopside-perovskite rock are predicted as a sequence of successive cumulate phase assemblages. It is hypothesized that the cumulate phase is precipitating from a liquid whose composition changes from a picrite to a tholeiite, through an alkali basalt to a composition equivalent to the intergrown diopside-ilmenite nodules to a kimberlitic composition with possible carbonatitic associations.

2. The sequence of primary phase assemblages olivine + orthopyroxene, olivine + orthopyroxene + garnet, olivine + orthopyroxene + garnet + Cr-diopside, hypersthene + gar-

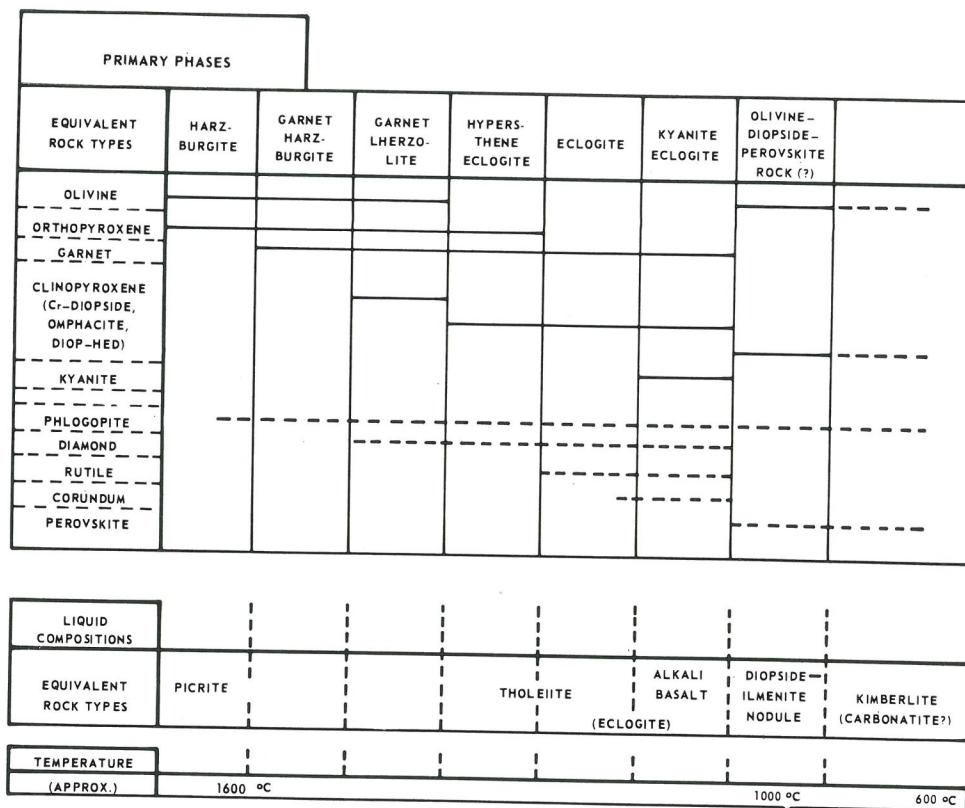


FIG. 5. A model for the genesis of kimberlite by the process of high pressure fractional crystallization of a mafic magma.

net+omphacite, and garnet+omphacite are precisely those which would be predicted from high-pressure experimental work (Davis, 1963; Ito and Kennedy, 1967; O'Hara, 1968). The composition of the liquid in equilibrium with olivine+orthopyroxene+garnet+Cr-diopside is experimentally estimated to be equivalent to a picrite. In the four-component system CaO-MgO-Al₂O₃-SiO₂ this 5-phase assemblage represents a peritectic and the 4-phase cumulate assemblage olivine+orthopyroxene+Cr-diopside+garnet would not be expected during fractional crystallization. However Davis (1963) indicated that the peritectic would become a eutectic with increasing pressure, and in the natural system the addition of other components could make a significant difference.

3. The suggestion that the kyanite-eclogites are a primary phase assemblage arises from the analytical data of Rickwood *et al.* (1968), Sobolev *et al.* (1968) and MacGregor and Carter (1969) on natural assemblages. It is also of interest that MacGregor and Carter's (1969) interpretation of their analytical data suggested the coexistence of a liquid phase, which has frozen in the eclogite facies, and which varies from a tholeiite to an alkali basalt in composition.

4. The further interpretation that there is a primary phase assemblage of olivine+diopside-hedenbergite+perovskite coexisting with a liquid that quenches to give the diopside-ilmenite xenoliths is based on preliminary experi-

mental data on the join diopside (CaMgSi₂O₆)-giekielite (MgTiO₃) at 20 kbar. Minimum melting compositions on this join are composed of approximately 50:50 mixtures of diopside and giekielite. With cooling diopside (silicate)-rich liquids become increasingly giekielite-rich and would be in equilibrium with the three primary phases forsterite+diopside+perovskite. The intergrown texture so characteristic of the diopside-ilmenite xenoliths is thus interpreted as a eutectoid texture. Olivine, diopside and perovskite are common xenocrysts in kimberlites and may be related to this stage of development.

5. The proposed liquid path from the diopside-ilmenite xenolith to the final kimberlite is not clear although it is apparent that H₂O and CO₂ become increasingly important components of the magma at this stage.

6. The proposed sequence of primary accessory phases is interpreted from their presence in the xenoliths. Diamonds have been reported from garnet lherzolites, eclogite and kyanite eclogite (Gurney *et al.*, 1970). Rutile has been reported both from eclogite and kyanite eclogite and corundum is occasionally found in eclogites and more commonly in kyanite eclogite. Perovskite is a common accessory in the kimberlite itself.

7. Phlogopite is proposed as a primary phase which is capable of crystallization throughout the cooling history. This interpretation is based on the presence of phlogopite in all the rock types, and although some of its textural

relationships obviously indicate later reaction or alteration, large primary-looking crystals may also be seen. In the model example of a single magma chamber it is probable that phlogopite crystals would float rather than sink. They would, therefore, be in continual contact with the liquid allowing for reaction and reequilibration during cooling. If phlogopite is a primary phase, it is probable that the high K content of kimberlite magmas results from a mechanical mixture of the kimberlitic liquid with phlogopite. The glimmerite (phlogopite-rich) xenoliths commonly found in kimberlite pipes may well be a portion of the separated primary phlogopite crystals.

8. Estimated temperatures are derived from experimental data on the melting of a dry lherzolite (Ito and Kennedy, 1967), wet peridotite (Kushiro *et al.*, 1968) and estimated temperatures of kimberlite intrusion.

9. Theoretical analysis of the process of fractional crystallization versus fractional fusion (Presnall, 1969) indicates that fractional crystallization is characterized by a series of discontinuous crystal cumulates and a continuous sequence of differentiating liquid, whereas in fractional fusion the reverse is expected. The xenoliths from kimberlites thus are compatible with a fractional crystallization trend, and the liquids should be thought of as a continuous differentiating sequence. Experimental evidence (O'Hara, 1968; Davis, 1963) supports the picrite→tholeiite and tholeiite→alkali basalt trends.

The degree to which the magma chamber model may be applied to the upper mantle is not clear since the dispersion of a fluid phase in the upper mantle is not well known. Seismic data indicates the existence of a low velocity zone,

which may be interpreted either as a partially molten zone between 110 and 320 km, with highly dispersed liquids, or as a thin liquid layer (Hales and Bloch, 1969). Thus the seismic data do not resolve the question of how the fluid phase is distributed, and it is not possible to predict the degree to which the above idealized model applies to processes within the upper mantle. The presence of kimberlitic magmas implies the accumulation of at least some confined volumes of liquid, but again the magnitude of any magma volume is highly speculative. At this stage the model is only an idealized example of a single situation. However, other more dispersed systems are governed by the same physico-chemical processes. It is probably valid to consider that the same general process occurs throughout the mantle with different portions fractionating with varying degrees of efficacy resulting in the quenching of primary phases with slightly different chemistry, and liquids at varying positions along the liquid trend. Perhaps the most emphatic statement that can be made is that fractional crystallization is the dominant process, and in this context the system is cognate, although the original juxtaposition of all the liquids and all the xenoliths still remains debatable.

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