Contrasting Geology and Near-Surface Emplacement of Kimberlite Pipes in Southern Africa and Canada

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ABSTRACT

Recent discoveries in Canada have highlighted the fact that not all kimberlite pipes conform to published models. This has prompted the re-evaluation of kimberlite pipe models and emplacement mechanisms and, to this end, the geology of many occurrences in southern Africa and Canada is reviewed. It is shown that kimberlites in different areas have contrasting pipe shapes and internal geology. At least three types of pipes have been identified: (i) deep, steep-sided pipes which comprise three distinctive zones (crater, diatreme, root) that are infilled by different textural types of kimberlite (extrusive volcaniclastic kimberlite, tuffisitic kimberlite breccia and hypabyssal kimberlite, respectively), (ii) shallow pipes which comprise only the crater zone and are infilled exclusively with volcaniclastic kimberlite (mainly pyroclastic), and (iii) small, steep-sided pipes infilled predominantly with volcaniclastic kimberlite that includes abundant resedimented material or, in less common instances, hypabyssal kimberlite. Different emplacement mechanisms must have been responsible for the formation of the contrasting types of pipes. There is a correlation between the type of pipe and the nature of the country rocks into which they were emplaced. The geological settings for the three types of pipes are: (i) competent country rocks which commonly contain igneous rocks, (ii) poorly consolidated sediments, and (iii) basement covered by a veneer of poorly consolidated sediments. This correlation suggests that the near-surface geological setting is a major factor in determining the emplacement process of each kimberlite. Different emplacement mechanisms are proposed that take into account the combination of pipe variety and geological setting, namely: (i) intrusive-extrusive magmatic eruptions from closed systems in which competent country rock barriers result in the sub-surface build up of juvenile volatiles, (ii) phreatomagmatic crater-forming eruptions relating to aquifers in poorly consolidated sediments and subsequent infilling by magmatic eruptions or resedimentation, and (iii) a third mechanism which does not conform to either of the other two processes, but is still poorly constrained.

Keywords: kimberlite, volcanology, diatreme, magmatic, fluidisation, phreatomagmatism, pyroclastic

1. INTRODUCTION

Understanding of the complex geology of kimberlite has increased substantially during the last two decades as a result of detailed studies undertaken on the extensive exposures created during mining and exploration activities. Kimberlites differ from many other volcanic rocks in that no extrusive magmatic rocks or plutonic equivalents have yet been found and there is no evidence for magma reservoirs, calderas or ring faulting. Unique styles of emplacement have been postulated for kimberlites occurring mainly in southern Africa (e.g. Clement, 1979, 1982; Clement and Skinner, 1979, 1985; Clement and Reid, 1989), which differ from most standard volcanic processes (e.g. Fisher and Schmincke, 1984; Cas and Wright, 1987; McPhie *et al.*, 1993).

In the last decade or two numerous new kimberlite pipes have been discovered in Canada and many of these do not conform to the pipe models or emplacement processes developed for the southern African occurrences. In this paper the geology of many individual pipes in southern Africa and Canada are reviewed. A great deal of this information has not previously been published (see Acknowledgements) and much, but not all, of the descriptions of the kimberlite geology were undertaken by the authors, Field and Scott Smith. Based on the review, it is proposed that (1) kimberlites in different areas have contrasting pipe shapes and internal geology, (2) different emplacement mechanisms must have been responsible for the formation of the contrasting pipes and (3) the near-surface geological setting is a major factor in determining the emplacement process of each kimberlite.

2. TERMINOLOGY

Kimberlites show significant differences from other volcanic rocks. The terms used to describe both the different zones within pipes and the contrasting textural varieties are commonly used in a kimberlite-specific sense and, therefore, require definition.

With respect to the shapes of kimberlite occurrences, the term "pipe" is used here in a non-genetic sense to describe a body that is not tabular or sheet-like in shape. The terms "crater", "diatreme" and "root" are used to describe the distinctive zones of kimberlite pipes, as originally proposed by Clement and Skinner (1979, 1985) and revised by Field and Scott Smith (1998). The term "diatreme" is only used if the pipe can be shown to have formed by fluidisation processes as indicated by the specific pipe shape together with the presence of the textural rock type referred to as tuffisitic kimberlite breccia (TKB). The term "kimberlite diatreme" thus becomes a very specific term, and is not used in a more general sense to describe any kimberlite body.

The terms used to describe the different types of pipe infill or textural varieties of kimberlites are summarised below (from Field and Scott Smith, 1998).

VK – Volcaniclastic Kimberlite describes extrusively formed fragmental kimberlite deposits for which the mode of deposition is not known.

RVK – Resedimented Volcaniclastic Kimberlite describes VK for which depositional mechanisms can be recognised and ascribed to "normal" sedimentary processes.

PK – Pyroclastic Kimberlite describes VK for which *prima facie* evidence shows direct deposition by explosive volcanic processes.

TKB (or TK) – Tuffisitic Kimberlite Breccia (or Tuffisitic Kimberlite) describes the typical intrusive infilling of the diatreme-zone. The terms are used as originally described by Clement and Skinner (1979, 1985), and have a very specific meaning. This rock type is typically composed of mixed country rock xenoliths and pelletal lapilli set in a fine-grained inter-clast matrix. It should be noted that the detailed nature of the lapilli and matrix is a vital feature of this rock type. For example, pelletal lapilli are not merely round juvenile lapilli. This type of kimberlite is described in more detail in section 3.1(a).

HK – Hypabyssal Kimberlite describes the intrusive "igneous" rock formed by crystallisation of a kimberlite magma which was not violently disrupted by fluidisation or pyroclastic eruption mechanisms. Most HKs are macroscopically uniform but in certain circumstances, usually when the magma is particularly volatile-rich, a globular segregationary texture can form. This type of kimberlite is described in more detail in section 3.1(a).

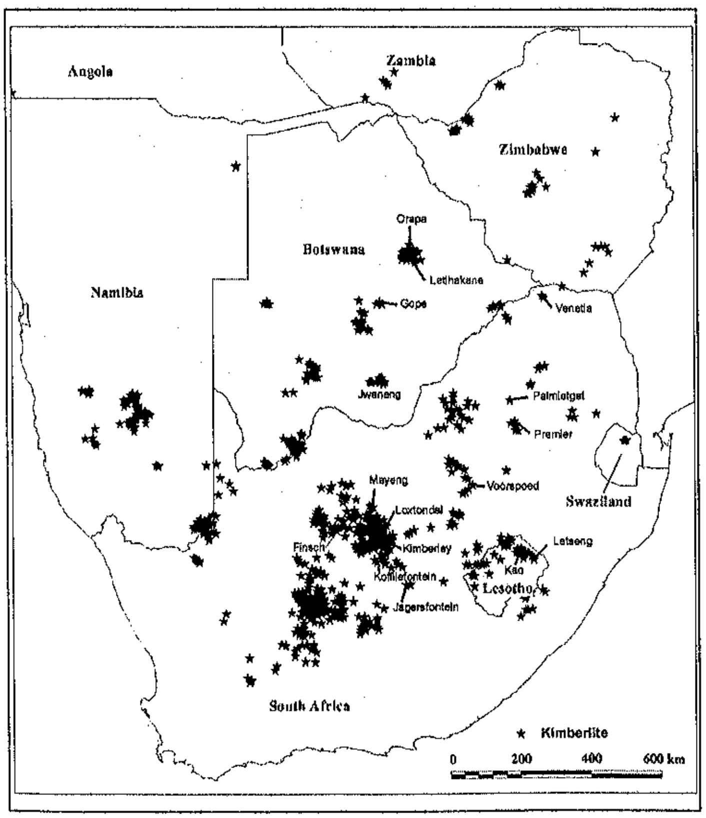
VK, RVK and PK typically dominate the crater zone, where a rock can be termed crater-facies kimberlite. VK can also occur within the top of the diatreme zone and in extra crater deposits. TK, and more commonly TKB, form the diagnostic infill of the diatreme zone where a rock can be termed diatreme-facies. HK typically occurs within root zones of pipes but can also occur in tabular or sheet-like bodies.

3. GEOLOGY OF SOUTHERN AFRICAN KIMBERLITE PIPES

3.1 Cretaceous-aged pipes

The majority of known kimberlite occurrences in southern Africa are of Cretaceous age (Fig. 1). These pipes include many operating mines, e.g. Kimberley, Finsch, Koffiefontein, Letlhakane and Orapa, as well as closed mines such as Jagersfontein and Letseng, where detailed studies are undertaken on large scale, continually changing three-dimensional exposures. Most of these pipes intruded through the Phanerozoic Karoo sequence. The presence of Karoo xenoliths derived from stratigraphic units no longer preserved in the surrounding country-rock sequence allowed Hawthorne (1975) to recognise that some pipes had been more deeply eroded than others. The constant country rock geology and varying depths of erosion are illustrated in Fig. 2. Based on this observation, Hawthorne (1975) then suggested that kimberlite pipes in this area had relatively constant pipe shapes (Fig. 2).

Figure 1. Location of kimberlites in southern Africa.



3.1(a) South Africa

The geology of pipes at Kimberley, Koffiefontein and Finsch are well described by Clement (1982) and Clement and Reid (1989), and therefore it is only necessary to summarise the information here.

In the Kimberley pipes only the lower diatreme and root zones are preserved (Fig. 2). The upper portions of the pipes having been removed by erosion. The root zones are characterised by complexity reflected by highly irregular shapes, including discrete columns and pillars as well as blind appendages. Contact breccias are a feature of root zones; many of these are in-situ or display only slight movement downwards from their original positions. Intrusion breccias or stockworks are also common.

The root zones are largely infilled by HK. Among the important facets of this rock type is the preservation of common segregationary and less common globular segregationary textural varieties, as well as the presence of abundant primary carbonate. The common segregations are usually irregular pools of late crystallising serpentine and carbonate located within a more uniform silicate matrix. Globular segregations are spherical bodies of the volatile-poor silicate fraction of the magma which crystallise typical HK-type carbonate-poor groundmass. Globular segregations may, or may not, have a crystal such as olivine or other clast as a kernel. When they do have kernels they typically have thick selvages. Globular segregations should not be confused with pelletal lapilli found in TKBs (see below). The inter-globular matrix is composed predominantly of carbonate and/or serpentine which represents the late crystallisation of the volatiles which have segregated from the magma. Neither the globular segregations nor the inter-globular matrix contain microlitic mineral grains. The globular segregationary textures are ascribed to the preservation of vapour-liquid-solid systems in a closed temporary hypabyssal environment (Clement, 1982). The fact that similar globular segregationary textures occur in dykes testifies to the fact they form by sub-surface processes. The globular segregationary textures highlight the volatile-rich nature of kimberlite magmas, and they provide evidence that some of the "gases" are released from the magma at a relatively shallow level within the earth's crust.

Diatreme zones have regular shapes and may extend vertically for ~1000 m (at least 845 and 995 m at Bultfontein and Wesselton

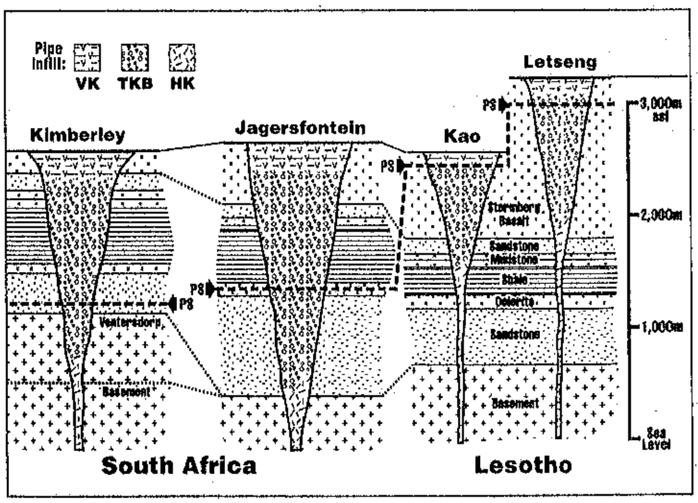


Figure 2. Selected kimberlite pipes in southern Africa showing the infill and geological setting reconstructed for the time of emplacement (after Helmstaedt, 1993). VK = volcaniclastic kimberlite; TKB = tuffisitic kimberlite breccia; HK = hypabyssal kimberlite. PS = present surface. The bold dashed line is a schematic representation of the varying level of erosion across this part of southern Africa.

respectively, Fig. 2). They have smooth, steep, inward dipping (80-85°) margins irrespective of the country rock geology. Contact breccias are rare, and no structural deformation of the wallrock sequence around them has been noted. Diatremes contain relatively few intrusive phases, sometimes only one. A common feature is the presence of large floating reefs that are typically peripherally located within the pipe. These "reefs" consist either of solid or brecciated wallrock sequences which have been displaced downwards (up to 1 km). Floating reefs, although displaced downwards, often crudely preserve the original stratigraphy of the wallrock sequence. Smaller xenolithic and juvenile components are thoroughly mixed, and impart a homogeneous or monotonous appearance to the diatreme infill. It is often possible to recognise fragments from the entire country rock sequence present at the time of emplacement in a single hand specimen.

Kimberlite *diatremes* are filled largely with tuffisitic kimberlite breccia (TKB). This very specific textural variety of kimberlite is composed predominantly of rounded juvenile bodies termed pelletal lapilli and abundant country rock fragments in addition to phenocrysts and macrocrysts which are mostly serpentinised olivine suspended (commonly matrix supported) in a fine-grained matrix. The pelletal lapilli represent magma droplets that are typically composed of a thin selvage of kimberlitic material surrounding a cognate or exotic clast. Both the rims of the pelletal lapilli as well as the inter-clast matrix can contain abundant quenched acicular microlites of diopside. These features show that the pelletal lapilli and the inter-clast matrix are related and both crystallised rapidly from magmatic material. The inter-clast matrix lacks carbonate and represents the condensate of residual kimberlitic fluids after degassing. The nature of the pelletal lapilli and the overall uniform inter-clast matrix is similar in most of the diatreme-facies kimberlites showing that they are texturally specific products from virtually the same emplacement process which has been repeated many times in this area. There is also a gradation in textures from TKB to the HK in the root below. Importantly, exotic fine clastic material is not a ubiquitous or common constituent of the inter-clast matrix and other features such as sorting or sedimentary structures are absent. Megascopically, TKBs are monotonous structureless rocks. The above features clearly indicate an intrusive igneous origin for TKB.

At Kimberley, the pipes are intruded through an Archaean Basement Complex composed of banded gneisses and schists, andesitic lavas and quartzites of the Archaean Ventersdorp Supergroup, shales of the Carboniferous Dwyka Group of the lowermost Karoo Sequence and a thick dolerite/diabase sill (Fig. 2). At Koffiefontein and Jagersfontein, Karoo Sequence rocks are deposited directly onto the Basement Complex (Fig. 2). The preserved Karoo Sequence includes Carboniferous Dwyka, Permian Ecca and some Permian-Triassic Beaufort Group rocks, whilst thick dolerite sills are also present. At Finsch, no Karoo Sequence rocks are preserved in the wall rock profile, but rocks of the Proterozoic Griqualand West Sequence are present. These rocks include dolomites and shales of the Passage Beds and Banded Iron Formation.

Studies of floating reefs in the Kimberley, Finsch, Jagersfontein and Koffiefontein pipes (Clement, 1982 and references therein) have shown that lavas and sediments from the upper Karoo sequence have been preserved as downrafted blocks within the diatremes, thus indicating the presence of an almost complete Karoo sequence at the time of kimberlite emplacement (Fig. 2). At Finsch the floating reefs include Jurassic Stormberg basalt lavas, Late Triassic Clarens Formation sandstones and Permian-Triassic Beaufort mudstones. The Voorspoed pipe is another example in which an extremely large floating reef of Stormberg basalt lava is present.

The Kamfersdam kimberlite pipe located on the north-western outskirts of Kimberley contains both HK and diatreme-facies TKB. Mapping of sampling tunnels by J. Robey and P. Bartlett (De Beers internal report) revealed a gradational transition between these rock types. The kimberlite is interpreted to represent a single intrusive event, with the interface between the deeper HK and the TKB being preserved as a sub-horizontal irregular surface. The textures preserved across this interface are particularly noteworthy. There is a gradual progression from uniform HK, to segregationary HK to TKB. The segregationary HK contains irregular pools of late crystallising primary serpentine and calcite. As the interface is approached, the abundance of segregations increases and the individual segregations begin to coalesce, thus isolating globular structures of the silicate matrix. The TKB has a typical pelletal lapilli texture, and the inter-pelletal matrix contains microlitic clinopyroxene set in serpentine. No carbonate is present. These textural variations clearly illustrate the transition from volatile-bearing HK to fluidised and degassed TKB within a single overall diatreme-forming magmatic event. The gradational interface, which is a few metres wide, represents a degassing front preserved at the time when the kimberlite condensed and emplacement ceased.

Kimberlite sills at Benfontein and Mayeng provide important evidence about the nature of kimberlite magma. Benfontein (Hawthorne, 1968; Dawson and Hawthorne, 1973) is located to the south-east of Kimberley and Mayeng (Apter *et al.*, 1984) occurs some 100 km north of Kimberley. These occurrences illustrate how dolerite sills can act as effective barriers to kimberlite intrusions. The kimberlite sills themselves may also act as temporary barriers for later pulses of kimberlite magma.

At Benfontein the kimberlite intruded through Karoo shales and ponded below the thick dolerite sill known as the "Kimberley sheet". This dolerite acted as a "cap-rock" (Dawson and Hawthorne, 1973) for the rising kimberlite magma. Similar sills occur at the nearby Wesselton floors, at the Wesselton water tunnels and at Kamfersdam. In all cases the dolerite sills were not penetrated by the kimberlite magmas.

At Mayeng the ~2 m thick kimberlite sheets intrude a horizontally layered sequence of Precambrian Ventersdorp lavas, Palaeozoic Karoo sediments and dolerite intrusions. Notably the uppermost sill occurs under the lowest dolerite sill showing that the kimberlite magma never managed to penetrate the first dolerite. The dolerite, therefore, was an effective barrier to the rising kimberlite magma. The main area of sill development takes advantage of a single, well-jointed Ventersdorp lava unit but kimberlite is notably absent in the adjacent poorly jointed lava units. Less well-developed sills occur only along the contacts between other country rock units.

The influence of dolerite sills in the country rock sequence on pipe shape is also well illustrated at the Loxtondal pipe, north-east of Kimberley, where there is a marked narrowing of the pipe in the vicinity of the sill (Clement, 1982).

The presence of Stormberg basalt as xenoliths in many Cretaceous kimberlite pipes in South Africa provides ample evidence that these lavas once covered the entire sub-continent. There is only one area in South Africa where the intrusion of kimberlite pipes into Stormberg lavas is preserved and described, namely the Springbok Flats area north of Pretoria. In the Palmietgat kimberlite pipes diatreme-facies TKB has been observed cutting across the boundary between the basalt and the underlying sandstone of the Clarens Formation.

The recognition of diatreme-facies TKB in numerous Cretaceous-aged kimberlites across South Africa has been documented, and illustrates that the kimberlite geology and geological setting recorded by Clement (1982) for the Kimberley, Finsch and Koffiefontein pipes is repeated at numerous other localities.

3.1(b) Lesotho

Numerous kimberlite pipes have been discovered in the Kingdom of Lesotho (Nixon, 1973). These slightly eroded Cretaceous kimberlite pipes have a very similar geological setting to both the Springbok Flats kimberlites and the Orapa province in Botswana (see below), as they intrude through the full Karoo sedimentary sequence and the Stormberg basalt lavas (Fig. 2). It is not surprising that classic TKB forms the main infill within these pipes. There are also suggestions of the presence of crater-facies rocks at Kao (Nixon, 1973, in particular Plates 32A-C, and Fig. 26). These pipes represent rare examples, other than at Orapa, where the uppermost diatreme and possibly part of the overlying crater are preserved and are worthy of further investigation. It is interesting that the model proposed by Helmstaedt (1993; Fig. 2) suggests that the pipes flare from the base of the Stormberg basalts.

3.1(c) Botswana

In the Orapa area of Botswana, more than fifty kimberlite intrusions have been discovered, including the Orapa A/K1 and Letlhakane D/K1 and D/K2 pipes that have been developed into mines. At Orapa A/K1, two kimberlite pipes intrude through Archaean Basement and the Phanerozoic Karoo sequence. The latter consists of the Permian Tlapana Formation (equivalent to the Ecca in South Africa), Triassic Thlabala Formation (Beaufort equivalent), Late Triassic Mosolotsane (equivalent of the Elliot Formation in South Africa), the Late Triassic Ntane Formation (equivalent of the Clarens Formation) and the Jurassic Stormberg basalt lavas. This country rock sequence is similar to that found at Kimberley at the time of kimberlite emplacement. Equivalent sedimentary Karoo rocks to those occurring at Orapa are found as xenoliths within the Kimberley pipes.

Field *et al.* (1995, 1997) have described the Orapa A/K1 kimberlite pipe in detail, and have shown that contrasting volcanic styles exist between the two lobes comprising this pipe. The north lobe is a steep-sided, regular-shaped pipe that extends over a known vertical distance of 600 m. At depth there is monotonous TKB, which closely resembles the TKB in the Kimberley area pipes. The upper parts of this lobe consist of crudely bedded deposits, in which layering is indicated only by the concentration of lithic clasts. These rocks are considered to be pyroclastic deposits. This PK contains poorly-developed juvenile lapilli that resemble the pelletal lapilli of the TKB. The lapilli are set together with lithic fragments in a matrix that contains abundant microlitic diopside that is also similar to the TKB that occurs below.

Field *et al.* (1997) suggests that the northern lobe was formed by a single eruption which produced both the diatreme-zone with intrusive TKB and the associated extrusive PK at higher levels. The PK derived from the eruption cloud that formed during the same overall volcanic event. The upper parts of the pipe were infilled by pyroclastic flow deposits composed of material very similar to the TKB. The presence of gas-escape structures within the bedded PK, the pervasive presence of microlitic diopside in the PK and TKB as well as the lack of a sharp contact between the PK with the underlying TKB provide convincing evidence for this.

The deeper parts of the southern lobe also comprise a steep-sided diatreme infilled with typical TKB. However, in contrast to the northern lobe, the top of the TKB is sharply bounded at a point that approximately coincides with a change in angle of the pipe walls. The southern lobe at Orapa has a flaring crater located above a steep-sided diatreme. The local dip of the flared edge of the crater varies according to the nature of the country-rocks in which it is developed. Contacts are near vertical in basalt, and as low as 28° in Karoo mudstones of the Tlhabala Formation. These angles closely match the theoretical repose angles calculated for the rock types using geotechnical-engineering parameters (J. Jacubec, pers. comm.). The variation in angle of the pipe contacts is a strong indication that the exposed rocks forming the Orapa South crater wall, following collapse, retreated to their natural repose angles.

The crater infill of the southern lobe consists of early heterolithic breccias that overlie the top of the diatreme-facies TKB. Thick, monotonous deposits of juvenile-rich VK overlie the basal breccias and are then covered by extensive fans composed largely of basalt. All these deposits contain boulders of basalt which were brecciated and cemented largely by carbonate prior to expulsion during crater formation. These boulders provide further evidence for pre-cursor breccias. In particular they show that brecciation of the cap rock basalts occurred before breakthrough. Basalt breccias of varying types are a constant feature of most of the pipes in the Orapa Province. Associated with the fans at Orapa are modified grain flow deposits of well-sorted, graded beds composed largely of kimberlite-derived pelletal lapilli and olivine grains. In contrast to Orapa North, the main infill in Orapa South is resedimented material. There is scant evidence of primary pyroclastic deposits. The southern lobe appears to have had a long-lived open crater that was gradually infilled by post-eruption sedimentary processes. This contrasts with the rapid primary pyroclastic infilling of the upper part of the northern pipe by syn-eruption processes.

The main part of the TKB diatreme in the southern lobe, which broke through to surface, contains basalt clasts which have been transported considerable distances from their original location in the uppermost wallrock sequence. Basalt clasts are present within the deepest levels penetrated by drilling of the main diatreme. On the northern and western sides of the southern diatreme, a blind pre-cursor breccia body has been identified. In contrast to the main TKB, the clasts within this breccia are locally derived, and displaced only slightly downwards. Clasts from higher stratigraphic levels are absent. This kimberlite is similar to some of the earlier sub-surface intrusion breccias described by Clement (1982) in the Kimberley and Finsch pipes.

Other pipes in the Orapa area provide further insight into the nature of kimberlite volcanism. Located some 400 m to the southeast of A/K1, is the small A/K2 pipe (~2 ha. at surface). The pipe provides evidence for a much smaller volcanic event (less powerful eruption) than the very large A/K1 pipe close by. The A/K2 pipe consists of two main lithofacies. The north-western portion of the pipe consists of a basalt-rich VK breccia, while the south-eastern area contains, steeply bedded (up to 35°), well sorted and bedded modified grain flow deposits. Both lithofacies are similar to those found in A/K1 and similar secondary deposition processes must have taken place. A further feature of A/K2 is the presence of pre-cursor kimberlite dykes, which are terminated against the pipe. These dykes indicate the high-level intrusion of magmatic dykes, prior to crater formation, and may illustrate that earlier dykes serve to enhance the sealing of fractures in the country rock prior to eruption of the pipe-forming intrusions.

On the northwestern side of A/K1 (approximately 150 m from the edge of A/K1), a small (<1ha.) sub-surface kimberlite intrusion known as A/K15 has recently been discovered. This intrusion consists of a periphery composed of in-situ highly brecciated basalt and sandstone, and a central core of HK. The HK has locally developed segregationary textures resulting from the presence of well-formed, ovoid, calcite-filled vesicle-like structures. This pipe is an example of a failed embryonic pipe that did not achieve breakthrough.

The B/K9 kimberlite is located 15 km east of A/K1. This kimberlite consists of three pipes that join at about 150 m below the present day surface to form a single elongated body. The northwestern and southwestern lobes of the body consist of HK, whilst the central lobe consists of a RVK-infilled basin which is underlain by TKB and HK. The RVK is composed mostly of a very coarse breccia, with dominant basalt clasts (up to 90 % by volume). Occasional juvenile (kimberlite)-rich layers are interspersed between the breccia. An important feature of this pipe is the presence of well developed country rock breccias below the RVK adjacent to the HK. The breccias are composed either of Stormberg basalt, Ntane sandstone or Mosolotsane mudstone. Most of the breccias occur close to their stratigraphic position in the adjacent country rocks. This occurrence represents another example of pre-cursor sub-surface breccias.

The B/K44 occurrence (20 km southeast of A/K1) provides further evidence of the diversity of kimberlite intrusions in the area. This body is a "blind" HK intrusion located within the Ntane Sandstone immediately below the Stormberg basalt. Only a few small veinlets of kimberlite appear to have penetrated the basalt. This is an excellent example of the presence of barriers within the country rock, which impede the upward movement of kimberlite magmas. The kimberlite has a well developed segregationary texture. The segregations consist of carbonate and serpentine. This shows that the kimberlite contained common juvenile volatiles which were never released from the closed system.

The Letlhakane occurrence consists of two separate pipes (D/K1 and D/K2) that are located 50 km southeast of Orapa A/K1. The two pipes appear to have been eroded to a greater extent than A/K1, as little or no crater-zone kimberlite is preserved in either pipe. The D/K2 kimberlite has not been mined or investigated to the same extent as D/K1. D/K2 consists of an earlier TKB intrusion which is intruded by a later HK phase. The D/K1 occurrence comprises a smooth steep-sided diatreme infilled with TKB. There is little or no obvious brecciation of the main country rock adjacent to the kimberlite contact. The limited breccias that are present predate the TKB and must represent embryonic pipe formation breccias that were subsequently eroded by the TKB.

The D/K1 pipe has two recognisable varieties of TKB at current mining levels (LM-1 and LM-2). The TKBs are petrographically identical consisting of typical pelletal lapilli, serpentinised olivine macrocrysts and country rock xenoliths set in a matrix of serpentine, smectite clay and microlitic diopside. The two intrusions are distinguished by style of alteration, xenolith and diamond content. Both of these kimberlites are texturally very similar to the Kimberley area TKBs, although they are superficially fresher in appearance and do contain small quantities of carbonate. In the LM-1 TKB there are some interesting vertical concentrations (10-25 m wide) of rounded basalt xenoliths up to 50-100 cm in size. There seems to be no other obvious explanation than they are degassing or gas streaming features within the TKB.

At Letlhakane the wallrock sequence is essentially the same as that at Orapa A/K1. Mining of the D/K1 pipe has exposed the contact between the kimberlite and the Stormberg lavas, as well as that with the underlying Ntane sandstones. There is no apparent change in intrusion angle across the lava/sandstone boundary. This provides evidence for the intrusive nature of the TKBs, since there is no evidence for collapse of the wallrock (c.f. Orapa South above).

At Gope, in the central Kalahari 160 km south-west of Orapa (Fig. 1) a small cluster of Cretaceous kimberlites occurs. The main pipe GO-25 is a steep-sided, TKB-filled diatreme, containing classic pelletal TKB, as well as some HK. The pipe is emplaced through Stormberg basalt and Ntane sandstone, and presumably the full Karoo sedimentary sequence.

3.2 Pre-Cretaceous kimberlites

3.2(a) Venetia

The ~500 Ma. Venetia pipe intrudes crystalline rocks of the Archaean Limpopo Mobile Belt (Allsopp *et al.*, 1995; Seggie *et al.*, 1998). At the time of intrusion, the Waterberg Group rocks were present as shown by the occurrence of distinctive Waterberg quartzite xenoliths within the kimberlite. Other xenoliths in the kimberlite appear to be derived from lavas that, compared to regional data, probably formed the base of the Waterberg and could have acted as a temporary barrier to rising magmas. The quartzites themselves may have been a relatively impermeable barrier, as they were already metamorphosed when the kimberlite intruded. The steep-sided pipe consists of typical diatreme-facies TKB and HK intrusions. The textural features of the TKB are comparable to TKBs elsewhere, e.g. Kimberley.

3.2(b) Premier

The ~1200 Ma. Premier pipe must have intruded rocks of the Early Proterozoic Transvaal Supergroup and Waterberg Group, as well as intrusive and extrusive rocks of the Bushveld Igneous Complex. This kimberlite pipe represents three overlapping classic diatremes, each of which are infilled mainly with typical TKB. Recent deep drilling has shown that two of the diatremes, the so-called brown and grey kimberlites, have separate roots and that TKB persists vertically for at least 1000 m. This represents the greatest proven vertical extent of TKB at any one locality. The Venetia and Premier pipes together show that similar diatreme formation has been repeated at different times on the Kaapvaal craton.

3.3 Contrasting pipes

3.3(a) Jwaneng

The ~240 Ma. Jwaneng kimberlite pipe in southern Botswana is an interesting exception to the emplacement pattern in southern Africa discussed above. Here three steep-sided kimberlite pipes coalesce some 100 m from the present day surface to form a 55 ha. body. This group of kimberlites was emplaced into Early Proterozoic Transvaal dolomites and shales, as well as thin sills of Proterozoic diabase/dolerite and syenite. The pipe infilling consists of chaotically bedded, extrusively formed VK. No TKB has been recognised. The VK contains significant quantities of consolidated and unconsolidated Karoo sediment which indicates that the cover rock at the time of emplacement included poorly consolidated Karoo mud, and that there was no competent cap-rock at the time of intrusion. The pipes pre-date the Jurassic Stormberg basalt lavas, and the radiometric age places the intrusion within the depositional period for Karoo sediments. It is not clear how much the pipes have been eroded since emplacement.

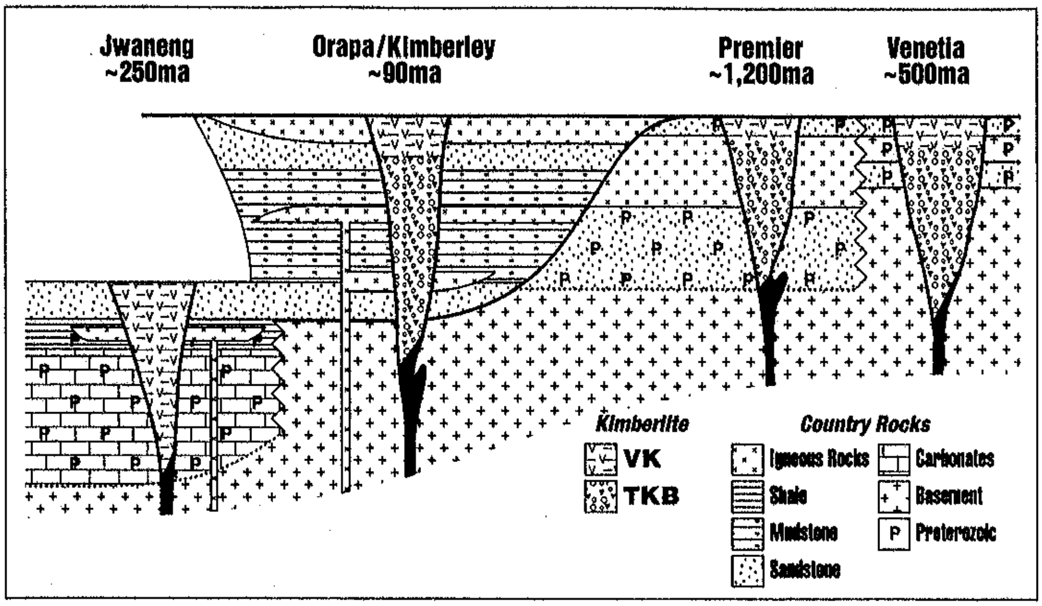


Figure 3. A schematic section across southern Africa summarising pipe shapes, pipe infill and geological setting for many kimberlites reconstructed for the time of emplacement. VK = volcaniclastic kimberlite; TKB = tuffisitic kimberlite breccia.

3.4 Summary of southern African pipes

In the above section the concept of a southern African kimberlite pipe model, first published by Hawthorne (1975) and developed by Clement (1982) has been reinforced. This model has now been demonstrated in numerous other Cretaceous kimberlites in southern Africa. In addition it can be shown that this model applies equally to older kimberlites where the similarities of the diatreme zones and infill is particularly noteworthy. It has also been demonstrated through studies of the less eroded kimberlites in Botswana, that the Cretaceous-aged kimberlites in that country are indeed similar to those found in South Africa, and that similar processes can be invoked to explain their emplacement (e.g. Field *et al.*, 1997). It has been shown, therefore, that many of the hundreds of kimberlites known in southern Africa (Fig. 1) conform to the same pipe model.

The geological setting of the numerous Cretaceous kimberlites is remarkably uniform, as they all were emplaced into the Phanerozoic Karoo sedimentary sequence which was capped by thick basalt lava flows and intruded by numerous dolerite sills (Table 1, Fig. 2, Fig. 3). There is ample evidence that parts of the country rock sequence, notably the igneous rocks, partially (e.g. Loxtondal) or totally (Mayeng, Benfontein, Orapa A/K15 and B/K44) impeded the upward movement of kimberlite magmas. In the rarer older kimberlites the country rock sequences included rocks that could have had a similar effect on the rising magmas (e.g. Waterberg lavas and quartzites and/or Bushveld).

A summary of the main features of the southern Africa kimberlite pipes, reconstructed for their emplacement ages, is presented in Table 1 and schematically illustrated in Fig. 3. It should be emphasized that in Fig. 3 the Orapa/Kimberley pipe represents a very large number of Cretaceous kimberlites, whose setting and infilling can be represented by this single composite pipe model. Similarly the Venetia and Premier models represent larger clusters of kimberlite pipes with characteristics established not only in these mines but also in other pipes in the cluster. At Jwaneng, only the main pipe is represented, as little is known about the other pipes in the cluster.

In Table 1, a relative simplified hardness estimate is given for each of the country rock varieties based on measurements for most of the rock sequences (in terms of uniaxial compressive strength). A feature of most of Karoo sedimentary rocks is that they were lithified when the kimberlites were emplaced, and occur as coherent xenoliths within the kimberlites. This is notably different to the poorly consolidated Karoo xenoliths found at Jwaneng where the sediments were largely unconsolidated when those kimberlite pipes formed. Thus the term "soft" is used in a relative sense in Table 1.

Figure 3 illustrates the classic southern African kimberlite pipe model which is characterised by the presence of steep-sided diatremes infilled with TKB. All of these deep pipes are emplaced through country rock sequences that contain competent barriers and cap rocks. Jwaneng is notably different, and an exception. Here a VK-filled pipe was emplaced into Proterozoic rocks covered by unconsolidated Karoo sediments.

4. GEOLOGY OF CANADIAN KIMBERLITE PIPES

During the last decade many new kimberlites have been discovered in Canada (Fig. 4). The available information for these and previously known occurrences suggests that, although some of them show similarities to the southern African occurrences, the geology of many of the pipes is significantly different. Three areas of Canada will be considered further : the Prairies, the Slave Province and Ontario. There is little published or detailed information on most of the Canadian kimberlites. This section is based on unpublished information as well as publicly available material (including assessment reports, press releases, reports such as Miller, 1995, numerous core shack displays and talks presented in Canada over the last few years which will not always be individually referenced e.g. Prospectors and Developers Association of Canada Annual Convention –

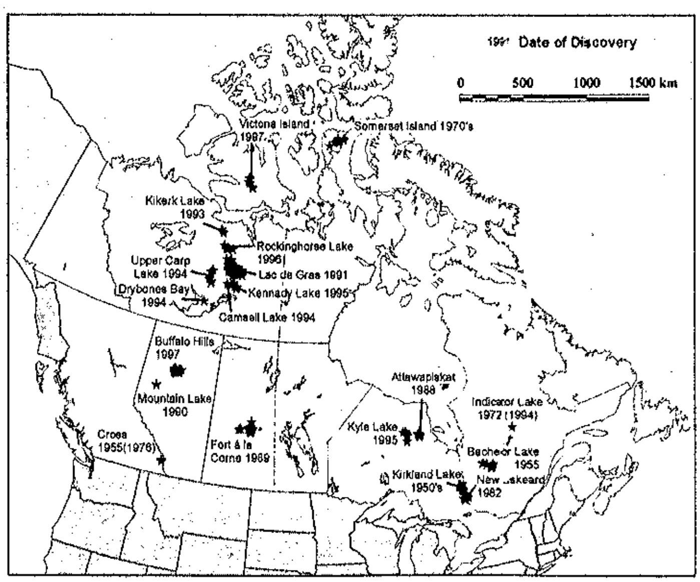


Figure 4. Location of kimberlites in Canada.

Table 1. Summary of the shape, infilling and country rocks for many kimberlite pipes in southern Africa, reconstructed for the time of emplacement. Hardness: H=hard, S=soft, B=brittle. Pipe size: Large > 15 ha., Medium 5-15 ha., Small < 5 ha. FR = floating reef, CR = country rock.

Country	Locality	Age	Pipe Shape	Infilling	Country Rock Sequence	Hardness	Original Surface Size	Orignal Vertical Extent (m)	Additional Comments
South Africa	Kimberley Dutoitspan Wesselton De Beers	Cret.	Steep diatremes Complex roots	TKB HK FR	Basalt Sandstone Mudstone Dolerite Vtrsdorp lavas Basement	H S S H H H	Large	1500	Type area kimberlite diatremes
South Africa	Finsch	Cret.	Steep diatreme Pre-cursors	TKB HK FR	Basalt Sandstone Mudstone Dolerite Prot. Shale Prot. Dolomite	H S S H B H	Large	1500	Dolerite xenoliths in precursors Pre-cursors follow fractures in CR
South Africa	Koffiefontein	Cret.	Steep diatreme	TKB HK FR	Basalt Sandstone Mudstone Dolerite Mudstone Basement	H S S H S H	Large	1500	Enlargened pre-cursor dykes
South Africa	Jagersfontein	Cret.	Steep diatreme	TKB FR	Basalt Sandstone Mudstone Dolerite Mudstone Basement	H S S H S B	Large	1000	
South Africa	Kamfersdam	Cret.	Steep diatreme	TKB HK FR	Basalt Sandstone Dolerite Mudstone Vtrsdorp lavas	H S H S H	Medium	?500	
South Africa	Voorspoed	Cret.	Steep diatreme	TKB FR	Basalt Sandstone Mudstone Dolerite Mudstone Basement	H S S H S B	Large	1500	
South Africa	Palmietgat	Cret.	Steep diatreme	TKB HK	Basalt Sandstone	H S	Medium	?	Full Karoo succession Little erosion ?
Lesotho	Letseng	Cret.	Steep diatreme	TKB HK	Basalt Sandstone	H S	Medium	1000	Full Karoo succession
Lesotho	Kao	Cret.	Steep diatreme	VK? TKB	Basalt Sandstone	H S	Medium	?	Possible bedded VK Full Karoo succession
Botswana	Orapa A/K1	Cret.	Flared crater Steep diatreme Pre-cursor	RVK/PK TKB HK	Basalt Sandstone Mudstone Shale/Coal Basement	H S S S H	Large	1500	North – steep crater with PK South – shallow crater with RVK Large pipe – 112 ha. Full Karoo succession
Botswana	Orapa A/K2	Cret.	Crater	RVK	Basalt Sandstone Mudstone	H S S	Small	100	Small crater close to A/K1
Botswana	Orapa B/K9	Cret.	Steep diatreme	RVK TKB HK	Basalt Sandstone Mudstone	H S S	Medium	400	Compressed crater, diatremes and HK
Botswana	Letlhakane D/K1 Letlhakane D/K2	Cret.	Steep diatremes	TKB FR HK	Basalt Sandstone Mudstone Shale/Coal Basement	H S S S H	Medium	700	Three joined diatremes
Botswana	Gope	Cret	Steep diatreme	TKB HK	Basalt Sandstone Mudstone	H S S	Medium	?500	
Botswana	Jwaneng	Perm.	Steep pipe	VK	Shales Prot. Shale Diabase Syenite Prot. Dolomite	S B H H H	Large	1000	Chaotically bedded VK No TKB Poorly consolidated upper CR
South Africa	Venetia	Ord.	Steep diatreme	TKB HK	Wtrberg Lavas Wtrberg Qtzite Limpopo Belt Metamorphics	H H H H	Large	1000	
South Africa	Premier	PreC.	Steep diatreme	TKB FR HK	Wtrberg Qtzite Bushveld Compl Tvl Quartzite	H H H	Large	1500	Late-stage dyke complex 1000m of continuous diatreme

PDAC – in Toronto; the annual Cordilleran Round Up and Pathways '98 held in Vancouver; the annual NWT Geoscience Forum held in Yellowknife).

4.1 Prairies

4.1(a) Saskatchewan

The first kimberlite to be discovered in Saskatchewan was found by Monopros Ltd in 1987 at Sturgeon Lake and subsequently Claude Resources located a second kimberlite nearby (Nixon *et al.*, 1993, Scott Smith, 1995, Scott Smith *et al.*, 1996). These two bodies are glacially transported mega-blocks of Cretaceous VK. The presence of common clast size grading and plane parallel bedding, suggested that the VK was deposited by primary subaerial pyroclastic airfall processes and is therefore PK. The PK is composed of juvenile lapilli and single crystals which are dominated by olivine. The juvenile lapilli are neither globular segregations, pelletal lapilli nor autoliths but are pyroclasts or juvenile lapilli that are glassy, vesicular and commonly have curvilinear to amoeboid outlines. Juvenile lapilli with these features had not previously been reported among kimberlites. The observed differences in the nature of the pyroclasts indicates that the Sturgeon Lake kimberlites probably represent the products of a different style of eruption to that found in the southern African TKB-bearing kimberlite pipes. A mica-like vermiform mineral occurs in these kimberlites. This mineral obliterates random primary textures and is secondary in origin so its orientation cannot be used to indicate pyroclastic flow as suggested by Nixon *et al.* (1993). Similarly, the common magnetite aggregates are interpreted here also as secondary constituents and not as accretionary lapilli as suggested by Nixon *et al.* (1993).

Subsequently the Fort a la Corne (FALC) Cretaceous kimberlite province was discovered by Uranerz Exploration and Mining Ltd. Since then evaluation of the approximately seventy bodies has continued by Uranerz and joint venture partners Cameco Corporation, Monopros Ltd and Kensington Resources Ltd. Kimberlites from this province have been described by Lehnert-Thiel *et al.* (1992), Scott Smith *et al.* (1994, 1995, 1998), Scott Smith (1996), Leckie *et al.* (1997a), Nixon and Leahy (1997) and Leahy (1997).

The FALC kimberlites with multiple drillholes appear to be mainly shallow champagne-glass-shaped pipes which have diameters ranging up to 1300 m and depths mostly less than 200 m from the present sub-glacial surface (Fig. 5, and in figures in Lehnert-Thiel *et al.*, 1992, Scott Smith, 1996, Leahy, 1997). The main bodies at FALC appear to be ~101-94 Ma. in age. The kimberlites were emplaced into poorly consolidated Cretaceous sediments comprising ~100 m of clay-rich fine material, silts and sandstone (Mannville Formation; ~119-100 Ma.) formed in coastal marine, subaerial flood plain and/or lacustrine environments and

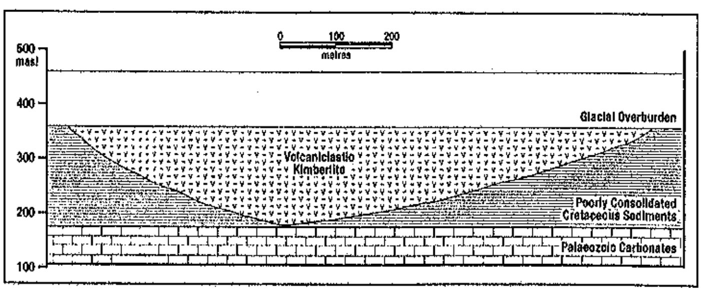


Figure 5. Cross section of kimberlite pipe 120 at Fort a la Corne, Saskatchewan, Canada (partly schematic; courtesy of Uranerz Exploration and Mining Ltd.).

~100 m of marine shales (Ashville Formation; ~100-91 Ma.) deposited towards the edge of the Western Interior Seaway. The Mannville unconformably overlies ~400 m of Palaeozoic sediments that are dominated by indurated carbonates below which is the Precambrian basement. The Cretaceous sediments observed in drillcores adjacent to the main kimberlites correlate with the regional stratigraphy showing that they are in-situ and undisturbed. When preserved in the drillcore, pipe contacts cross cut the sediments. Many of the pipes appear to flare from the sandstone that forms the base of the Cretaceous sediments. In terms of the pipe shapes, there is no evidence for the development of any diatreme or root zone below any of the craters.

The FALC bodies are composed of xenolith-poor VK consisting predominantly of a mixture of juvenile lapilli and single crystals which are mainly olivine. The inter-clast matrix is composed mainly of serpentine, carbonate and magnetite. The FALC rocks, and more specifically the juvenile lapilli, are broadly similar to the Sturgeon Lake blocks and similar comments apply. Some juvenile lapilli contain primary carbonate, and fresh olivine is common. HK or TKB or diatreme-facies rocks have not been encountered in any of the bodies. In the one example of a deeper (>350 m) and possibly steeper sided pipe, only bedded VK was found. Some parts of the FALC pipes contain kimberlite that appears to have been reworked, but these rocks are volumetrically minor. The FALC pipe shapes and pipe infill are different from the majority of southern African kimberlite diatremes and suggests that different mechanisms must have been responsible for their emplacement. Below some of the main FALC champagne-glass shaped pipes, there are volumetrically unimportant, small conformable and sometimes graded beds up to 5 m thick of xenolith-poor VK which occur mainly within, and at many stratigraphic levels throughout, the Mannville Formation sediments.

To the north of FALC, more kimberlite occurs at Candle Lake on the War Eagle Mining Company Ltd property. Kennecott Canada Exploration Inc. is currently investigating these kimberlites, which are thought to have a similar age and geological setting to FALC. The kimberlites are ~100 m deep and have shallow country rock to kimberlite contacts which flare from a poorly consolidated sandstone at the base of the Cretaceous as found at FALC. The crater infill appears to be VK very similar to some of the pyroclastic lapilli tuffs at FALC with the presence of amoeboid shaped juvenile lapilli (as shown in Plates 3, 4, 19 and 20 in Mitchell, 1997). Based on this information, it appears that the Candle Lake occurrence is also at variance with the southern African diatreme model and is probably similar to the FALC province. In contrast to FALC, the Candle Lake occurrence has an elongate keel, the significance of which is not known.

4.1(b) Alberta

The first kimberlitic rocks to be discovered in Alberta were found by Monopros Ltd at Mountain Lake, near Grande Prairie (Fig. 4; Wood *et al.*, 1998; Leckie *et al.*, 1997b). These occurrences are late Cretaceous or younger in age (<68 Ma.). There are at least two pipes at Mountain Lake which appear to be smaller, steeper sided and deeper than the FALC craters. The largest southern body in plan view is ~20 ha. in size and kimberlitic rocks occur to a depth of at least 350 m. Some inwardly dipping steep pipe wall contacts (~70°) have been established. Both of the pipes are infilled with partly bedded VK. Diatreme-facies or hypabyssal material was not found. The southern body is infilled mainly by PK, which contains common juvenile lapilli that do not resemble pelletal lapilli or globular segregations. The northern body is composed of VK, probably RVK, which contains common xenocrysts of quartz, much less juvenile material and large blocks of sediments.

At Mountain Lake the Archaean basement is covered by 2500 m of Phanerozoic sediments including ~1200 m of relatively undisturbed Cretaceous sediments deposited within the Western Interior Seaway. The uppermost Cretaceous sediments (<65-71 Ma.; Maastrichtian) are ~175 m thick and comprise still poorly-consolidated sandstones, siltstones, shales and coal formations that formed in a non-marine flood plain or alluvial environment close to the western limit of the Seaway during its last main regression. Below that are ~575 m Upper Cretaceous sediments that are dominated by marine shales that were deposited during the period of highest sea levels within the Western Interior Seaway. Between ~750-1200 m from surface are lower Cretaceous sediments which are composed mainly of sandstone with less common shale. Below that are 300 m of Permian to Jurassic mixed sediments which may be dominated by shales, then 500 m of Carboniferous and 900 m of Devonian sediments which are dominated by carbonates.

Kimberlite pipes have been discovered 180 km to the north east of Mountain Lake in the Buffalo Hills, Alberta by Ashton Mining of Canada Inc., the Alberta Energy Co. Ltd and Pure Gold Minerals Inc. (Fig. 4; Carlson *et al.*, 1998). To date seventeen kimberlites have been confirmed. The pipes appear to range in size up to 45 ha. and kimberlite has been shown to occur to a depth of 200 m, this being the limit of drilling. One body, K14, has been drilled sufficiently to define a preliminary pipe shape. This pipe has been shown to be at least 400x400 m in plan view size. The pipe wall contacts appear to be steep in the south (70-80°) but a much shallower flange occurs in the north west of the body. At 200 m the body may be less than 200 m in diameter. These data show that the body is asymmetric in shape with an upper flaring at about 100 m from the present sub-glacial surface.

The pipes are infilled with partly bedded xenolith-poor, juvenile lapilli-bearing, olivine crystal VK. Diatreme- or hypabyssal-facies kimberlites have not been found. The VK contains pyroclastic juvenile lapilli which are spherical to amoeboid in shape and in some instances the lapilli are vesicular. The olivine is commonly fresh. Carbonate is present in some juvenile lapilli. The Buffalo Hills occurrences again contrast with the kimberlite diatremes of southern Africa. The rocks display some similarities to the FALC kimberlites and similar processes may have been involved in their formation, although it is possible that more reworking has occurred.

The Mountain Lake and Buffalo Hills bodies occur on opposite sides of the Peace River Arch (which has been active since the Proterozoic) and their geological setting is somewhat different. In the area of Buffalo Hills there are ~1600 m of Phanerozoic sediments overlying the Archaean basement (R. Pryde of the Alberta Energy Co. Ltd pers. comm.; Mossop and Shetsen, 1994). The country rocks adjacent to the 88-86 Ma. Buffalo Hills kimberlites consist mainly of the 103-98 Ma. Shaftesbury Formation. These sediments are dominated by shales to silty shales. Grey black mudstones of this formation are observed in the drillcores adjacent to the kimberlites to within ~75 m of surface. The nature of the xenoliths of this mudstone that occur within the kimberlites show that these shales were poorly consolidated at the time of kimberlite emplacement. It is not clear if any of the younger 98-93 Ma. Dunvegan Formation that is dominated by sandstone overlie the shales. If it does, it must be relatively thin. The shales form the upper part of ~325 m of Cretaceous sediments. Between the Cretaceous and the basement are ~1300 m of Devonian carbonates.

4.1(c) Summary

All the kimberlites in the Canadian Prairies appear to be shallow (<500 m) crater-like shaped bodies which are infilled with VK. The VK appears to be dominated by PK, the nature of which is different to that from other previously known kimberlites. The pipes in Alberta appear to have steeper pipe walls (up to 70°) than most of those in Saskatchewan. There is no apparent development of a kimberlite diatreme or root zone in any of these pipes and no TKB or HK has been encountered. These kimberlites are clearly different types of volcanic pipes to those that dominate in southern Africa. All the Prairies kimberlites were emplaced during the Cretaceous into varying thicknesses of sediments deposited in the Western Interior Seaway. The uppermost sediments which form the immediate country rocks to the pipes were poorly consolidated at the time of kimberlite emplacement.

4.2 Slave Province, NWT

In less than a decade hundreds of kimberlites have been found within the Slave Archaean craton, north and northeast of Yellowknife, NWT (Fig. 4; also see reviews by Pell, 1995, 1996, 1997a, b which include detailed locations of pipes). The Slave Province is a small craton that has been stable since the Archaean and is composed mainly of granite and gneiss. Parts of the Archaean are covered by Proterozoic (2.7-2.6 Ma.) meta-sedimentary rocks with less common metavolcanic rocks (the Yellowknife Super Group). Syn- and post-volcanic granitoid plutons form 65 % of the Slave Province. Several swarms of Proterozoic diabase/dolerite dykes have been emplaced in the area. Kimberlites in the Slave Province appear to be emplaced into all of these rock types (e.g. Graham *et al.*, 1998). The only preserved cover in the Slave Province is recent glacial material which is generally not very thick. The kimberlites that occur within the Slave Province can broadly be divided into two groups (a) Upper Cretaceous to Tertiary kimberlites which occur only in the Lac de Gras area and (b) the Pre-Cretaceous kimberlites which occur away from Lac de Gras.

4.2(a) Upper Cretaceous-Tertiary kimberlites, Lac de Gras area

The first kimberlites to be discovered in the Slave Province, NWT occur within the BHP-Dia Met Exeter Lake Property in the area of Lac de Gras (Carlson *et al.*, 1995, 1996). At least one hundred pipes are now reported to have been found on this property alone (Kirkley *et al.*, 1998) and five of these, together, form the new Ekati Mine. Forty-nine kimberlites have been found on the adjacent Diavik property (Graham *et al.*, 1998). Many other kimberlites have been found in other adjoining claims (e.g. McKinlay *et al.*, 1997, 1998; Doyle *et al.*, 1998, this volume). The size of the Lac de Gras province (~120x75 km) is large compared to other better-defined kimberlite provinces worldwide. Age determinations for the Lac de Gras kimberlites, some of which are based only on palynology of shale xenoliths, are all Upper Cretaceous to Early Tertiary. Some 50 km north west of Lac de Gras are the Yamba Lake kimberlites which are similar to the BHP-Diamet and Diavik kimberlites (T. Chartier public comm. NWT Geoscience Forum, 1994) and also Cretaceous in age (McKenzie and Canil, 1997). North west of Yamba Lake is the Ranch Lake body found by Lytton Minerals. Based on the presence of bedding and mudstone xenoliths, this kimberlite must also be Tertiary-Cretaceous in age (NWT Geoscience Forum, 1996; Assessment Report No. 083256). Until further detailed data are available, all these kimberlites will be considered together. Preliminary data, however, suggest that the

Lac de Gras field include a range of ages from 47 to 86 Ma. suggesting that treating all the kimberlites together as one province may be an oversimplification (47.5 Ma. in Davis and Kjarsgaard, 1997; early Tertiary by Nassichuk and McIntyre, 1995; 47.5 and 52.1 Ma. in Armstrong and Moore, 1998; 52 Ma. by Carlson *et al.*, 1996; 73 Ma. Kjarsgaard, 1996a; 74 Ma. and 86 Ma. by Heaman *et al.*, 1997; 75 Ma. and 81 Ma. in Pell, 1996, 1997a).

Individual Lac de Gras pipes are mostly less than 15 ha. in size, with many pipes being less than 5 ha.. Examples of small pipes include the four Diavik pipes A154S and A154N, A21 and A418 which have areas of 0.9 to 1.6 ha. (~100-200 m diameter Aber Resources Ltd, 1996 Annual Report) and those reported at Hardy Lake are less than 4 ha. (McKinlay *et al.*, 1998). In the Exeter Lake property some pipes are less than 5 ha. in size (or <~250 m in diameter; including Misery at 180x160 m or 1.5 ha., Panda at 200 m or 3.1 ha., Koala at 300x200 m or 4.5 ha.; noted in BHP replies to NWT Water Board Mining Industry Questionnaire for Water License Applications, 1995). Larger bodies are also present in the Exeter Lake property (e.g. Leslie at 295 m diameter or 6.8 ha., Fox at 540x380 m or 14.7 ha. BHP op. cit.), and at Point Lake and Grizzly at ~14 ha.. Examples of larger bodies also occur on other properties such as the 9 ha. DO27 (Doyle *et al.*, 1998, this volume) and the 12 ha. Ranch Lake bodies. Most of the pipes have sub-circular outlines in plan view, and those for which there is sufficient drilling and available public information, appear to be steep-sided pipes (>70°) and reach 400-500 m in depth from the present surface (Diavik bodies, Aber Resources op. cit.; BHP-Dia Met bodies Leslie, Koala, Misery, Panda from BHP Diamonds Booth at PDAC97 and Pell, 1997b). Some of the pipes have variable kimberlite-country rock contacts but most taper with depth. The Diavik pipe A21 tapers out at only ~300 m depth. It seems likely that significant parts of the pipes do not penetrate much deeper than 500 m.

The kimberlites at each of the Lac de Gras properties and the more northerly claims display some broad geological similarities and appear to be composed of two broad textural types of kimberlite, VK and HK. The mainly VK and HK infilled pipes cannot be referred to as diatremes following the definitions presented in section 2. Bodies composed predominantly of HK appear to be less common (e.g. Graham *et al.*, 1998) except within the Hardy Lake property (McKinlay *et al.*, 1998). Kirkley *et al.* (1998) state that among one hundred known kimberlites on the Exeter Lake property "in at least one case HK fills the entire pipe". There have been many reports of "diatreme-facies kimberlite" (e.g. Carlson *et al.*, 1995, 1996; Doyle and Stephenson, 1995; Nassichuk and McIntyre, 1995; numerous displays and assessment reports; BHP Diamonds PDAC97 and PDAC98 booths suggest TK is present below 500 m in the Koala pipe as well as in the Fox and Sable pipes). In contrast, the many observed public rocks and photomicrographs have included no rocks that resemble classic TKB. Most of the Lac de Gras rocks notably lack country rock granite xenoliths and there has been no evidence to substantiate the presence of the hallmark features of TK, pelletal lapilli or microlitic clinopyroxene. In fact, *the most notable feature of the Lac de Gras bodies actually is the lack of TK or TKB.* Graham *et al.* (1998) also reach this conclusion for the Diavik pipes. Pell (1997b) and Kirkley *et al.* (1998) suggests that diatreme-facies kimberlite is not common at Lac de Gras. In summary, the presence of any true diatreme-facies kimberlite has yet to be confirmed in the Lac de Gras field. It is possible that the so-called diatreme-facies rocks are massive VK.

Most of the pipes appear to consist of extrusively-formed bedded or massive VK which persists to depths of greater than 400-500 m (Carlson *et al.*, 1996; Kirkley *et al.*, 1998; J. Burgess public comm. NWT Geoscience Forum, 1997). The VK is commonly sorted with single samples usually having restricted olivine grain sizes while a suite of samples together display a wide range in grain sizes (from <0.2 mm to >10 mm). A distinctive feature of the VK is the paucity of granite and the presence of common xenoliths of shale and mudstone and pieces of wood (e.g. McKinlay *et al.*, 1998; Doyle *et al.*, 1998, this volume; Nassichuk and McIntyre, 1995). Shale blocks up to 20 m thick have been noted (J. Burgess, public comm. Geoscience Forum, 1997). The shale clasts must have been derived from sedimentary cover which overlay the Precambrian basement at the time of kimberlite emplacement, but that has since been eroded. All reported data show that the xenoliths derived from Cretaceous and Early Tertiary sediments which are mainly of marine origin. Two kimberlites at Hardy Lake in the eastern part of the Lac de Gras Province contain discrete shale xenoliths each of which are characterised by palynomorphs of a limited age range that must be derived from different stratigraphic units within the cover (McKinlay *et al.*, 1998). Together the xenoliths span the whole of the Upper Cretaceous. Some Early Tertiary sediments are also present in this area. Similar data have been reported for kimberlites on the Diavik property (100-55 Ma. mudstones, I. Graham, public comm. NWT Geoscience Forum, 1996; Graham *et al.*, 1998). These data show that the Western Interior Seaway extended over the Slave Province during the Upper Cretaceous, which is the period characterised by the highest sea levels in the history of the Seaway (Caldwell and Kauffman, 1993). Many of the shale clasts display features such as 'plastic' deformation and mixing with kimberlitic constituents along their margins, which show that the shale was poorly consolidated when incorporated into the kimberlite.

Much of the VK contains shale-rich inter-clast matrices (many display rocks, Graham *et al.*, 1998, McKinlay *et al.*, 1998, Doyle *et al.*, 1998, this volume). In two pipes at Hardy Lake, McKinlay *et al.* (1998) have shown that the inter-clast matrix is composed of thoroughly mixed disseminated shale derived from multiple stratigraphic horizons within the sedimentary cover present at the time of kimberlite emplacement. VK with such shale matrices is most likely to have been deposited by resedimentation processes (RVK). Similar features are reported by Graham *et al.* (1998) in material which they interpret as being debris flow. Kimberlitic mudstones, siltstones and sandstones are also reported to occur within the VK. Carlson *et al.* (1996) and Pell (1997b) note that non-kimberlitic clay, silt and gravel layers of sedimentary origin have been observed in some pipe at depths of over 100 m and 400 m respectively. These sediments include thinly laminated, water lain, crater infill (Graham *et al.*, 1998; Kirkley *et al.*, 1998; Scott Smith, public comm. CIM meeting, Vancouver, 1994) and some rocks display convoluted laminated bedding. Other more juvenile-rich material is also interpreted as being resedimented (e.g. Graham *et al.*, 1998). These observations suggest that a large proportion of the Lac de Gras pipes have been infilled with RVK. PK has been reported and can form a small or major part of some bodies (Doyle *et al.*, 1998, this volume; Graham *et al.*, 1998; Carlson *et al.*, 1996, Kirkley *et al.*, 1998). Juvenile lapilli are difficult to detect and appear to be not well developed. Olivine-rich PK appears to be more common. Interestingly the PK includes at least one mega-graded bed 42-46 m thick in the Diavik pipe A154N (E. Thomas, Aber Resources, pers. comm.).

Each VK infilled pipe has very different internal geology. For example, at Tli Kwi Cho two overlapping and a third nearby pipe are each infilled with contrasting types of VK (e.g. Doyle *et al.*, 1998, this volume). On the Diavik property it is reported that pipe A154S is internally uniform while in pipe A154N there is layering (Northern Miner 25/9/95). On the BHP-Dia Met property the Koala pipe is composed mainly of VK reported to be composed of several stacked sub-horizontal units (Northern Miner 18/7/94) while Panda is composed of very chaotic but uniform VK with no horizontal layering.

There have been various suggestions of different inter-relationships between HK and VK within one pipe (e.g. Pell, 1997b; Kirkley *et al.*, 1998) but little detailed evidence has been presented to allow further comment. In most cases it seems that HK is lacking in the VK infilled pipes (e.g. Doyle *et al.*, 1998, this volume; Graham *et al.*, 1998; McKinlay *et al.*, 1998). At Diavik, Graham *et al.* (1998) suggest that HK occurs only as feeders to the pipes. At Tli Kwi Cho, HK occurs only as a sub-surface sill complex which was emplaced prior to excavation of the pipes containing VK (Doyle *et al.*, 1998, this volume). Although this HK can occur directly below, and in contact with, the VK the two rock types have no direct emplacement relationship. Other bodies at Lac de Gras appear to be composed predominantly, or completely, of xenolith-poor, commonly fresh typical HK (e.g. McKinlay *et al.*, 1998; Pell, 1997a, b and BHP Diamonds PDAC97 and PDAC98 booths) which can be exposed at the present surface (e.g. Pell, 1997b; Kirkley *et al.*, 1998; McKinlay *et al.*, 1998).

With respect to pipe models, it is important to estimate the amount of erosion in the Lac de Gras area. Although all the sediments have been lost, erosion of the basement since kimberlite emplacement is presumed to be minimal (also proposed by Pell, 1997a). The thickness of the Cretaceous sediments which were present at the time of kimberlite emplacement is difficult to estimate. By comparison with regional data, these must have been less than 300 m in thickness, and possibly of the order of only 100-150 m. Similar thicknesses have been proposed by Pell (1997a) and Kennecott Canada Exploration Inc. (I. Graham, pers. comm., public comm. at NWT Geoscience Forum, 1996). Carlson *et al.* (1996) also suggest that the Cretaceous sediments formed a veneer. None of these estimates are well-constrained and the thickness of the Cretaceous cover must have varied over the craton and perhaps even within the Lac de Gras area. The sediment thickness may also have varied between the different times of kimberlite

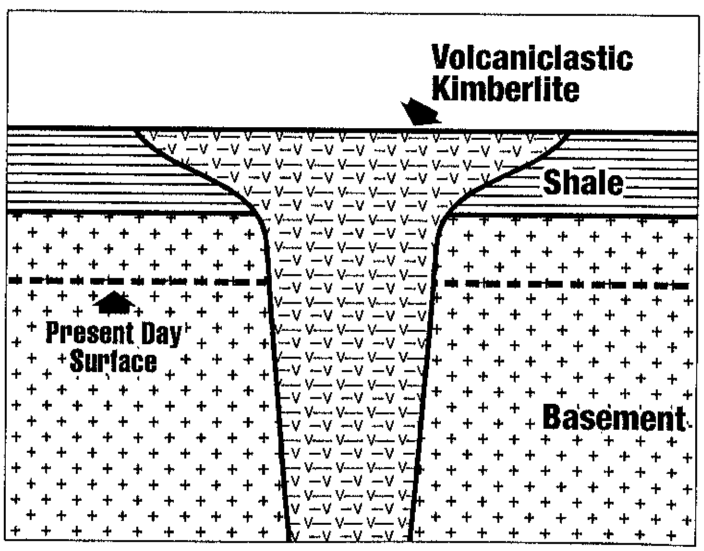


Figure 6. Schematic model of a Lac de Gras kimberlite pipe at the time of emplacement (from poster of McKinlay *et al.*, 1998).

emplacement. The available information, however, suggests that the original vertical extent of the pipes may be in the order of 600-700 m. A simplified reconstructed Lac de Gras kimberlite pipe model is shown in Fig. 6.

4.2(b) Pre-Cretaceous kimberlites of the Slave Province

To the north of Lac de Gras several kimberlites have been discovered in the Rocking Horse Lake area (Fig. 4). The best known pipe is Jericho on the Lytton Minerals property (Cookenboo, 1996; Cookenboo, 1998b; Kopylova *et al.*, 1998a, b) which has an age of 172 Ma. (Heaman *et al.*, 1997). Jericho has a very irregular shape and the proposed emplacement history suggests that an initial ~300 m elongate dyke-like body of fresh calcite HK was cut by three small pipe-like lobes up to 90 m in diameter. In contrast to the HK, the later pipe-like kimberlites are lithic breccias (with blocks up to 3 m in size) which are strongly serpentinised and lack groundmass calcite. The presence of microlitic clinopyroxene, the hallmark of TKBs (poster presentation of Kopylova *et al.*, 1998a) adds convincing support for the suggestion that the pipe rocks are true diatreme-facies kimberlites (TKB). Two other kimberlite bodies occur nearby. The larger of the two pipes, JD-3, is ~150x200 m in size and at least 300 m deep. This pipe has more regular steep-sided walls and is infilled with more consistently fragmental kimberlite. Large blocks of country rock and/or kimberlite breccia up to 7 m are present within the pipe. This pipe is suggested to represent a more typical diatreme zone (i.e. higher above any root zone than Jericho; Cookenboo, 1998a). The conclusions for Jericho and JD-3 are supported by the nature of many public display samples. Monopros Ltd has discovered additional bodies west of Jericho. Among these the Muskox pipe (~170x200 m) contains at least two texturally-distinct types of kimberlite. One is a fresh carbonate-bearing monticellite HK. The other main rock type is a much paler-coloured carbonate-poor TK which contains totally serpentinised olivines and microlitic clinopyroxene in the inter-clast matrices. These textures are typical of diatreme-facies kimberlites. Some of the textures, however, are transitional between HK and TK. Other Monopros kimberlites in this area include HK and VK.

The present country rocks surrounding the Rocking Horse Lake pipes are Archaean granitoids. However, Jericho, JD-3 and Muskox all contain common, and distinctive, xenoliths of limestone which are derived from now eroded sedimentary cover. The xenoliths from Jericho (Cookenboo and Daoud, 1996) and Muskox are Devonian limestones typical of open shelf platform deposits that are similar to outcrops some 400 km to the southwest and on Victoria Island to the north. The Middle Devonian to Mississippian periods correspond to the highest sea levels in the pre-Cretaceous. The absence of older xenoliths suggests that these limestones were deposited directly on the basement, which is consistent with regional data. The lack of younger xenoliths may indicate that the limestone cover may have been restricted in thickness at the time of kimberlite emplacement, probably less than 300 m (Cookenboo and Daoud, 1996). Regional data also suggest that Pennsylvanian to Jurassic sediments are unlikely to have been deposited in the Slave Province. If only less than 300 m of sediments have been lost, it suggests that the pipes were originally small in size.

The less well studied kimberlites discovered to the west of Lac de Gras could represent a broadly similar situation to that at Rocking Horse Lake. At Upper Carp Lake, the Monopros Jean and Rich pipes are composed of probable TKB in addition to HK. The xenoliths in the breccias include limestone and other fine grained sediments. The age of the Monopros kimberlites is not known. Approximately 20 km to the south east of Jean, on the Ashton-Pure Gold property, is the Cross pipe. This pipe is small, less than 2 ha. in size and 450 Ma. in age (Pell, 1997a, b). The kimberlite also contains common mid-Palaeozoic carbonate xenoliths (Pell, 1997a, b). Rocks from this body have been referred to as diatreme- and crater-facies but no more data are available. Although detailed information is not available, it is possible that the country rock geology comprised carbonates overlying basement which is broadly similar to that at Rocking Horse Lake.

To the south of Lac de Gras, kimberlite pipes occur at Camsell Lake and Kennady Lake (Fig. 4). On the Winspear Resources Ltd-Aber Resources Ltd property at Camsell Lake, the CL25 kimberlite pipe is 100-150 m by 50 m in size. The pipe is composed mainly of uniform TKB which contains pelletal lapilli and microlitic clinopyroxene. Some rocks have transitional textures between typical HK and TK. The age determinations for this kimberlite were unsuccessful. The country rocks consist of granitic basement. The nature of the rare apparently non-granitic xenoliths in the kimberlite has not been determined. It is therefore difficult to comment on the country rock setting at the time of emplacement.

At Kennady Lake four small pipes, including three new ones found by Monopros Ltd, are now known on the Mountain Province-Camphor property. One pipe (5034) has a reportedly precise age of 538 Ma. (Pell, 1997b). The four pipes are composed of HK and typical TKBs containing common pelletal lapilli and microlitic clinopyroxene. In parts, the textures grade from typical TKB to HK. Pipe 5034 has an irregular kidney shape. All the xenoliths in these kimberlites appear to be granites. There is no evidence for the presence of other cover rocks, which is consistent with the regional geology for that time.

A different situation appears to occur at Drybones where a 31 ha. body (900x500 m) is located close to Yellowknife on the south western edge of the Slave craton (Fig. 4). The pipe was discovered by D. Smith (of Yellowknife) and is under investigation by Trade Winds Resources Ltd. This kimberlite has yielded a spectrum of ages by different techniques that vary between 270 and 480 Ma.. The pipe appears to comprise two parts; a western portion with steeper dipping contacts and an eastern part with shallower dipping contacts of 20-60°. The pipe is infilled with xenolith-poor juvenile-lapilli-bearing olivine crystal VK. There is no evidence for the presence of TK, TKB or HK. Most of the xenoliths are granite similar to the country rock adjacent to the kimberlite pipe. In contrast to the other kimberlites in the Slave Province, the most common exotic material, other than basement, comprises common single grains of quartz found mainly in the eastern part of the body. The xenocrystic quartz appears to be concentrated towards the top of graded beds which are 2-10 m thick. Elsewhere the kimberlite appears to be more uniform and structureless. It is not clear if resedimentation is required to explain the incorporation of the quartz grains. Some varied sedimentary xenoliths appear to include more common buff coloured sand-bearing probable dolomite, less common but distinctive red coloured sediment and rare mudstone. The xenoliths, and therefore the cover rocks at the time of emplacement, are different from those at both the early Tertiary-Cretaceous and the other Pre-Cretaceous pipes on the Slave Province.

4.2(c) Summary

The Cretaceous and early Tertiary kimberlites of the Lac de Gras area comprise predominantly relatively small steep-sided pipes (>70° contacts) which were probably originally less than 600-700 m deep (Fig. 6). The country rocks appear to have been competent Archaean basement covered with a veneer of poorly consolidated Cretaceous and early Tertiary shales. Most of the pipes are infilled with VK that includes both common shale-rich RVK as well as some juvenile-rich PK. A few pipes are composed of mainly HK. Both HK and VK are exposed at surface. The most notable feature of these pipes is the lack of TK and/or TKB which indicates that they are different from the majority of pipes in southern Africa. In contrast, many of the pre-Cretaceous pipes contain common TK and/or TKB as well as HK. It appears that Jericho, Muskox and JD-3 at Rocking Horse Lake and the four pipes at Kennady Lake and the one pipe at Camsell Lake represents typical small diatremes (composed of only TK or TKB) and/or lower diatreme to root zones (with mixed HK and TK+/-B), all of which are comparable to kimberlites in southern Africa. It appears that these pipes were emplaced either into basement only (Kennady Lake and probably Camsell Lake) or into basement with a cover of possibly less than 300 m Palaeozoic limestones (at Rocking Horse Lake). Upper Carp Lake may be a similar situation to Rocking Horse Lake. A different situation occurs at Drybones Bay where a large irregular pipe was excavated into the basement and infilled with mainly juvenile-rich VK at a time when the basement was covered with different sediments that liberated common single grains of quartz.

4.3 Ontario

4.3(a) New Liskeard and Kirkland Lake

The kimberlites in Ontario are emplaced into the Superior Archaean Craton. Many kimberlites occur in two clusters at New Liskeard and Kirkland Lake near the Quebec border (Brummer *et al.*, 1992; Sage, 1996; Burgers *et al.*, 1998). Both groups of kimberlites are ~155 Ma. in age (142-160 Ma.; Brummer *et al.*, 1992, Kjarsgaard, 1996a, Sage, 1996). Many of these kimberlites contain significant amounts of TKB (e.g. Plates 45 to 50 in Mitchell, 1997). This feature, together with the presence of common HK, the small pipe sizes (<6 ha) and the shapes of some of the bodies suggests that they may represent the diatreme and root zones comparable to the southern African diatremes. The kimberlites occur at the southern edge of the craton where it is composed of granite-greenstones mainly of the ~2.7 Ga. Abitibi Subprovince. Brummer *et al.* (1992) shows that the country rocks adjacent to many of the kimberlites are varied and include Archaean volcanics of the Blake River group consisting of lava flows, pyroclastic rocks, sills, stocks and dykes as well as granitic stocks and rhyolites. Country rocks adjacent to specific kimberlites are described as andesite, andesitic tuff, dacite, basalts, sericite schist, diabase/dolerite, greywacke and quartzite. Based on the nature of xenoliths within the kimberlites, at the time of emplacement the basement must have been covered with Ordovician-Devonian carbonates, mudstone and other sediments (Sage, 1996). Armstrong and McCracken (in Sage, 1996) estimated that at the time of emplacement the kimberlites probably penetrated over 700 m of Palaeozoic sediments. Interestingly gabbros and diabase/dolerite are noted as xenoliths in the kimberlites (Brummer *et al.*, 1992; Sage, 1996, Burgers *et al.*, 1998).

4.3(b) Attawapiskat

Further north in Ontario near the west coast of James Bay along the Attawapiskat River, another province of ~180-155 Ma. kimberlites has been emplaced into greater than 250 m of Palaeozoic sediments which overlie the basement (Kong *et al.*,

Table 2. Summary of the shape, infilling and country rocks for many kimberlite pipes in Canada, reconstructed for the time of emplacement.

Province	Locality	Age	Pipe Shape	Infilling	Country Rock Sequence	Hardness	Original Surface Size	Orignal Vertical Extent (m)	Additional Comments
Saskatchewan	Sturgeon Lake	Cret.	Glacial blocks	PK	Shale block	S	?	?	
Saskatchewan	Fort a la Corne	Cret.	Shallow craters	PK	Shale Mudstone	VS VS	Large	200 m	Poorly consolidated CR
Saskatchewan	Candle Lake	Cret.	Shallow crater	PK	Shale Mudstone	VS VS	Small	100 m	Poorly consolidated CR
Alberta	Mountain Lake	Cret. or less	Shallow/steep craters	PK RVK	Sandstone Mudstone	VS VS	Medium	<500 m	Poorly consolidated CR
Alberta	Buffalo Hills	Cret.	?Shallow/steep craters	PK ?RVK	Mudstone Sediments	VS	Large	>200 m	Poorly consolidated CR
NWT	Lac de Gras	Cret. Tert.	Steep pipes	RVK, PK or HK	Shales Basement	VS H	Small	<600-700 m	Poorly consolidated upper CR
NWT	Rocking Horse Lake	Jur.	Steep diatremes	TKB HK	Carbonates Basement	?H H	Small	?>500 m	Indurated carbonates
NWT	Camsell Lake	?	?	TKB	Basement	H	Small	?	
NWT	Kennady Lake	Camb.	Steep diatremes	TKB HK	Basement	H	Small	>300 m	?No cover sediments
NWT	Drybones	Pal.	Shallow/steep pipe	VK	Sediments Basement	?S H	Large	>300 m	Poorly consolidated upper CR
Ontario	Kirkland Lake New Liskeard	Jur.	?Steep diatremes	TKB HK	Carbonates Basement	?H H	Small	?>800 m	Indurated carbonates
Ontario	Attawapiskat	Jur.	?Steep pipes	PK or HK	Carbonates Sediments	?H	Medium	?<500 m	Indurated carbonates

1998, this volume). These sediments are dominated by Silurian carbonates but other clastic sediments occur at depth. No igneous rocks are reported in this area. The kimberlites here include pipes up to 18 ha. in size (up to 300 m in diameter). The shapes of the pipes are not well known but they include some steep kimberlite to country rock contacts of at least 60-75°. It is possible that the pipes flare from the base of the Palaeozoic sediments. The pipes are infilled predominantly with xenolith-poor PK. The juvenile lapilli contain common apparently primary carbonate and no microlitic clinopyroxene is present. No TKB was found and HK is the main infill of some of the smaller bodies. There may be similarities in the nature of the kimberlites on Somerset Island, NWT to those at were also emplaced into Palaeozoic sediments with the present exposure comprising Silurian carbonates. The kimberlites include HK and possible PK. These occurrences deserve further attention.

4.3(c) Summary

In Ontario a number of kimberlites have been emplaced into Palaeozoic sediments which overlie the basement. At New Liskeard-Kirkland Lake some TKB-bearing diatremes have formed that are comparable to the southern African pipes while the notable feature of the Attawapiskat PK and HK-infilled bodies is that TKB is lacking. It is interesting to note that igneous rocks are reported in the country rock sequences at New Liskeard-Kirkland Lake but not at Attawapiskat.

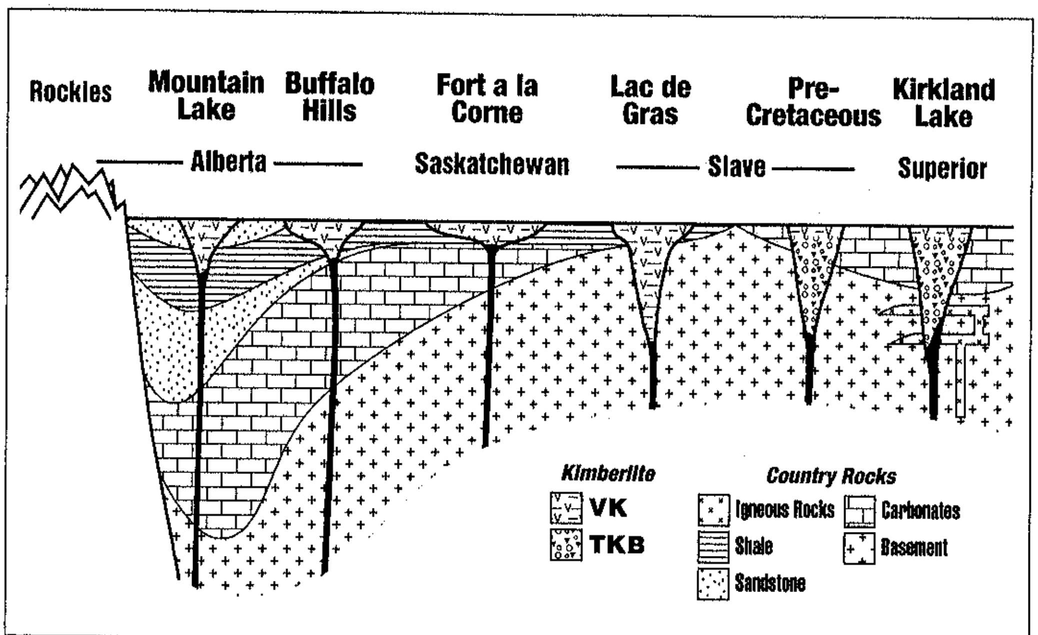


Figure 7. A schematic section across Canada summarising pipe shapes, pipe infill and geological setting for many kimberlites reconstructed for the time of emplacement. VK = volcaniclastic kimberlite; TKB = tuffisitic kimberlite breccia.

4.4 Summary of Canadian pipes

The main features of the Canadian kimberlites are summarised in Fig. 7 and Table 2 (note, that the hardness is only a visual estimate and has not been measured). Contrasting types of pipes occur in different areas. In three (possibly four) areas, the pipes appear to represent eroded TKB and/or HK-bearing diatremes that are very similar to those which dominate southern Africa. At New Liskeard-Kirkland Lake and at Rocking Horse Lake the pipes were emplaced into basement covered with ~300-700 m of indurated Palaeozoic carbonates. At Camsell and Kennady Lakes there may have been no cover rocks over the basement. Other pipes in Canada appear to contain no TK or TKB basement. Other pipes in Canada appear to contain no TK or TKB but are infilled with mainly VK or, less commonly, with HK. At Attawapiskat the pipes were emplaced into indurated Palaeozoic sediments which overlie the basement (not shown on Fig. 7). The other pipes occur where variable thicknesses of Cretaceous sediments overlie the basement. In the Canadian Prairies the pipes appear to be relatively shallow craters confined within poorly consolidated sediments. The pipe shapes vary, possibly in concert with the nature of the immediate country rocks. In Saskatchewan very shallow pipes formed in clay and mud-rich sediments while at Mountain Lake in Alberta steeper sided pipes formed in sandstone. Where only a veneer of sediments was present over the basement at Lac de Gras, small steep-sided pipes were formed within the underlying basement. The pre-Cretaceous irregular pipe at Drybones Bay also formed within the basement but the nature of the overlying sediments is not well understood.

5. NEAR-SURFACE EMPLACEMENT PROCESSES

Throughout sections 3 and 4 above, the varying pipe shapes and pipe infilling of kimberlites in southern Africa and Canada have been discussed (Figs. 3 and 7, Tables 1 and 2). In most of southern Africa, steep-sided carrot-shaped pipes correlate with the presence of TKB as an infilling (Fig. 3). This part of the pipe is termed the diatreme. Clement and Skinner (1979, 1985) recognised this relationship in the development of their textural-genetic classification scheme. Although a complete uneroded kimberlite is not known, it has been shown that the diatreme zone can extend vertically for up to 1000 m and the crater and root zones each up to 500 m. This reveals that these pipes can be relatively large edifices, and that the full volcanic structure can be up to 2 km in vertical extent as suggested by Hawthorne (1975). The kimberlites are infilled with VK, TKB and HK in different parts of the pipe. This type of pipe is not an entirely southern African phenomenon, as similar kimberlites appear to occur in Canada in both the Slave and Superior Provinces as well as in other parts of the world such as Tanzania and India (unpublished information, Scott Smith, 1989 respectively). The Canadian examples, however, are generally smaller than those in southern Africa.

In contrast, the kimberlites in the Canadian Prairies appear to be large shallow craters, possibly limited to less than 500 m in vertical extent. The craters are infilled only with VK, whilst TKB and HK appear to be absent. The VK which is present is petrographically distinct from the VK observed in southern African pipes. This type of kimberlite may not be restricted to the Canadian Prairies as similar shaped kimberlites are known from the Democratic Republic of Congo (Demaiffe *et al.*, 1991, Fieremans *et al.*, 1984; Fieremans and Fieremans, 1993) and northern Angola (Zuev *et al.*, 1988), but little is known about the infill of these pipes.

The Lac de Gras kimberlites of the Slave Province represent a third type of kimberlite pipe. They have steep-sided shapes similar to the southern African pipes but they are smaller (<600-700 m deep). The Lac de Gras pipes are infilled with VK and less common HK. Little or no TKB is present. The Jwaneng and Drybones pipes may also belong to this category.

Based on this discussion, *there appear to be at least three different types of pipes, most of which can be shown to have been repeated in space and time. The different types of kimberlite pipes must have formed by different emplacement processes.* Most of the kimberlites in Canada and South Africa appear to be typical Group 1 kimberlites. The nature of the erupting magmas, therefore, appears to be consistent in the different areas and cannot explain the contrasting emplacement styles. However, a relationship does appear to exist between the type of kimberlite pipe and the country rock geology. The most marked contrast is between the Cretaceous kimberlites that were emplaced into the sedimentary basins of southern Africa and the Canadian Prairies (compare Figs. 3 and 7). The southern African TKB-filled diatremes were emplaced into consolidated sedimentary rocks which contained common igneous rocks as sills and a thick lava capping, a distinctive feature of the Karoo Basin. In contrast, poorly consolidated country rock sediments host the much shallower craters of the Prairies. No igneous rocks occur in the Western Canadian sedimentary basin. Other pipes comparable to the southern African Cretaceous pipes were emplaced into different types of competent rocks (e.g. parts of Slave and Superior cratons). The Lac de Gras, Jwaneng and possibly Drybones kimberlites represent cases where pipes were formed within competent basement or Proterozoic country rocks that were overlain by a veneer of poorly consolidated sediments. In the cases where indurated sedimentary carbonates overlie the basement, mixed types of kimberlite pipes have formed. These include the TKB-bearing pipes of the northern Slave Province and south eastern Ontario and the TKB-absent pipes of northern Ontario. These variations deserve further attention.

The correlation between the type of pipe and the country rocks suggests that *the geological setting has a major impact on the style of emplacement of each kimberlite.* This concept is reflected in the contrasting emplacement mechanisms discussed below.

5.1 Southern African model

The emplacement model developed for the Kimberley and Orapa pipes by Clement (1982), Clement and Reid (1989) and Field *et al.* (1997) is schematically illustrated in Fig. 8. The unusual geological features that are explained by this emplacement model have been found at many other localities (as discussed in section 3.0). Thus, many aspects of this model have been validated elsewhere. It should be noted that for simplicity, only a single sequence of the intermittently repetitive sub-surface events that culminate in explosive breakthrough and short-lived fluidisation has been illustrated. Evidence from the Kimberley and other pipes indicates that several sequential episodes of such pipe-formation occurred. It is possible that multiple periods or episodes of activity are mandatory for the formation of relatively large and deep pipes. Multiple overlapping events can yield endless variations.

For the purposes of the model presented here, a simplified reconstructed stratigraphy from the Kimberley and Orapa areas in Cretaceous times is presented in the left hand column of Fig. 8(a). This country rock sequence comprises Archaean basement, Ventersdorp Archaean quartzites and lavas overlain by the consolidated Karoo sediments which contain three dolerite sills and a thick cover of Stormberg basalt. The same country rock sequence is shown in most of Fig. 8 with the rock type ornamentation replaced by cross hatching which is a schematic representation of the jointing in the country rocks. The jointing will obviously vary between, and within, different rock types.

The kimberlite emplacement process is illustrated in Figs. 8(a) to (f) by a series of ten diagrams (numbered 1 to 10). There is abundant evidence that during the last ~3 km the magma does not rise rapidly, and that prior to breakthrough the volatile-rich kimberlite behaves essentially as a closed system. Kimberlite magma (indicated by the dashed ornamentation) intrudes along jointing in the country rock (diagram 1 in Fig. 8a). This magma rises relatively slowly by stoping and wedging (diagram 2 in Fig. 8a). The magma is volatile-rich. The volatiles migrate to the head of the magma/gas column. Exsolved volatiles concentrate to form a gas cap. The volatiles aid the migration into, and along, discontinuities in the country rock. There is intensified local fracturing around the head of the intruding magma column (shown by thickened joint lines in diagram 2 and subsequent diagrams). The upward journey of the magma towards surface is intermittent. The magma/gas column rises until it encounters a temporary barrier. In diagram (2) the barrier represents a change in nature of the rocks within the Basement/Ventersdorp sequence. Other processes such as magma withdrawal could temporarily halt the upward movement of the magma.

Where the rising magma meets a barrier, there is a temporary halt in ascent and a build-up of the gas cap. Eventually after pressure build up and further fracturing, breaching of the barrier occurs by more explosive brecciation in an envelope around the head of the magma column (diagram 3, Fig. 8a). Blocky joints form the outer boundary of each envelope of breccia. The breccia contains country rock clasts (illustrated by the solid triangles) that have moved little or no distance. Kimberlite magma may, or may not, form the matrices to these breccias. Breakthrough of the barrier allows further local degassing, after which upward migration of the magma is re-established as a relatively slow intrusive process.

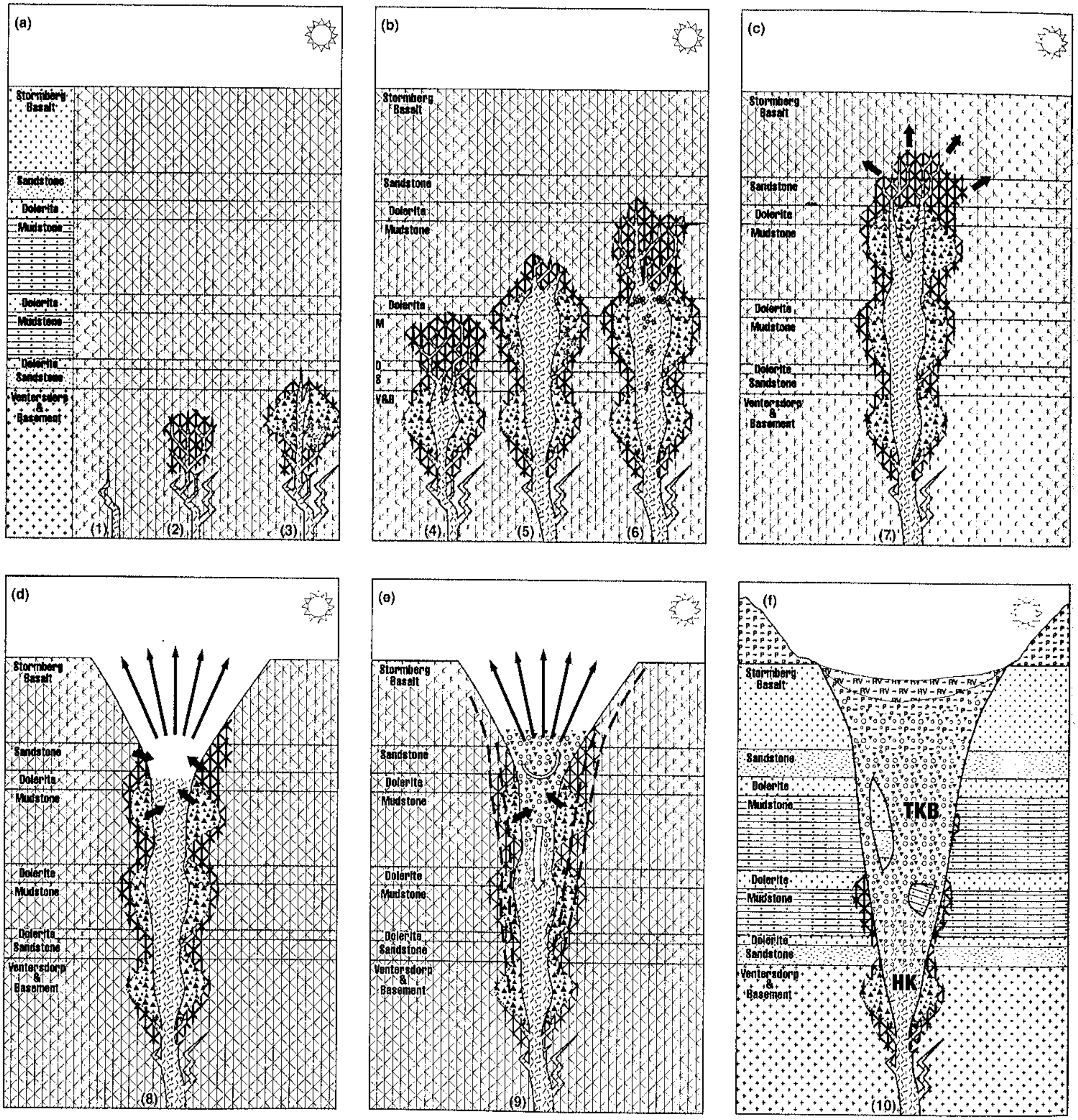


Figure 8. Schematic emplacement model for southern African kimberlites (after drawings by C.R. Clement; based on Clement, 1982, Clement and Reid, 1989, Field *et al.*, 1997). See text for details (section 5.1).

Magma and gas rises through the breccia 'front' and starts to move upwards along higher level discontinuities in the country rock. The breccia zone is preserved, at least temporarily, under "overhangs" of country rock. It is under these overhangs that globular segregationary textures are commonly preserved and testify to the importance and abundance of volatiles in the emplacement process.

The magma-gas column continues to invade the more easily penetrated areas of country rock. As the magma migrates upwards through the sediments and first dolerite sill, the magma column becomes larger (diagram 4, Fig. 8b). The second dolerite sill acts as a barrier and temporarily halts the magma migration. Volatiles continue to accumulate at the head of the magma column and below the barrier. The resulting pressure build-up again leads to explosive breaching of the barrier and the formation of another sub-surface breccia (diagram 5, Fig. 8b). The country rock stratigraphy is largely retained within the breccia (illustrated by the fine wavy lines within all the breccias). Magma migration is re-established. The size of the magma/gas column continues to increase.

The magma continues to rise by exploiting country rock discontinuities (diagram 6, Fig. 8b). The bubbles within the magma shown in diagram 6 illustrate the ongoing upward migration of volatiles. The volatiles accumulate at the head of the magma column resulting in increasing fracturing of the country rock. As the magma approaches surface, stoping and wedging will be a more effective process. The third dolerite sill halts the rise of the magma. The accumulation of volatiles below the barrier results in breaching and the formation of another breccia (diagram 7, Fig. 8c).

The Stormberg basalts act as the final barrier to magma ascent. The overall pressure and volume of exsolved volatiles continues to increase. Volatiles are forced into the country rock (illustrated by arrows in diagram 7, Fig. 8c). Fracturing and intrusion into the lower part of the Stormberg basalts occurs. All these processes (slow wedging and stoping, faster barrier breaching) gradually affect increasingly larger areas of the country rock as the surface is approached. This is due to the increasing volume of magma, the increase in volume of exsolved volatiles, the reduced confining pressure and the related greater penetration of the volatiles into country rock. Magma withdrawal at any point will cause implosion and assist the brecciation process. Prior to breakthrough to surface, a large volume of country rock has been pre-conditioned by successive sub-surface brecciation fronts (referred to by Clement as an "embryonic pipe").

Explosive breakthrough occurs when the volatile pressure exceeds the confining pressure of the last barrier, the Stormberg basalt (diagram 8, Fig. 8d). A crater is excavated. After breakthrough the uppermost part of the magma column begins to degas (illustrated by the long thin arrows). The volatiles within the country rock now migrate inwards (illustrated by the reverse direction of the short arrows compared to diagram 7). This leads to authigenic brecciation (venturi-like brecciation due to depressurisation of volatiles rammed into the country rock prior to breakthrough) which is an important process in the modification of the "embryonic" pipe that is about to occur.

The carbon dioxide and other volatiles continue to rapidly exsolve from the magma (diagram 9, Fig. 8e). This massive volatile streaming causes fluidisation of the magma and the formation of magma droplets (pelletal lapilli illustrated by open circles in diagram 9) in a volatile-rich host. As degassing progresses the interface between gas and liquid (shown by change in ornamentation from triangles and open circles to dashes), or the degassing front, moves downwards (shown by thick white arrow in diagram 9) while the magma continues to move upwards. Above the degassing front is streaming gas with entrained magma droplets in an exsolving magma (dashes). Pneumatically transported material can continue to move upwards above the interface. This powerful and turbulent fluidisation process (illustrated by the thin white arrow) aids the implosion (short black arrows) and causes erosion of the country rock to form the smooth sided, largely joint bounded, diatreme. The diatreme excavation process moves downwards with the fluidisation bed and the diatreme is gradually widened (indicated by thick dashed lines). The base of the crater is enlarged by similar erosion and collapse. Abundant small angular fragments of the country rock are incorporated into the fluidised magma (illustrated by the solid inverted triangles). Thorough mixing occurs. Sinking particles are buoyed upwards by the fluidised system. Only larger blocks of country rock move downwards. The size of the clasts that sink will vary with the degree of degassing. Most of the carbon dioxide is lost from the fluidised system.

The fluidisation stage is not long lived. The system cools rapidly (diagram 10, Fig. 8f). The remaining vapour phase condenses to produce quenched microlitic textures (the hallmark of TKBs) in the matrix of the fluidised kimberlite or TKB. The volatiles in the system are reactive and result in the total alteration of olivine (most commonly to serpentine). Much of the country rock, in the order of 50 %, remains within the diatreme ranging from small xenoliths (illustrated by inverted solid triangles) to floating reefs (two examples shown in diagram 10) and forms an essential part of the TKB. Fluidisation has shaped the diatreme by incorporating most of the pre-brecciated areas and material produced by authigenic brecciation.

As fluidisation wanes, the resultant system including the TKB, may deflate. The kimberlite magma below the fluidised system crystallises to form HK (dashes). The gradational HK to TKB boundary represents the preserved degassing front at the time of solidification. Some of the early formed irregular intrusive contacts and pre-cursor breccias are preserved in this root zone because fluidisation has not persisted long enough and deep enough to remove all traces of sub-surface pre-breakthrough activity. Contemporaneous with the events described above, juvenile and xenolithic material is ejected from the crater and forms a pyroclastic eruption cloud and the crater is infilled by PK (-P-). Extra crater deposits will also form. The PK is composed of the same constituents as, and resembles, the TKB below. The boundary between the PK and TKB is gradational. The PK may be poorly bedded. Any remaining vacant areas in the crater are infilled by post-eruption resedimentation processes (-RV-).

The pipe infill shows a gradual and progressive change in kimberlite textures with depth from partly bedded PK to intrusive monotonous TKB to HK breccia to HK. RVK which is commonly well bedded is deposited on the top of the PK. Each of these textural types of kimberlite dominates a different zone within the pipe. HK and the associated breccias occurs in the irregular root zone, TKB in the steep-sided diatreme and PK+RVK in the shallower crater. All zones of the resulting pipes are largely joint bounded.

The processes described above can be repeated and some intrusions may fail to breakthrough to surface. Multiple feeders in one location can also be involved to form interconnected pipes. Pipes with complex internal geology result and hence complex formational histories must be invoked, particularly prior to breakthrough to surface. Kimberlite pipes are not the same size. This may reflect variations in magma volume, volatile content and lateral variations in the country rock. It is also evident that some batches of HK can intrude into earlier TKB. Although many late stage intrusions have tabular, dyke-like form (e.g. Premier and Finsch) other cases are more plug-like (e.g. Orapa B/K9 and Letlhakane D/K2). To complicate matters further there are some cases of multiple TKB intrusives in single pipes (e.g. F1 and F8 kimberlite varieties at Finsch and the LM-1 and LM-2 varieties at Letlhakane).

Lorenz (1973, 1979, 1985, and 1993) has proposed that the same southern African kimberlite pipes were formed by a very different emplacement process, namely by phreatomagmatic maar processes. In Lorenz's interpretation the pipes are explosion craters which were back-filled by erosion of the crater rim deposits. In general, evidence for phreatomagmatic maar/crater formation processes is provided by the nature of the resulting base-surge deposits which occur in extra-crater deposits surrounding maars. No such deposits are preserved at any known kimberlite locality so direct evidence does not exist for the southern African kimberlite pipes. Lorenz (op cit.) also suggests that one process, namely phreatomagmatism, explains the formation of both maars, kimberlites and other diatremes (sensu lato), irrespective of magma type and nature of the pipe infilling. This review should help to dispel that notion by at least showing that contrasting emplacement processes must have been involved to form the different types of kimberlite pipes, irrespective of the nature of the processes. It is clear that in certain circumstances, phreatomagmatism is important in crater excavation, but only the sudden release of confined juvenile gases can lead to the formation of diatremes as well as the concomitant fluidisation of the magma. The latter is a magmatic process. Clement (1982) also posed the question "How does sufficient water enter the system sufficiently rapidly to be vapourised and maintain fluidised conditions in major diatremes?", to which there is no ready explanation. It is also noteworthy that the hydrogeological environment into which the different pipes were emplaced is variable while kimberlite diatreme shapes and infill is remarkably uniform. In his model, Lorenz (op cit.) relies on numerous individual phreatomagmatic blasts to produce the numerous base surge beds in the crater rim deposits. Kimberlite diatremes by contrast commonly display good evidence for one major eruption (e.g. Orapa North). The nature of the infilling of both kimberlite diatremes and the few known overlying craters contain no evidence for phreatomagmatism.

There is overwhelming evidence that shows that the main mechanism forming kimberlite diatremes was not phreatomagmatism. Most maars are shallow craters, have a unique internal geology and an underlying diatreme is seldom proven. In contrast most kimberlite pipes have proven diatremes (sensu this paper) which are deep, steep-sided pipes infilled with magmatic material (TKB) that is remarkably uniform worldwide. Many features in the kimberlites clearly show that the diatreme-infilling, TKB, does not result from resedimentation but rather from magmatic intrusive processes. These features include the lack of sedimentary structures, the consistent presence of a magmatic inter-clast matrices in the PK and TKB (presence of diopside microlites), the absence of exotic fines in the TKB and PK that are typically present in reworked material, the consistent pelletal shape of the juvenile lapilli in the TKB and PK, the gradation in textures from PK to TKB to HK with depth in the pipe, the complex morphology of root zones with the associated in-situ sub-surface breccias often preserved under overhangs and the absence of ring faults surrounding kimberlite diatremes. Also TKBs show none of the features considered to be characteristic of phreatomagmatically formed deposits such as the accretionary or blocky lapilli. In addition kimberlite diatremes are constantly smooth sided irrespective of the country rock geology. In contrast, pipes which remain vacant for periods of time during resedimentation have complex shapes depending on the angle of repose of the different country rock units in the pipe wall.

5.2 Canadian Prairies Model

The kimberlites found in the Canadian Prairies are different to those in southern Africa and so must have formed by different emplacement mechanisms. The lack of diatremes and root zones as well as their characteristic TKB-HK infill shows that the processes that formed most of the southern African pipes did not occur here. The nature of the PK within the Prairies pipes also supports the absence of any southern African-style fluidisation process. Among the features which show this are the common amoeboid shapes and vesicular textures of the juvenile lapilli, the presence of common fresh olivine, the absence of microlitic clinopyroxene and presence of common carbonate both within the juvenile lapilli and in the inter-clast matrices as well as the general paucity of xenoliths. An emplacement process for the Prairies kimberlites is discussed below. This model has not been developed to the same level of detail as the southern African kimberlite model because less detailed work has been undertaken as these pipes have not been mined.

All the Prairies kimberlite pipes are relatively shallow and crater-like in shape. These pipes represent explosion craters excavated into the in-situ country rock sediments. The pipes are all infilled with xenolith-poor VK which shows that the pipes must be formed by a two stage process : (1) crater excavation and (2) crater infilling. During crater excavation, little or none of the disrupted material was deposited back within the craters. Extra-crater deposits have not been found, hence further evaluation of the crater forming events is not possible. At FALC and Candle Lake a porous sandstone unit occurs at the base of the Mannville which is a well known aquifer. This aquifer occurs at the depth from which many of the craters flare. This observation provides circumstantial evidence suggesting that the Saskatchewan bodies were excavated by phreatomagmatic maar-like processes. There is insufficient data to show whether a similar correlation holds for the Alberta pipes, although aquifers are known to occur within the sediments where the pipes were emplaced. The Western Canadian sedimentary basin contains many long lived aquifers especially within the Cretaceous. In the Buffalo Hills area there is a well-known palaeoaquifer (the Wabiskaw/Blue Sky sandstone) at ~300-325 m below surface which forms the basal part of the Cretaceous. The single known pipe shape is consistent with flaring from this aquifer. If so, this would offer some support for a phreatomagmatic pipe excavation process. Deep seismics show that well known reflectors within the country rocks are disrupted down to at least 1600 m which is the top of the basement. Carlson *et al.* (1998) suggest that this shows that the pipe flares from this point. However, the disruption of the reflectors could be caused by the feeder to the craters rather than indicating that true excavated pipes extend to that depth.

At Mountain Lake the southern body has been shown to be deeper and steeper sided than those at FALC. If these pipes formed by phreatomagmatic maar-like processes, the difference in shape could result from a deeper explosive event associated with a deeper aquifer and/or differences in the immediate country rocks. At Mountain Lake the uppermost crater walls are composed of sandstone while the uppermost crater walls are poorly consolidated clay-rich sediments at FALC.

The crater infilling in all the Prairies pipes appears to result predominantly from subaerial, magmatic, pyroclastic eruptions. Other features which support the lack of resedimentation are most evident at FALC and include: the low particle density; in-situ impact fragmented xenolithic bombs; the occurrence of composite lapilli showing that some mixed lapilli populations result from recycling not resedimentation; the presence of different phases of eruption with sharp internal contacts; the lack of abrasion or breakage of the pyroclasts; the lack of cross bedding and other sedimentary features; the presence of thick graded beds (up to at least 90 m) with associated marker horizons and the overall lack of fines and incorporation of country rock material. Limited resedimentation appears to have occurred at FALC but this process may be more common in the Buffalo Hills pipes. At Mountain Lake, the two pipes have been infilled by contrasting processes. The southern pipe appears to have been infilled predominantly by primary pyroclastic airfall resulting in juvenile-rich volcaniclastics with minor dilution by country rock material. The northern pipe must have had a different infilling history to explain several contrasting features, such as the high proportion of xenocrystic quartz and the presence of very large blocks of sediments. It is suggested that much of the infilling resulted from secondary resedimentation processes of extra-crater deposits and material perhaps derived from the southern body during its formation.

Although the overall nature of all the pipes in the Prairies appears to be similar, each pipe is different. Within FALC it can be seen that the styles of eruption were very variable. The less explosive activity ranged from lava spatter with welding/molding and no bedding to higher lava fountains and possibly more explosive Strombolian-style eruptions resulting in bedding up to perhaps 12-15 m thick. These eruptions form juvenile lapilli by the fragmentation of non-fluidised magma due to high exit velocities or degassing. The juvenile lapilli vary in shape from spherical or ovoid to the unusual irregular-curvilinear or amoeboid types. Although not always present, amoeboid-shaped lapilli are considered diagnostic and a hallmark of this type of kimberlite eruption. Some of the juvenile lapilli contain vesicles. The nature of these lapilli is markedly different from those formed in kimberlite diatremes during fluidisation. At FALC some pyroclastic deposition into crater lakes resulted in better sorting and thinner bedding. However, the overall paucity of ash at FALC is suggested to indicate that most of the eruptions occurred in dry conditions with the fines being lost by wind action. In contrast to the southern body at Mountain Lake, the presence of common fine grained material as well as armoured lapilli, suggests deposition from wet subaerial eruption clouds.

At FALC a more explosive type of eruption resulted in the deposition within the crater of individual graded beds up to at least 90 m in thickness. The latter appear to be unique in the geological record. These deposits appear to contain a different type of pyroclastic juvenile lapilli which only has a thin selvage of kimberlite magma on pre-existing clasts. These eruptions are considered to result from the rapid and massive degassing of magmas close to surface.

At FALC, the conformable thin beds of xenolith-poor VK including some PK occur within the Mannville Formation below the main craters. These kimberlites are thought to have been deposited at different times during most of this period of sedimentation onto the subaerial flood plains (~119-100 Ma.). These kimberlites formed prior to the deposition of the overlying Ashville shales and the subsequent excavation of the main FALC craters into the full sequence of sediments.

In summary, the main Prairies kimberlites were emplaced by two distinct processes : crater excavation and crater infilling. Crater formation may have resulted from maar-like phreatomagmatic processes with the excavated (and juvenile) material deposited mainly as extra-crater deposits. The craters were subsequently rapidly infilled by subaerial primary pyroclastic magmatic processes with overall limited but varying amounts of resedimentation. No diatreme or root zones or related textural types of kimberlite are present. This emplacement model, therefore, is different from the classic southern African diatreme model. The size, shape and nature of the infill of the Prairies kimberlites is comparable with maars.

Alternate emplacement models for the Prairies kimberlites have been proposed by Leckie *et al.* (1997a and b). Most of the interpretations of the nature of the kimberlites, the associated sediments and even the style of eruption are very similar to that suggested by Scott Smith (numerous unpublished reports), Scott Smith *et al.* (1994, 1995, 1998), Scott Smith, (1996) and Wood *et al.* (1998). At FALC Scott Smith (op cit.) investigated 44 drillcores from 25 bodies including the single drillcore reported by Leckie *et al.* (1997a). The uppermost part of the drillcore investigated by Leckie *et al.* (1997a) contains one of the rare examples of RVK and of interbedded sediments which occur in the drillcores examined by Scott Smith (op. cit.). The principal difference in interpretation between Scott Smith (op cit.) and Leckie *et al.* (1997a) is whether the main FALC kimberlites were deposited as volcanic cones at surface or within craters excavated into the sediments (respectively). The crater model is proposed by Scott Smith (op cit.) to take account of the undisturbed sediments and the upward flaring shape that was found for all the bodies into which multiple holes were drilled. Also the breccia or marker horizon that forms the base of the ~90 m mega-graded bed in one body mirrors the upward flaring pipe shape shown by drilling. Other features which support the excavation of craters are cross cutting contacts, the absence of intercalated sediment beds and the presence of different types of partly consolidated sediments in intersections of all sizes up to 13 m. The latter are interpreted as xenolithic clasts based on the clast shapes, variable steep and non-conformable contacts, different attitudes of the bedding within the clasts relative to the host kimberlite and the fact that some xenoliths appear to occur below their stratigraphic level in the adjacent country rock. Leckie *et al.* (1997a) also do not explain how newly deposited PK volcanic cones would survive the marine transgression.

Leckie *et al.* (1997a) suggest that the main kimberlite volcanism occurred at 101 Ma. based mainly on the single isotopic age determined in their work. Stratigraphic relationships, although not tightly constrained, led Scott Smith (op cit.) to suggest that the main kimberlite emplacement at FALC occurred during a period of 5-10 Ma., possibly between 98 and 91 Ma. Younger isotopic ages of 94-98 Ma. consistent with such a period of emplacement have been determined but Leckie *et al.* (1997a) suggest these are erroneous. The stratigraphic constraints also suggest that the single body examined by Leckie *et al.* (1997a) is the oldest of the bodies for which there are suitable data, which may be consistent with the isotopic age of Leckie *et al.* (1997a). Periodic eruptions from one or more centres is characteristic of most volcanic rocks, not only kimberlites.

Similar differences occur between the emplacement models for Mountain Lake in Alberta. Wood *et al.* (1998) present evidence which not only supports the deposition of VK into excavated craters but also appears to contradict the model of Leckie *et al.* (1997b) who suggest that the PK formed a positive relief volcanic feature or cone. The evidence includes body shapes with inward dipping country rock to kimberlite contacts and the recognition of xenoliths occurring in the kimberlite below their stratigraphic level in the adjacent country rock.

In the Prairies emplacement model presented here, the proposed crater excavation does not exclude the possibility that positive relief deposits also formed. In fact it is considered likely that they did form, both within and outside the craters. Also the Prairies model does not exclude the possibility of kimberlites erupting without crater formation. If no aquifer was encountered during magma ascent, then any magma reaching surface would have to form extrusive deposits on top of the surface. This is the process considered most likely to explain the conformable pre-cursor kimberlites that occur within the Mannville sediments at FALC.

Nixon and Leahy (1997) and Leahy (1997) describe some small intersections of VK (up to 14 m thick) at FALC as extra-crater or apron deposits. Given the location of these kimberlites along the periphery of known craters, it is equally possible that they could represent a thin distal flange within the crater of one of the nearby kimberlite pipes. The evidence presented does not clearly distinguish between these two options. One example is described as interbedded with sediments deposited in subaerial swamps and tidal flats, a situation which superficially appears to be comparable to the pre-cursor beds found within the Mannville Formation below many of the other main craters. Nixon and Leahy (1997) and Leahy (1997) suggest that the kimberlites they describe are composed of PK and RVK. Leahy (1997) attempts to identify reworking of VK using the degree or rounding of olivine grains but takes no account of the fact that a typical kimberlite contains olivines with different pre-eruption shapes. Kimberlites, including many of those at FALC, contain two generations of olivine : (1) large anhedral macrocrysts (typically up to 10 mm) which commonly have rounded shapes and (2) smaller (typically <0.5 mm) phenocrysts that are usually euhedral in shape. Although rounding can be an indicator of reworking, it may not be simply applied to kimberlite-derived olivines. For example, different kimberlites within the FALC province contain different proportions of the two generations of olivine before eruption. Some kimberlites lack the macrocrysts. In other instances the two generations of olivine can be separated by pyroclastic depositional process to form rocks dominated by either rounded macrocrysts or by euhedral phenocrysts. These variations could explain some of the contrasting proportions of rounded grains observed by Leahy (1997). The reported presence of cross bedding, fish debris, bivalves, ripple marks, increased clast density and marine shales are more convincing evidence for reworking for some of the FALC kimberlites.

5.3 Lac de Gras, Slave Province

The lack of granitic material within the pipe infill of the Lac de Gras pipes, whether VK or HK, suggests that the pipes formed by two distinct processes : (1) pipe excavation and (2) subsequent pipe infilling. It is evident that all the disrupted granite resulting from pipe excavation must have been deposited outside the crater. After the pipes were completely excavated, the infilling was probably a relatively long lived process as many pipes contain not only shale-rich RVK but also non-kimberlitic sediments at considerable depths. These pipes must, therefore, have remained open for a significant period of time. Primary pyroclastic activity also contributed to the VK infilling of the pipes including at least one mega-graded bed. Some pipes, possibly overall only rare examples, must have been excavated and then infilled with HK. It is suggested that only limited erosion has occurred in the Lac de Gras area and that essentially only the veneer of Cretaceous and younger sediments has been removed. If so, the HK must have reached very close to surface. It is not clear whether the HK displaced previous kimberlitic material or infilled a void pipe. If the latter, the kimberlite magma would essentially have formed a lava lake, a feature not previously recognised in kimberlites.

The Upper Cretaceous shale which overlay the basement at the time of kimberlite emplacement, was deposited mainly under marine conditions. In contrast, the youngest sediment xenoliths examined from the Hardy Lake kimberlites are terrestrial (McKinlay *et al.*, 1998). These data suggest that at least the younger kimberlites in the Lac de Gras area were emplaced under subaerial conditions. This conclusion is supported by the presence of common wood in many of the pipes.

The most intriguing feature of the Lac de Gras occurrences is the nature of the process which excavated the pipes. With respect to the two emplacement models discussed above, the two stage process, pipe excavation and subsequent infilling proposed for the Canadian Prairies kimberlites superficially appears most similar. Phreatomagmatism should therefore be considered as a possible process but seems to be an unlikely candidate for the Lac de Gras situation given the lack of any traditional aquifers, the strength of the country rock, the confining pressure, the pipe shapes and the fact that the hydrogeological setting is probably not consistent over the whole Lac de Gras kimberlite province. It must, therefore, be considered whether processes similar to those forming the southern African diatremes apply at Lac de Gras. The steep joint bounded pipe shapes appear to be broadly similar to the southern African diatremes (cf. Clement, 1982). The main problem is the lack of TKB which is an integral part, and the product, of the diatreme formation/fluidisation process. It is not obvious, therefore, whether such a fluidisation process could have occurred here. In this respect the confirmation of the presence or absence of any true TKB in this province is vital.

It has been proposed above that the southern African-style diatremes can occur only in a closed system imposed by the country rock geology. It is possible that at Lac de Gras, the basement rocks could have offered a relatively difficult route to surface which allowed for some build up of sub-surface juvenile volatiles which in turn could have caused the excavation of diatremes. Small diatremes containing TK and/or TKB did form in similar basement elsewhere in the Slave Province (see section 4.2(b)). Although at Lac de Gras wider craters must have developed above the present pipes in the overlying poorly consolidated sediments (Fig. 6), overall, the pipes appear to be significantly smaller in both diameter and depth than many of the southern African pipes where estimated pre-erosion sizes of greater than 50 ha are common (compare Tables 1 and 2). This suggests that less powerful or shorter-lived eruptions may have occurred at Lac de Gras. If the eruptions were southern African-style fluidisation events, the small pipe size could perhaps reflect the absence of the effective igneous cap rocks. When the Lac de Gras kimberlite magmas reached 100-150 m from surface, they would have encountered the Cretaceous shales, much of which may have been wet mud. This is in marked contrast with the uppermost rocks of the Cretaceous in southern Africa which were massive basalts. At Lac de Gras breakthrough would have been relatively easy, and perhaps even enhanced by phreatomagmatic explosions resulting from magma-wet sediment interaction. It is possible that any diatreme-style emplacement process would be either aborted or changed when the cover sediments were encountered. This scenario may or may not be able to account for the lack of TKB. Interestingly, the pre-Cretaceous kimberlite diatremes in the Slave Province were emplaced before the deposition of the shales over the basement.

Well constrained emplacement models for any kimberlites result from long-term detailed investigations based on extensive three dimensional exposures. Based on this comment, it may be premature to discuss further any possible emplacement scenarios for the Lac de Gras kimberlites. A third emplacement process may be applicable. *It is clear, however, that neither of the two emplacement mechanisms that have been proposed above, the southern African diatreme and the Canadian Prairies maar-like models, can completely explain the Lac de Gras kimberlites.*

5.4 Pre-Cretaceous kimberlites, Slave Province

The presence of steep-sided pipes containing TKB away from Lac de Gras shows that the southern African diatreme-fluidisation model is applicable in parts of the Slave Province, perhaps only before the deposition of the Cretaceous sediments. The Rocking Horse Lake (and probably Upper Carp Lake) pipes were emplaced into basement covered by lithified carbonates while at Camsell and Kennady Lakes there appears no cover over the basement. It appears, therefore, that *different country rock settings have allowed southern African-style diatremes to form,* presumably by both the basement and overlying indurated carbonates providing a closed system for the kimberlite magma prior to breakthrough. It may be significant that these pipes are all substantially smaller than many found in southern Africa. This again may relate to the lack of cap rocks as effective as the basalts of southern Africa. The contrasting nature of the Drybones Bay irregular shaped VK-infilled pipe that lacks TKB, perhaps relates to the fact that, at the time of emplacement, the basement may have been covered by sand-bearing, possibly poorly consolidated sediments. As such, this pipe could have similarities with Jwaneng and Lac de Gras.

5.5 Ontario

At New Liskeard-Kirkland Lake typical TKB-infilled diatremes are present which shows that a process comparable to the southern African diatreme emplacement mechanism must have occurred here. In contrast, the Attawapiskat kimberlites lack TKB. The lack of xenoliths in these pipes shows that the PK- and the less common HK-infilled pipes were formed by a two stage process, pipe excavation and pipe infilling. The pipes were infilled primarily by primary pyroclastic processes. There is no evidence, however, to indicate the nature of the pipe excavation process. Both types of pipes were emplaced into 500-700 m of Palaeozoic sediments. It is interesting to note that igneous rocks appear to be present in the new Liskeard-Kirkland Lake area while they are absent at Attawapiskat. Better constrained data are required to allow more meaningful comment.

5.6 General kimberlite emplacement processes

It is proposed above that most southern African kimberlites are deep steep-sided pipes that comprise three distinctive zones (crater, diatreme, root) which formed by an intermittent intrusive-extrusive process driven by the build up of juvenile gases confined below surface when the magma ascent is impeded by temporary barriers/caps producing a closed system. The barriers/caps commonly include numerous dolerite sills and basalts. Sudden breakthrough results in a fluidised system that excavates the diatreme and *contemporaneously* fills it with xenolith-rich TKB. The Prairies kimberlites are thought to result from a contrasting maar-like emplacement mechanism which forms shallow pipes that comprise only one zone, the crater. The Prairies kimberlite magmas were offered an easy route to surface through the poorly consolidated sediments which lack any barriers such as igneous rocks. This situation provided an open system for eruption that precluded diatreme formation. Near surface aquifers prompted phreatomagmatic crater excavation. *Subsequent* magmatic eruptions infilled the craters with xenolith-poor PK and some RVK. The PK is texturally different to that occurring in the southern African pipes. If aquifers are absent, volcanic cones may form without any pipe excavation.

The two contrasting environments of emplacement, the closed and open systems, are imposed on the kimberlite magmas by the country rocks. *The nature of the country rocks encountered by an erupting magma, therefore, must be a major control on the emplacement mechanisms of any kimberlite.* A third, as yet less well understood, emplacement mechanism must occur where VK-infilled small steep pipes are emplaced into Archaean or Proterozoic basement covered by a veneer of poorly consolidated, perhaps wet, sediments. A relationship between the geological setting and the mode of emplacement has been proposed previously. Cas and Wright (1987, see Fig. 13.16) show in western Victoria, Australia that phreatomagmatic craters occur where a cover of aquifer-bearing sediments overlies the basement. Where the cover sediments are absent, scoria cones and lava shields form.

It is proposed that the Prairies maar-like style of pipe excavation process is driven mainly by the interaction of magma with an aquifer. In contrast, the southern African pipe formation has been shown to be driven primarily by juvenile volatiles. Neither of these proposed extremes in emplacement processes precludes the involvement of the other mechanism. For example, the subsurface brecciation that occurs during embryonic pipe formation in diatremes could be enhanced if water is encountered along the joints in the country rock. In the maar-like situation, exsolution of juvenile volatiles near-surface could aid crater excavation.

The formation and infilling of diatremes distinguishes many kimberlite pipes from those formed by other intrusives. The TKB which infills kimberlite diatremes is a texturally unusual rock type with equivalent rocks observed only among melnoitic magmas. Although the Prairies maar-like process is analogous to that observed in other rock types and the products of the pyroclastic eruptions that infill these pipes show similarities to other volcanic rocks, they also display features that appear to be unique to kimberlites. These features include the presence of mega-graded beds up to at least 90 m thick. The unique aspects of kimberlite pipes shows that, although the country rock geological setting is a major control on the mechanism of emplacement, the high carbon dioxide contents of kimberlite magmas also have an important impact on the style of emplacement. The southern African-style of pipe formation and the Prairies mega-graded beds could not occur without the presence of the abundant volatiles that degas near-surface. Kimberlites are unusual in that they retain a large proportion of juvenile volatiles, notably carbon dioxide, when the magmas approach surface. Dreibus *et al.* (1995) show that in kimberlite magmas a major degassing event appears to occur at ~45 kb but further degassing does not occur until pressures are less than 10 kb.

Another important aspect of emplacement is the surface environment. It is interesting to note that most of the observed kimberlites are interpreted as having erupted under subaerial conditions. No submarine kimberlites have been identified despite the fact that many kimberlites erupted during periods of overall marine conditions (e.g. Prairies, Lac de Gras, Jwaneng).

On a smaller scale the more detailed nature of individual pipes will be affected by many factors, such as the nature and strength of the local country rocks, magma volumes, volatile contents, depth and size and nature of any aquifers, and the number and timing of volcanic events at one eruptive centre, and so on.

6. CONCLUSIONS

Comparing and contrasting kimberlite pipes in southern Africa with those in Canada shows that different types of pipes are present. There is variation in both pipe shape and the pipe infilling. At least three main types of pipes have been identified: (1) deep, steep-sided pipes typical of southern Africa which comprise three zones (crater, diatreme, root) that are infilled by different textural varieties of kimberlite (VK, TKB and HK respectively), (2) shallow pipes typical of the Canadian Prairies which comprise only the crater zone and are infilled only with VK, and (3) small steep-sided pipes typical of Lac de Gras in the Slave Province which are infilled mainly with VK. The different types of kimberlite pipes appear to have been repeated in space and time. Different emplacement mechanisms must be involved in the formation of the different types of pipes. Contrasting kimberlite emplacement models, therefore, are valid and necessary.

There appears to be a correlation between the type of pipe and the geological setting. The types of pipes listed above have the following setting: (1) competent country rocks which contain common igneous rocks, (2) poorly consolidated sediments, and (3) basement covered by a veneer of poorly consolidated sediments (respectively). This suggests that the near-surface geological setting into which kimberlites are emplaced is a major control in determining the mechanism of pipe formation for any kimberlite. The different emplacement mechanisms are suggested to be : (1) the southern African diatreme model which is driven by juvenile volatiles in magmas that erupt from closed systems and (2) the Canadian Prairies maar-like model in which pipe formation is driven by meteoric water in phreatomagmatic eruptions occurring in open systems and (3) a different emplacement mechanism which is presently poorly constrained but does not conform to either (1) or (2). The closed versus open systems proposed for mechanisms (1) and (2) are imposed on any ascending magma either by competent (closed-system) or poorly consolidated (open-system) country rocks. When compared to other rock types, all the kimberlite emplacement processes have unique aspects that reflect the abundance of juvenile volatiles, especially carbon dioxide, which are still incorporated in the magma close to the time of eruption.

Further work is required to constrain the concepts proposed in this paper further, as well as to explain the origin of some pipes which do not appear to conform to either of the two proposed emplacement mechanisms. A major omission of this work is the lack of discussion of the kimberlites of Yakutia which appear to show other variations in kimberlite geology (e.g. Mitchell, 1995).

This review also presents new evidence which strongly supports the southern Africa Cretaceous pipe model and emplacement processes proposed by Hawthorne (1975), Clement (1982), Clement and Skinner (1985) and Clement and Reid (1989). It is also shown that the same process has occurred at different geological times in southern Africa and in other parts of the world. This model and emplacement mechanism alone, however, cannot explain the nature of the contrasting types of pipes.

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