Abstract

Field and Scott Smith [Field, M., Scott Smith, B.H., 1999. Contrasting geology and near-surface emplacement of kimberlite pipes in southern Africa and Canada. Proc. 7th Int. Kimb. Conf. (Eds. Gurney et al.) 1, 214–237.] propose that kimberlite pipes can be grouped into three types or classes. Classical or Class 1 pipes are the only class with characteristic low temperature, diatreme-facies kimberlite in addition to hypabyssal- and crater-facies kimberlite. Class 2 and 3 pipes are characterized only by hypabyssal-and crater-facies kimberlite. In an increasing number of Class 1 pipes a new kimberlite facies, transitional-facies kimberlite, is being found. In most cases this facies forms a zone several metres wide at the interface between the hypabyssal- and diatreme-facies. The transitional-facies exhibits textural and mineralogical features, which are continuously gradational between the hypabyssal and the diatreme types. The textural gradations are from a coherent magmatic texture to one where the rock becomes increasingly magmaclastic and this is accompanied by concomitant mineralogical gradations involving the decline and eventual elimination of primary calcite at the expense of microlitic diopside. Both transitional- and diatreme-facies kimberlites are considered to have formed in situ from intruding hypabyssal kimberlite magma as a consequence of exsolution of initially CO₂-rich volatiles from the volatile-rich kimberlite magma. The transitional-facies is initiated by volatile exsolution at depths of about 3 km below the original surface. With subsequent cracking through to the surface and resultant rapid decompression, the further catastrophic exsolution of volatiles and their expansion leads to the formation of the diatreme facies. Thus diatreme-facies kimberlite and Class 1 pipes are emplaced by essentially magmatic processes rather than by phreatomagmatism.

Distinctly different petrographic features characterize crater-facies kimberlite in each of the three pipe classes. In crater-facies kimberlites of Class 1 pipes, small pelletal magmaclasts and abundant microlitic diopside are characteristic. These features appear to reflect the derivation of the crater-facies material from the underlying diatreme zone. Most Class 2 pipes have shallow craters and the crater-facies rocks are predominantly pyroclastic kimberlites with diagnostic amoeboid lapilli, which are sometimes welded and have vesicles as well as glass. Possible kimberlite lava also occurs at two Class 2 pipes in N Angola. The possible presence of lava as well as the features of the pyroclastic kimberlite is indicative of hot kimberlite magma being able to rise to levels close to the surface to form Class 2 pipes. Most Class 3 kimberlites have very steep craters and crater-facies rocks are predominantly resedimented volcaniclastic kimberlites, in some cases characterized by the presence of abundant angular magmaclasts, which are petrographically very similar to typical hypabyssal-facies kimberlite found in Class 1 pipes. The differences in crater-facies kimberlite of the three classes of pipe reflect different formation and depositional processes as well as differences in kimberlite composition, specifically volatile composition. Kimberlite forming pipe Classes 1
and 3 is thought to be relatively water-rich and is emplaced by processes involving magmatic exsolution of volatiles. The kimberlite magma forming Class 2 pipes is CO₂-rich, can rise to shallow levels, and can initiate phreatomagmatic emplacement processes.

Field and Scott Smith (1999) recognize at least three distinct types of kimberlite pipe based on pipe shape and internal geology and propose that the different types formed by different emplacement processes. The first type or class of pipe (see terminology below) is the so-called classical pipe first described by Hawthorne (1975) based on examples from southern Africa. These pipes are characterized by root, diatreme and crater zones, but their origin is controversial with both magmatic and phreatomagmatic emplacement processes being advocated (Field and Scott Smith, 1999; Lorenz, 1993). The second type or Class 2 pipes are mainly characterized by shallow crater zones as epitomized by the Canadian Prairies, Fort a la Corne kimberlite clusters. Emplacement processes are believed to include phreatomagmatic excavation with subsequent magmatic or sedimentary infilling of the crater (Field and Scott Smith, 1999; Webb et al., 2003). Class 3 pipes include many of the Ekati pipes at Lac de Gras in Canada as well as the Jwaneng pipe in Botswana. These pipes are steep-sided and are infilled with abundant resedimented volcaniclastic kimberlite and lesser pyroclastic kimberlite. Machin (2000) advocates dominant magmatic and lesser phreatomagmatic processes for the Jwaneng pipe. An important aspect to recognition of the three classes is that the diatreme zone is unique to Class 1 pipes.

In this contribution we present new petrographic and geological information, which bears on the emplacement processes for each of the three types or classes of kimberlite pipe. We also describe hitherto unrecognized in-situ transition zones, found between diatreme-and hypabyssal-facies kimberlite in Class 1 pipes, which supports a magmatic emplacement model for this class of pipe.

2. Terminology

Use of the designator ‘type’ is widely used in the kimberlite literature—for example Type 1 and 2 eclogites; Type 1 and 2 (or Group 1 and 2) kimberlites. To avoid confusion we propose to use the term ‘class’ for the three types of kimberlite pipe identified by Field and Scott Smith (1999). In describing kimberlite rock varieties we continue to follow the terminology of Clement and Skinner (1985) with respect to hypabyssal-facies kimberlite (HFK), diatreme-facies kimberlite (DFK) and crater-facies kimberlite (CFK), but define and describe a new transitional-facies kimberlite (TFK) in this paper. It has become common to drop the ‘facies’ designator in kimberlite classification (Field and Scott Smith, 1998), but we retain it here because we prefer the ordering offered by the use of ‘facies’ and because more than one kimberlite rock type is contained in each facies.

Rocks crystallized from kimberlite magma in the root zone have textures, which are commonly uniformly magmatic and rarely segregationary (Clement and Skinner, 1985). In each of the kimberlite facies are rocks composed, in part, from rounded bodies of disrupted kimberlite magma or ‘magmaclasts’ a term introduced by Field and Scott Smith (1999). A magmaclast is a discrete body of magma ranging in size from microscopic (i.e. < 1 mm) to boulder size (i.e. up to about 100 mm diameter), formed during emplacement but before solidification and is usually distinguished by having a thin selvage of fine-grained crystalline material. Rocks having a high proportion of magmaclasts are described as ‘magmaclastic’. Field and Scott Smith (1998) recognize three different types of juvenile magmaclast; globular-segregations, pelletal lapilli, and pyroclastic lapilli. It is unfortunate that the term ‘globular-
segregation’ has been used for a clast of magma as it causes confusion with the term ‘segregationary’, which is used for a magmatic texture, which Clement (1975) believed resulted from immiscibility. We propose restricting use of the term ‘globular segregationary’ to describing highly segregationary HFK and to use the terms ‘magmaclast’ and ‘magmaclastic’ to describe components of and types of TFK, DFK and CFK.

The identification of the different types of magmaclasts is difficult. We have not used the terms ‘pelletal lapilli’ in descriptions of Class 1 kimberlites, because most of the magmaclasts in these kimberlites are not of lapilli size (>2 mm). Instead the terms ‘pelletal magmaclast’ (<2 mm) and ‘globular magmaclast’ (>2 mm) are used. Pelletal magmaclasts are small spherical fragments usually consisting of single olivine grains with thin selvages of fine-grained material. Globular magmaclasts are larger spherical fragments consisting of more than one olivine grain plus finer groundmass. Use of the term ‘pelletal lapilli’ is still appropriate in the case of Class 2 and 3 kimberlites, where magmaclasts tend to be of lapilli size. For the HFK we use the term groundmass for finer grained material and matrix for all primary constituents including groundmass and larger sized phenocrysts. This term excludes any xenolithic material including olivine and other mantle-derived xenocrysts or macrocrysts.

Varieties of crater-facies kimberlite include volcaniclastic kimberlite (VK), pyroclastic kimberlite (PK) and resedimented volcaniclastic kimberlite (RVK) after Field and Scott Smith (1998), and rare possible kimberlite lava. In this paper any magmaclast that has been macroscopically initially classified as VK has been reclassified as either PK or RVK after detailed microscopy.

3. Overview of pipe classes

Class 1 pipes are deep (up to 3 km) and comprise three zones: (1) the uppermost, often flared, crater zone containing a variety of volcaniclastic materials or CFK; (2) the intermediate, steep-sided, diatreme zone containing DFK, and (3) the lowermost, irregular, root zone characterized by HFK (see Hawthorne, 1975, p. 10). The crater zones of Class 1 pipes may be up to 680 m deep (e.g. Mwadui). All Class 1 pipes have well-developed diatreme zones characterized by walls with steep slopes of around 82° irrespective of the nature of the country rock (Hawthorne, 1975). The diatreme zone is unique to Class 1 pipes and is filled by typical diatreme-facies kimberlite as described by Clement (1982) and Clement and Skinner (1985). In this paper we present new petrographic evidence showing that Class 1 pipes also have distinct zones (tens of meters wide) of kimberlite, which are petrographically transitional between DFK and HFK and which, in most cases, occur at the interface between the two facies. The nature of this transitional-facies kimberlite (TFK) is remarkably similar in many Class 1 pipes.

In contrast, Class 2 pipes have shallow saucer-shaped craters <500 m in depth (refer to figure presenting an overview of the geology of Canadian kimberlites, in Hetman et al., this volume; Webb et al., this volume). Class 2 pipes are found in the Canadian Prairies, northeast Angola and Siberia (e.g. the Jubilee pipe). The crater-fill is dominated by PK and the pyroclastic juvenile lapilli or pyroclasts of Class 2 pipes are very different to juvenile magmaclasts of Class 1 and Class 3 pipes (see later discussion).

Class 3 pipes occur in Canada, Africa and Siberia and include many pipes in the Ekati cluster (Carlson et al., 1999; Nowicki et al., 2003) and other parts of Canada (Field and Scott Smith, 1999), the Jwaneng pipe in Botswana (Machin, 2000), several pipes in north-eastern Angola (including the 162 ha Camafuca Camazambo pipe) and the Sytikanskaya and Aichal pipes in Siberia. Most Class 3 pipes have steep-sided craters usually >500 m deep, although the Camafuca Camazambo pipe in Angola is shallower (see later discussion). The fill of Class 3 pipes is mainly RVK and lesser PK. Both of these rock types may contain angular magmaclasts that exhibit petrographic features that are typical of HFK (see later discussion).

4. Class 1 pipes

On the basis of petrography and location within the pipe, kimberlites have previously been classified into
HFK, DFK and CFK (Clement and Skinner, 1985) but there is little information on the details of the petrographic changes accompanying the transition from HFK to DFK. In the section below we review the petrographic features of HFK to DFK, with particular attention to the character of the transition zones between them.

4.1. Hypabyssal-facies kimberlites (HFK)

Clement and Skinner (1985) give concise petrographic descriptions of HFK, and these will not be repeated here other than to emphasize features, which are critical. By far the most abundant type of HFK is a uniformly textured, coherent, macrocrystic kimberlite whereas kimberlites with segregationary textures are relatively rare. The groundmass of most, if not all, HFKs contain variable but significant proportions (up to 50 modal %; Skinner and Clement, 1979) of calcite and antigorite. In uniformly textured kimberlites (e.g. Fig. 1) groundmass calcite and antigorite commonly occur as interlocking anhedral grains enclosing monticellite and apatite. Antigorite also occurs as relatively evenly distributed small, irregular masses enclosing euhedral calcite and apatite.

The petrographic evidence clearly supports the primary nature of the groundmass calcite, i.e. it has crystallized from residual kimberlitic liquid. However, the origin and significance of the associated antigorite is obscure and requires comment. Many kimberlites contain unaltered olivine macrocrysts in a groundmass that includes antigorite. In uniformly textured kimberlites (e.g. Fig. 1) groundmass calcite and antigorite commonly occur as interlocking anhedral grains enclosing monticellite and apatite. Antigorite also occurs as relatively evenly distributed small, irregular masses enclosing euhedral calcite and apatite.

The rare segregationary HFKs are characterized by globular and pelletal segregations consisting largely of earlier crystallized minerals including olivine, phlogopite, melilite, monticellite, opaque spinels and perovskite set in an inter-globular matrix of late crystallizing, minerals which include apatite, calcite and serpentine (see illustration in Clement, 1975, p. 53). These rocks were initially thought to be a type of DFK (Clement, 1975) but subsequent discovery of similar rocks in dykes and root zones indicates that they are a variety of HFK.

Country rock xenoliths, when present, are highly altered with extensive replacement by kimberlitic minerals and the term ‘kimberlitized’ could be used to describe this feature. Primary diopside is rare in HFK, except in some Group II kimberlites but secondary clinopyroxene may form in reaction haloes around silica-rich xenoliths in some Group I kimberlites.

In summary, most HF kimberlites have the following important features: Textures are uniform magmatic (coherent) and rarely segregationary. Unaltered olivine is not unusual and the groundmass contains abundant primary calcite and serpentine, which is regarded as a devitrification product of quenched kimberlitic glass. Primary diopside is absent or rare. Country rock xenoliths, when present, are always highly altered.

4.2. Diatreme-facies kimberlite (DFK)

Diatreme-facies kimberlite consists largely of magmaclastic kimberlite (Fig. 2) with variable proportions of country rock xenoliths giving rise to two main varieties; tuffisitic kimberlite (TK with <15% xenoliths) and tuffisitic kimberlite breccia (TKB with >15% xenoliths). Typical DFK is thus composed of a juvenile component, which includes serpentinized olivine and pelletal and globular magmaclasts, and a xenolithic component, which includes country rock xenoliths and xenocrysts derived from xenoliths. These are all set in a fine-grained matrix dominated by serpentine. The globular magmaclasts usually consist of more than two grains of serpentinized olivine set in a fine-grained groundmass of primary but usually altered monticellite, altered melilite, phlogopite, opaque minerals and perovskite set in a base of calcite and serpentine. The mineralogy and granularity of these globular magmaclasts is thus typical of normal HFK. In contrast, the pelletal magmaclasts commonly consist of individual serpentinized olivine grains with thin selvages of fine-grained material. This material is similar to that, which occurs as selvages around the larger globular magmaclasts and some altered xen-
Fig. 1. Venetia K1 pipe, NE complex, sample 204. Bar scale = 0.12 mm. An example of a hypabyssal-facies kimberlite showing zonally altered olivine macrocrysts and phenocrysts set in a groundmass of phlogopite (cleaved grains, e.g. bottom, left), smaller crystals of monticellite and opaque minerals (e.g. left) and irregular “pool-like” segregations of serpentine enclosing apatite (centre, right) and calcite crystals (e.g. bottom, centre).

Fig. 2. Ebenhaezer pipe, sample 34/K2/4. Bar scale = 0.27 mm. An example of a diatreme-facies, pelletal, tuffisitic kimberlite breccia containing relatively fresh country rock xenoliths (e.g. shale, centre, left), serpentinized olivine grains (e.g. bottom, right), globular and pelletal structures with kernels mainly of olivine surrounded by finer-grained primary constituents (e.g. altered melilite laths) and ultra-fine, dark material (mainly diopside) all set in a matrix of mainly serpentine.

Fig. 3. Finsch pipe, F8, sample 504. Bar scale = 0.05 mm. An example of a diatreme-facies kimberlite at high magnification showing pelletal structures cored by serpentinized olivine (e.g. top, left) or small globules (e.g. right, top and bottom). Note the small acicular laths of white diopside microlites associated with ultra-fine phlogopite in the selvages around the pellets and also in margins of altered olivine grains.
ololiths, and which is also scattered through the serpentine matrix of the rock. In relatively fresh DFK this fine-grained material can be optically resolved as microlites of diopside with an acicular habit (Fig. 3). It is interpreted as the product of quenching. In many cases the diopside microlites appear to have replaced primary minerals such as monticellite, phlogopite and, to a lesser extent, groundmass opaque minerals and perovskite. In contrast to HFK primary calcite is notably absent within the groundmass.

Country rock xenoliths are a significant constituent of DFK and it can be demonstrated that they are always derived from stratigraphic horizons surrounding or overlying the diatreme zone (Clement, 1982). Importantly, these xenoliths show little evidence of thermal or chemical alteration, which characterizes the country rock xenoliths within HFK. This suggests that they have been included in the DFK during formation of the diatreme system.

In summary, pelletal and globular magmaclasts, serpentinized olivine, a groundmass with serpentine, abundant microlitic diopside, but an absence of primary calcite characterize most relatively fresh DFKs. Country rock xenoliths are angular and relatively unaltered. Important differences compared to HFKs are in the degree of alteration of the xenoliths and olivine, the presence of diopside microlites and the absence of primary calcite.

4.3. Transitional-facies kimberlite (TFK)

Kimberlite that exhibits petrographic features transitional between HFK and DFK has been identified at a growing number of localities worldwide. In this paper these kimberlites are referred to as transitional-facies kimberlites (TFK). Transitions between other facies such as between DFK and CFK, if they exist, are not discussed here. In this study, the petrographic features characterizing TFK represent a synthesis of observations made on over 500 thin sections from many southern African kimberlites, plus several kimberlites in Angola and in West Africa (Skinner et al., 2003). TFK of this sort has now also been found in Canadian pipes (Hetman et al., 2003). TFK occurs in zones of up to tens of metres thick, spatially located between HFK and DFK in individual pipes. Within such zones the characteristics of the TFK grades continuously between two main end-member varieties; a hypabyssal type with features close to normal HFK and a diatreme type, which is similar to DFK. Specific petrographic features include the following:

(a) Olivine may be unaltered or partly altered in the hypabyssal type but is completely serpentinized in the diatreme type.
(b) Microlitic diopside is relatively rare and only patchily distributed in the hypabyssal type but is abundant and omnipresent in the diatreme type.
(c) Calcite may be present as a primary matrix constituent in the hypabyssal type, but is usually entirely absent in the diatreme type.
(d) Segregationary textures are rare in the hypabyssal type but are common in the diatreme type. Most hypabyssal types exhibit uniform magmatic textures whereas in the diatreme type the host kimberlite is typically magmaclastic with common pelletal magmaclasts (<2 mm) but rare globular magmaclasts (>2 mm).

The detailed spatial relationship of TFK to the HFK and DFK is variable as is illustrated in the descriptions of some South African examples of TFK presented below. These include occurrences at the Kamfersdam Mine pipe in Kimberley, the Premier Mine pipe near Pretoria and some of the Venetia Mine pipes near Messina.

4.3.1. Kamfersdam pipe

An excellent description of the kimberlite in the Kamfersdam pipe on the 225 m level is presented by Field and Scott Smith (1999, p. 216). This is probably the first account of TFK in the literature although its full significance was perhaps not recognized. At this mining level (Fig. 4), the pipe consists of an outer intrusion of HFK (petrographically similar to that shown in Fig. 1) that encloses or partly encloses two inner bodies of DFK (petrographically similar to those shown in Figs. 2 and 3). Zones of TFK (petrographically similar to those in Figs. 6 and 9) a few metres wide separate the DFK from the HFK (Fig. 4). Uniform magmatic textures, fresh olivine and small microscopic segregations of serpentine and calcite in the groundmass characterize the HFK. Other groundmass minerals include abundant monticellite,
rare phlogopite, opaque spinels and perovskite. The following marks the gradual progression from uniform HFK through TFK to DFK:

(a) the appearance of globular and pelletal magma-clasts set in a base of primary calcite and serpentine and the steady increase in the abundance of magma-clasts and decrease in groundmass calcite as the DFK is approached;
(b) the appearance and steady increase in microlitic diopside from the HFK to the DFK.

The DFK is characterized by the presence of abundant pelletal and less abundant globular magma-clasts, by the altered nature of the olivine, by the absence of primary calcite, and by the relative abundance of unaltered xenoliths of shale, mudstone and dolerite. This xenolith suite contrasts with the few altered xenoliths in the HFK and TFK.

We regard the transitional sequence HFK-TFK-DFK with diffuse contacts to reflect progressive textural and mineralogical modification within a single pulse of kimberlitic magma during its emplacement.

4.3.2. Premier pipe

Information presented here is derived from samples taken in underground workings of the mine from near surface down to the 730 m level and also from borehole cores drilled to depths of >400 m from collar locations on the 730 m level. The Premier pipe consists of two large intrusions of DFK known as the Brown and Grey kimberlite (Bartlett, 1998). In the western part of the pipe, a complex of at least four different kimberlites intrudes the Grey kimberlite. These include the Black, Pale Piebald and Dark Piebald kimberlites as well as late-stage, calcite kimberlite dykes. The Black kimberlite consists of at least three different facies, namely DFK, TFK and HFK. The progressive changes in the TFK from hypabyssal to diatreme types, with all the petrographic features described above from Kamfersdam, are present. All three facies occur over a vertical extent of >1 km within this single intrusive body of kimberlite, indicating that, at least in this pipe, the transition from HKF or from root zone to DFK is not horizontal as depicted in the model of a Class 1 kimberlite pipe (Hawthorne, 1975). The simple
Fig. 5. Premier pipe, Black kimberlite-hypabyssal-facies, sample 1323. Bar scale = 0.05 mm. Serpentinized olivine phenocrysts are set in a groundmass of finer-grained abundant serpentinized monticellite, rare phlogopite, opaque minerals, perovskite and serpentine.

Fig. 6. Premier pipe, Black kimberlite-transitional-facies, sample 1320. Bar scale = 0.12 mm. This rock is characterized by pelletal or orbicular structures of inwardly pointing diopside with cores of serpentine (e.g. left), but patches of almost normal kimberlite occur where groundmass opaque minerals are evenly distributed (e.g. bottom, right).

Fig. 7. Premier pipe, Black kimberlite-diatreme-facies, sample 1336. Bar scale = 0.27 mm. This rock is characterized by smaller pelletal structures consisting of altered olivine with thin selvages of grey, very fine diopside and larger kimberlite globules (e.g. bottom, left, which has a groundmass replaced by fine grey diopside). Also present are country rock xenoliths and xenocrysts (e.g. bottom, right). Larger components are all set in a base of serpentine.
upward change from HFK through TFK into DFK as indicated by Hetman et al. (2003) does not occur in this case. Below the 730 m level a single drill core has passed in some cases from HFK, through TFK into DFK and then back into TFK and HFK and so on. Photomicrographs of the three different facies of the Black kimberlite are presented in Figs. 5–7. The Pale Piebald and calcite kimberlite dykes are exclusively HFK, whereas the Dark Piebald kimberlite consists of zones of both HFK and TFK with no DFK being present. From the mine workings and the drill core evidence, it is apparent that the Dark Piebald kimberlite is vertically continuous as a relatively thin column over a depth of more than 1 km. This kimberlite is interpreted to represent kimberlite magma that developed towards DFK by forming areas of TFK but for some reason, possibly due to insufficient volatile exsolution, failed to develop further into DFK (see later discussion).

4.3.3. Venetia pipes

The Venetia cluster consists of six main kimberlite pipes (Seggie et al., 1999). A plan view of the internal geology of K1, the largest of these pipes, is presented in Fig. 8. The following data are derived from the petrographic study of isolated samples of borehole core drilled into K1 from near surface (but relative depths from surface within the pipe are not clearly understood). Close to surface the pipe is dominated by two phases of DFK (similar to Fig. 3), each of which enclose large “floating reefs” of bedded CFK. Small bodies of typical HFK (e.g. Fig. 1) are also present. Two zones of TFK, occurring between the HFK and DFK, are present in the western and northeastern parts of the pipe, and one zone of TFK occurs in the southeast corner adjacent to DFK but apparently without associated HFK. In the first two localities the TFK resembles that at Kamfersdam, where a progressive petrographic gradation from hypabyssal-to diatreme-type occurs. A photomicrograph of the western occurrence of TFK is presented in Fig. 9. This is a typical hypabyssal-type TFK characterized by a patchy distribution of microlitic diopside. The TFK in the southeast corner of K1 is of diatreme-type. Large masses of TFK also occur in the Venetia K2, Venetia K3 (as a core within surrounding DFK) and Venetia K4 pipes.

4.4. Crater-facies kimberlite (CFK)

In this study we have investigated samples of CFK from Orapa in Botswana, Mwadui in Tanzania (the two best-preserved and exposed Class 1 CFKs) as well as two occurrences in Angola. In these Class 1 pipes, CFKs include a large variety of rock types.
(e.g. Field et al., 1997; Stiefenhofer and Farrow, 2003). These range from proximal-facies kimberlite grits and finer-grained, distal-facies kimberlite sandstones and shales (which are clearly RVKs) to fine-grained turbidite deposits (mainly of externally derived quartz, with little Kimberlitic material). Also present are debris-avalanche-collapse breccias (which are not obviously RVKs) ranging from coarse-grained, Kimberlite-poor, country rock-rich breccias to finer-grained, Kimberlite-rich, grain-flow deposits, both created by downward slumping of tuff-ring material and inward collapse of sidewall material.

Crater-facies PKs include well-bedded, normally graded and reversibly graded ash and lapilli tuffs, poorly bedded ash and lapilli tuffs as well as very coarse-grained heterolithic breccias (e.g. Field et al., 1997). Relatively coarse-grained, proximal-facies RVKs are characterized by altered olivine macrocrysts, country rock xenoliths, and xenocrysts, and rare magmatic sets in a matrix of mud. Variable proportions of externally derived quartz grains may also be present. In abraded examples, olivine macrocrysts are rounded and less abundant and magmatic sets are extremely rare. Relatively coarse-grained PKs tend to contain similar larger-sized constituents as the proximal RVKs but juvenile material (including olivine and magmatic sets) tend to be more abundant and the matrices tend to be dominated by a matrix of serpentine. In many of the RVKs, the Kimberlitic components may be extensively abraded but in some RVKs and in many PKs, petrographic features that are similar to the underlying DFK occur. These Kimberlites contain magmatic sets that are commonly small (<2 mm), have pelletal shapes, and contain olivine that is in all cases altered. Also present are relicts of microlitic diopside, but primary calcite is absent. In addition, the grain sizes of the primary finer-grained matrix minerals within larger sized magmatic sets, when not replaced by microlitic diopside, are similar to grain sizes of those in typical HFKs.

5. Class 2 pipes

Class 2 Pipes are predominantly characterized by CFK. In this study we have investigated samples from Jubilee (Siberia) and several Angolan kimberlites. Included in these samples are possible lavas from two pipes in northeast Angola as well as pyroclastic and resedimented volcaniclastic rocks. PK dominates the CFK in Class 2 pipes. Regardless of location, the PKs contain magmatic sets that are of lapilli size, may be amoeboid in shape, contain olivine that is often relatively unaltered, are typically calcite-rich and contain vesicles that are commonly calcite-filled. Microlitic diopside is noticeably absent from these lapilli and grain sizes of the finer-grained primary matrix minerals may be very small (indicative of rapid crystallization) and glass may be present. These features indicate that the magmatic sets are pyroclastic juvenile lapilli.

The two examples of possible Kimberlite lava mentioned above may be, to our knowledge, the first account of Kimberlite lavas and are thus worthy of further description. The two examples occur at localities known as 86X154 and 121X007. As determined by core drilling, at both these localities Kimberlite with petrographic features of typical HFK overlies PK, and at 86X154 the PK in turn overlies RVK. In both cases the Kimberlites with hypabyssal-facies character have been interpreted as lavas because of their positions relative to other Kimberlite rock types. At 86X154 the possible lava is a poorly-macrocrystic, spinel-rich (grains up to >0.15 mm in size), monticellite Kimberlite, altered by secondary carbonate minerals. It is located at a depth of 124 m below younger cover rocks. The underlying PK is magmaclastic with pyroclastic pelletal lapilli; it is vaguely bedded and poorly sorted. The lapilli are irregular to round, some are amoeboid and some contain rare calcite-filled vesicles. The last two petrographic features are characteristic of PK found in Class 2 pipes. Associated possible RVK material at this site contains, in addition to abundant magmaclasts, small (<0.5 mm) rounded quartz and feldspar grains which form between 10 and 40 vol.% of the rock. At locality 121X007 the possible lava underlies younger cover rocks at a depth of 12–15 m. It is a macrocrystic kimberlite containing a few altered country rock xenoliths. The fine-grained matrix is heavily altered to carbonate and apart from euhedral opaque minerals in the groundmass no other primary minerals can be identified. Below 15–19 m depth the HFK is underlain by PK, which varies from fine
Fig. 9. Venetia K1 pipe, Western complex, sample 140. Bar scale = 0.27 mm. An example of a moderately metasomatized transitional-facies kimberlite showing kimberlite with evenly distributed opaque minerals in the groundmass (left) and a patch of kimberlite where the matrix is extensively replaced by microlitic diopside (right).

Fig. 10. Camafuca Camazambo pipe, Lobe 5, crater-facies. Bar scale = 0.27 mm. An example of resedimented volcanlastic kimberlite from a Class 3 pipe showing subrounded to angular altered dark olivine macrocrysts (e.g. centre), rounded xenoliths and xenocrysts mainly of quartz and feldspar, rare fragments of hypabyssal-facies kimberlite (centre, right) all set in a matrix of clay.

Fig. 11. Camafuca Camazambo pipe, Lobe 2, crater-facies. Bar scale = 0.27 mm. An example of pyroclastic kimberlite from a Class 3 pipe showing relatively abundant serpentinized olivine macrocrysts and phenocrysts, angular magmaclasts of hypabyssal-facies kimberlite (e.g. right), rare xenoliths and xenocrysts (e.g. garnet, left) set in a matrix of serpentine.
magmatic ash tuff (magmaclasts < 2 mm) to very coarse magmatic tuffs (magmaclasts up to >10 cm). The smaller magmaclasts have a shape, which ranges from spherical to amoeboid whereas the larger magmaclasts are angular and probably represent broken fragments of HFK. Welding of magmaclasts is apparent and some contain relatively abundant calcite-filled vesicles. These petrographic features are consistent with PK from Class 2 pipes. In the light of these discoveries, it is suggested that other HFKs found at shallow level with crater facies rocks at other Class 2 pipes may also be lavas (e.g. at Victor, Webb et al., 2003).

6. Class 3 pipes

Crater-facies kimberlite in Class 3 pipes is dominated by RVK varieties but PKs may also be abundant. In this study we have investigated samples from Jwaneng, Botswana, several Angolan kimberlites including Camafuca Camazambo, and the Sytskanskaya and Aichal pipes in Siberia. The proximal RVKs (i.e. those that are hydraulically slumped, such as those at Jwaneng, Machin, 2000) consist of olivine macrocrysts, magmaclasts and country rock xenoliths and xenocrysts, all set in a matrix of mud. Distal RVKs (e.g. as at Camafuca Camazambo, Fig. 10) have fewer olivine macrocrysts and rare magmaclasts. Country rock xenoliths and xenocrysts are commonly abraded. Many of the PKs at these different localities are petrographically similar to the Jwaneng RVKs except for the presence of abundant matrix serpentine (Fig. 11). Magmaclasts in the PKs and the Jwaneng RVKs are frequently broken and vary in size from ash to lapilli. In these magmaclasts olivine is characteristically altered and groundmass calcite is common. Grain sizes of the finer-grained primary matrix minerals (which may be relatively unaltered) are similar to the grain size of typical HFKs. Most of the Ekati cluster kimberlites described by Nowicki et al. (2003) contain so-called MRVK (mud-rich RVK), so-called OVK (olivine-rich volcaniclastic kimberlite, which we believe is probably also RVK) and so-called PVK (primary volcaniclastic kimberlite, which we believe is probably PK) at depth. Some minor intermixing of RVK and PK is apparent at the boundary between RVK and PK but none of these descriptions contradict our findings. In contrast, the Fox kimberlite (which is part of the Ekati cluster) is clearly a Class 1 kimberlite.

7. Discussion

The main aspects arising from the descriptions presented above can be summarized as follows:

(a) We confirm the existence of the three classes of kimberlite pipe as suggested by Field and Scott Smith (1999).
(b) We describe further examples of these classes and expand on the criteria, particularly petrographic criteria, for the recognition of each pipe class.
(c) We describe the occurrence of a newly recognized transitional-facies kimberlite (TFK) between the diatreme-facies and hypabyssal-facies in the Class 1 kimberlite pipes that are so common in southern Africa but which also occur elsewhere in the world.
(d) The TFK shows systematic gradational variations in texture and mineralogy from HFK through to DFK and its gradational nature implies that diatremefacies kimberlite is a textural and mineralogical modification of an intruding hypabyssal-facies kimberlite.
(e) The petrographic characteristics of the CFK in each of the three classes of pipe are very different and confirm proposals that they result from different emplacement processes.

This section discusses these features and explores the implications for the emplacement of the different classes of pipe.

7.1. The transition from hypabyssal to diatreme-facies kimberlite

Detailed observations of the contact between the DFK and HFK indicate that it is not sharp but is characterized by a zone of gradational transition in texture and mineralogy over several metres. Specifically the coherent magmatic textures of the HFK are replaced by that indicative of magma disruption and
there is a concomitant mineralogical change in which calcite and monticellite disappears at the expense of diopside and extensive serpentinization of olivine macrocrysts occurs.

The mineralogy of the HFK and DFK and the mineralogical transitions evident in the TFK can be summarized as follows:

**Hypabyssal-facies kimberlite:**

olivine + phlogopite + monticellite + calcite

+ antigorite + spinel + perovskite + apatite

phenocrysts

groundmass

**Diatreme-facies kimberlite:**

olivine + phlogopite + diopside + antigorite

phenocrysts

groundmass

Leaving aside the minor amounts of groundmass apatite, spinel and perovskite, this mineralogical transition from HFK to DFK can be expressed by the following reaction:

\[
2 \text{CaMgSiO}_4 + \text{CaCO}_3 + \text{MgO} + 4 \text{SiO}_2 = 3 \text{CaMgSi}_2\text{O}_6 + \text{CO}_2
\]

Monticellite  CaCO\(_3\)  MgO  4SiO\(_2\)  Diopside  CO\(_2\)

= Liquid  Gas

Alternatively if we include serpentine (antigorite) which occurs in both facies, the reaction is:

\[
\text{CaMgSiO}_4 + \text{CaCO}_3 + \text{Mg}_{48}\text{Si}_{34}\text{O}_{85}(\text{OH})_{62} + 2.32\text{SiO}_2 + 0.02\text{O}_2 = 2 \text{CaMgSi}_2\text{O}_6 + 0.98\text{Mg}_{48}\text{Si}_{34}\text{O}_{85}(\text{OH})_{62} + \text{CO}_2 + 0.62\text{H}_2\text{O}
\]

Monticellite  CaCO\(_3\)  Mg\(_{48}\)Si\(_{34}\)O\(_{85}\)(OH)\(_{62}\)  Liquid  Gas

= Diopside  Antigorite  CO\(_2\)  H\(_2\)O

These equations demonstrate that in a kimberlite magma with dissolved CO\(_2\)–H\(_2\)O, the exsolution of a CO\(_2\)-rich gas phase will favour the crystallization of a diopside-bearing assemblage. Although experimental data are unavailable for volatile-rich Si-undersaturated magmas like kimberlite, existing data indicate the following trends. Solubility of H\(_2\)O in the melt decreases but solubility of CO\(_2\) increases with decreasing SiO\(_2\), and the relative solubilities determine the partitioning of H\(_2\)O and CO\(_2\) into the vapour phase during volatile exsolution. In tholeiitic melts CO\(_2\) is very strongly fractionated into the vapour phase relative to water and this effect persists into Si-poor compositions such as nephelinite, although the CO\(_2\)–H\(_2\)O fractionation factor is much lower and also decreases with increasing pressure (Dixon, 1997). It seems very likely that vapour phase exsolution from kimberlite will fractionate CO\(_2\) preferentially into the vapour, driving the reaction above to the right to favour stabilization of the diopside + antigorite assemblage.

The mineralogical transitions are accompanied by textural changes, specifically the formation of incipient magmaclastic textures with globular clasts comprising an assemblage of silicate minerals in a volatile-rich matrix of calcite and antigorite. In the hypabyssal types of TFK, rocks with incipient magmaclastic textures may be difficult to distinguish from segregationary HFK. It is possible that an immiscibility process that leads to segregationary HFK (Clement, 1975) may result in volatile concentrations in one of the liquid phases to the extent that volatile exsolution is initiated leading in turn to the development of TFK. Due to the unusually high volatile content of the kimberlitic magma exsolution does not produce the characteristic vesiculation textures (i.e. gas bubbles enclosed in a continuum of silicate liquid) of common volatile-poor magmas. Rather, the silicate magma becomes substantially fragmented in a manner, which is the antithesis of normal magma vesiculation. It should be noted that vesicles are extremely rare in magmaclasts from Class 1 and Class 3 pipes, but are a particularly common feature of magmaclasts in Class 2 pipes.

Thus the proposal that the exsolution of CO\(_2\)-rich volatiles results in the mineralogical changes noted in the HFK-TFK-DFK transition is consistent with the observed textural evidence for increasing volatile-induced fragmentation of the magma across this transition. Volatile-exsolution is initiated in the hypabyssal environment by decompression and crystallization (first and second boiling—see Burnham, 1985;
Cas and Wright, 1987) but probably becomes catastrophic once the surface is breached resulting in explosive eruption and the formation of DFK. This is discussed in detail below.

7.2. Formation of diatreme-facies kimberlite

From the discussion presented above there is strong evidence for the formation of DFK from HFK by magmatic exsolution of juvenile volatiles by both first and second boiling as the kimberlite rises to within 3 km of the surface. Unfortunately, the complete lack of data relating to volatile contents and solubilities in kimberlite magma hampers detailed evaluation of the process. We propose that the initial exsolution of volatiles results in hydraulic fracturing of the surrounding rocks at depth (i.e. between 3 and 2 km), initially to form contact breccias (see Section 7.3 below). But at shallower levels (i.e. from 2 km) the mechanical energy released by volatile exsolution can cause cracking through to surface. Once the surface is breached major decompression, increased exsolution, expansion, adiabatic cooling and explosive eruption occurs.

Evidence from several southern African Kimberlites, some of which have been eroded by as much as 1.4 km (Hawthorne, 1975), indicates that diatreme zones may be initiated at depths of about 2 km below the original surface. This corresponds to a lithostatic pressure of the order of 600 bars. The presence within the DFK of unaltered country rock xenolithic material, and the presence of inter-clast groundmass serpentine suggests that formation of the DFK is accompanied by a rapid drop in temperature from about 1150 °C (the probable temperature of kimberlite magma) to <250 °C (the crystallization temperature of serpentine). We suggest that exsolution and rapid expansion of gasses, once the surface is breached, contribute significantly to this cooling.

Volatile exsolution can generate enormous amounts of energy particularly if it occurs within a small time frame over a significant depth interval within the kimberlite magma column. Evidence from the occurrence of DFK in the Kimberley mines indicates that this interval lies between the base of the crater (at around 700 m) to at least 2 km below the original surface (Hawthorne, 1975; Clement, 1982). Moreover, the emplacement of Class 1 pipes is interpreted to involve only a few separate large explosive eruptions. This is indicated by the presence of only a few large bodies of DFK in any one pipe (Clement, 1982; Clement and Reid, 1989) and by the fact that the geology of the crater-facies kimberlites of Class 1 pipes is relatively simple. This consists mainly of undisturbed RVK overlying undisturbed PK (e.g. at Mwadui; Stiefenhofer and Farrow, 2003) produced by one pipe-forming event.

Phreatomagmatism is the other main cause of volcanic eruptions and is thus a potential process in the emplacement of DFK (e.g. Lorenz, 2000). In the case of a possible phreatomagmatic kimberlite system, kimberlite magma must rise to levels shallower than about 700 m below the surface, the depth in a normal lithostatic setting above which water becomes subcritical. Groundwater must be available such that the hot kimberlite magma mixes with the water. If low energy shock waves pass through the magma-water premix, the vapour film that has formed around the magma can collapse quasi-coherently (Wohletz and Zimanowski, 2000), resulting in a phase and attendant volume increase. Any cracking through to the surface would be followed by a dramatic expansion driven explosion. The amount of energy generated at each explosion would be limited by the extent of the interface between water and magma. However, very many explosions are likely, as new magma would come into contact with new water. Compared with magmatic explosions, phreatomagmatic explosions are likely to be much smaller but they would be considerably more numerous and the total energy generated could be similar.

We suggest that phreatomagmatism is unlikely to generate Class 1 pipes because this process cannot explain the petrographic and mineralogical differences of the different kimberlite facies in these pipes. Available evidence (e.g. Clement, 1982; Clement and Reid, 1989) also places the initial formation of these rocks, prior to breakthrough to surface, at depths where water is supercritical prohibiting the initiation of phreatomagmatic explosions. Finally, we believe that the consistent geological and petrographic character of Class 1 pipes, regardless of age and geological setting, is compelling evidence for their emplacement relying on a process intrinsic to the kimberlite magma itself, rather than on a process requiring the chance encounter of magma with some external feature such as abundant groundwater.
Explosions induced by magmatic volatile exsolution will be diminished or possibly even excluded if volatile saturation is delayed because juvenile water is locked-up in high-temperature, early-crystallizing, water-bearing minerals, like phlogopite. Or if crystallization (which leads to second boiling) is inhibited by the presence of relatively high proportions of dissolved CO₂ (see later discussion). In such cases relatively hot kimberlite magma could rise to shallow levels where meteoric water is abundant. Under such conditions phreatomagmatism is likely and may play a role in the emplacement of Class 2 pipes.

7.4. Crater zones of classes 1, 2 and 3 pipes

Individual craters of all the pipe classes appear to be formed by only a few and perhaps only one large explosion. This exhausts all cap-rock leaving a large hole in the ground, as at the Class 1 Mwadui pipe (e.g. Stieffenhofer and Farrow, 2003), the Class 2 Victor pipe (Webb et al., 2003) and the Class 3 Ekati pipes (Nowicki et al., 2003). In the case of craters of Class 1 pipes, the original pipe shape with walls inclined at 82° tends to be modified by later collapse, as has occurred at Orapa (Field et al., 1997) and Mwadui (Stieffenhofer and Farrow, 2003). In the case of Class 2 pipes, many have relatively shallow, saucer-shaped craters (such as at Fort a la Corne), and Field and Scott Smith (1999) propose that their formation was influenced by country rock conditions at the time of emplacement. However, some Class 2 pipes are deeper and steeper as is the case at Victor (Webb et al., 2003). In the case of Class 3 pipes, Field and Scott Smith (1999) describe the Ekati pipes and the Jwaneng pipe as having deep, steep-sided craters, but the Camafuca Camazambo pipe in Angola, interpreted as a Class 3 pipe in this study, has crater walls sloping at <45°. In all cases we follow Rice (1999) in maintaining that the shape of the initial crater is more a function of depth of explosion rather than kimberlite type or the nature of the local geology.

8. Eruption mechanisms

8.1. Class 1 pipes

It is envisaged that within a Class 1-pipe complex, an individual pipe-forming event is an essentially magmatic process involving volatile exsolution through first and second boiling. This process leads initially to the formation of in situ TFK and later to redistributed DFK, which is generated in a large explosion. This explosion is initiated from about 700 m below the original surface and is instantaneously propagated downwards through the magma column to depths of just over 2 km. The three-dimensional shape of the diatreme-zone, a cone with a slope angle of approximately 82°, is similar to the shape of deep explosive vents produced by man-made explosions (Rice, 1999). The shape is consistent with
a single explosive event rather than the multiple-staged downward reworking postulated by Clement (1982). The initial large subsurface explosion probably generates potent shock waves, which rebound from the surface and create explosive spalling of cap-rock material. Much of this cap-rock is exhausted from the vent as shown by the relative scarcity of this material in many DFKs, but in other cases downward sinking of some large cap-rock fragments into the DFK does occur to produce the so-called “floating reef” structures (Clement, 1982). An upward rush of expanding kimberlite gases and solid components follows. Within the vent accelerated mixing of the gases and mainly solidified pelletal kimberlitic components creates the ideal conditions for the generation of a fluidized system (McCallum, 1985). Convective overturning (spouting) of the fluidized system occurs in order to produce the homogeneity seen in the diatreme-facies rocks. At initially high gas velocities kimberlite is erupted from the vent, a deep crater is produced and fallback kimberlite is deposited around and within the crater. The eruption process is very rapid and the elapsed time from initial explosion to final settling of the fluidized system is relatively short (minutes rather than hours).

8.2. Class 2 and 3 pipes

Insufficient information is available to provide detailed proposals relating to the likely eruption mechanisms in Class 2 and 3 pipes, but some factors can be discussed here. In Class 2 and 3 pipes, where zones filled by typical DFK do not exist, the petrographic features of the CFK are thought to relate not only to eruption and depositional processes, but also to differences in kimberlite composition, particularly the volatile content. Differences in the CO$_2$/H$_2$O ratio of the fluid phase will influence the nature of the kimberlite solidus provided this influence is similar to that summarized for peridotite by Wyllie (1987). The solidus of water-rich peridotite magma has a pronounced negative PT slope, which steepens and becomes positive with increasing CO$_2$/H$_2$O of the fluid phase (Fig. 12). Thus wet kimberlite magma is likely to behave differently to carbonatitic kimberlite magma as it approaches the surface. Specifically, water-rich kimberlite is likely to crystallize at depth and will not rise to the surface unless it undergoes explosive emplacement. Both Class 1 and Class 3 pipes contain kimberlite that is water-rich. Alternatively CO$_2$-rich kimberlite magmas or those rendered water-poor by phlogopite crystallization may approach the surface as hot magma. This appears to be the case with respect to Class 2 kimberlites.

The ability of hot kimberlite magma to rise to very shallow levels increases the likelihood of the magma encountering ground water and consequent phreatomagmatic activity. As discussed by Field and Scott Smith (1999) crater excavation of Class 2 pipes is probably caused by phreatomagmatic explosions with pyroclastic sequences filling the craters being deposited by magmatic eruption processes such as fire fountaining. This is consistent with the petrography of PKs of Class 2 pipes (discussed earlier) which provides evidence for the presence of hot kimberlite magma at or close to surface.

Regarding Class 3 pipes, Machin (2000) proposes that mainly magmatic processes have generated the Jwaneng craters, but as discussed earlier Class 3 pipes do not contain DFK and thus they obviously have not undergone the same magmatic processes as Class 1 pipes. It is possible that specific compositional differences from Class 1 pipe kimberlites may have

![Fig. 12. Solidus surfaces for peridotite-H$_2$O and peridotite-CO$_2$ (X$_{\text{H}_2\text{O}}$=1.0 and X$_{\text{CO}_2}$=0.6) after Wyllie (1987). Hypothetical cooling curves ab and cd at similar cooling rates intersect the respective solidi at pressures S$_1$ and S$_2$.](image)
inhibited the volatile exsolution process. In respect of Class 3 pipes, much of the crater fill, including some RVKs (e.g. at Jwaneng) and most PKs (e.g. at Camafuca Camazambo, Fig. 11), is characterized by the presence of relatively large irregular magmaticlasts which differ petrographically from those of other pipe classes. These magmaticlasts are virtually identical to typical HFK and they are interpreted as broken fragments of earlier crystallized kimberlite. Such kimberlite must have crystallized at depth, and this kimberlite may have in some way contributed to the emplacement as explosive pipes of later kimberlite. The earlier crystallized kimberlite may itself have formed an effective lithological barrier and gas trap to later upwelling volatile-rich kimberlite magma. An entrapped body of gas may have grown to a point where explosive eruption occurred. Exactly what happened is uncertain but the evidence of the characteristic CFK clearly indicates that earlier crystallized kimberlite was fragmented and incorporated in the crater infill.

9. Conclusion

Kimberlite pipes can be classified into three pipe classes. Eruption processes that create these three pipe classes must be different. Only Class 1 pipes contain DFK as well as the newly recognized TFK, which has petrographic and mineralogical features that are intermediate and gradational between HFK and DFK. In all cases where HFK is found in association with DFK, transition-facies kimberlite occurs at the interface between the two. TFK represents a kimberlite magma in which volatile exsolution was initiated as a consequence of decompression and crystallization-induced exsolution. DFKs are interpreted to form as a consequence of the same processes but after the surface is breached resulting in explosive eruption. In the rare instances where TFK has been found on its own without DFK this may represent a situation where volatile exsolution was initiated but cracking through to the surface did not occur and the diatreme-forming process was terminated without explosive eruption. Thus TFK and DFK are formed by the textural and compositional modification of the HFK magma during emplacement at depths reaching to approximately 2 km below the original surface. Importantly, these two facies types have formed in situ and do not represent kimberlitic material formed elsewhere and transported to their present locations by re-sedimentation processes.

Contrary to conclusions reached by Field and Scott Smith (1999), there are instances where the three different classes of pipe are found in the same geological setting, examples being in NE Angola and in Siberia. Similarly at Ekati, both Class 3 and Class 1 pipes are present, e.g. the Fox pipe (Carlson et al., 1999), and some of the minor pipes at Misery. Petrography shows that the crater-facies rock types in the different classes of pipes are distinctly different. This points to an emplacement style influenced by compositional (volatile) differences, particularly in the case of Class 2 pipes, rather than geological setting.

The slope of the solidus for hydrous kimberlites will result in crystallization of the kimberlite magma at depth, and in the case of Class 1 and possibly Class 3 pipes, kimberlite reaches the surface only as a function of explosive eruption. However, in some cases, kimberlite does reach the surface as hot magma as is evidenced by the occurrence of possible kimberlite lavas associated with some Class 2 pipes. The occurrence of relatively hot magma at surface is due to the high CO₂/H₂O of the dissolved volatile phase in the kimberlite magma. The presence of hot magma near to the surface may have resulted in phreatomagmatic explosive eruption and crater formation but the massive nature of the crater infill deposits suggests that subsequent magmatic eruption also occurs.

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