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Canadian kimberlites: Geological characteristics relevant to emplacement

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Abstract

In Canada more than 770 kimberlites have erupted in diverse tectonic settings over a period of 1000 Ma and over an area at least 5000 km across. The kimberlites represent at least 30 comagmatic fields. One pipe type dominates each of the different kimberlite fields. Even with the discovery of a significant number of new kimberlite fields, this review of recent data substantiates the previous proposal that there are at least three distinct classes of kimberlite pipes which show a correlation with the nature of the country rocks into which they were emplaced. New data show that a variation on the Prairies pipe type occurs when kimberlites were emplaced into competent Paleozoic sediments resulting in steeper-sided pipes infilled with similar pyroclastic kimberlite. New data for each pipe type are summarised and the contrasting characteristics of the three pipe types are considered to reflect fundamentally different styles of eruption and deposition. Apparently uniform, near-surface, olivine- and volatile-rich kimberlite (PK), tuffisitic kimberlite (TK) and associated hypabyssal kimberlite (HK) or resedimented kimberlite (RVK) dominating each type of pipe. The substantiated correlation of pipe type with country rock geology could indicate variable constraints on volatile exsolution which affected the nature of the magmatic eruptions in different settings. © 2007 Elsevier B.V. All rights reserved.

Keywords: kimberlite; emplacement; pyroclastic; tuffisitic; hypabyssal; diamond

1. Introduction

Increased exploration activity in Canada during the last two decades has resulted in the discovery of hundreds of kimberlites. At least 770 bodies are currently known (figure courtesy of De Beers Canada Inc.), a significant number of which are economic including: three mines; two imminent mines; and a number of advanced evaluation projects (Fig. 1). The requisite detailed investigations to develop these mineral resources have resulted in a wealth of new data. The geological characteristics of many Canadian kimberlites are summarised below to provide crucial evidence for the understanding of emplacement processes.

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2. Kimberlite magmatism

Canadian kimberlites, which occur across at least ~5000 km (Fig. 1), were emplaced into diverse tectonic settings (Slave and Superior Archaean cratons, Buffalo Head and Sask possible cratons, Rae, Hearne, Trans-Hudson, Torngat and Arctic partly reworked peri-cratonic areas; e.g. Hoffman, 1988; Levinson et al., 1992). Ages of emplacement range from 1100 to 45 Ma (Heaman et al., 2004). An array of ages commonly occurs in each of the tectonic settings (e.g. 613–45 Ma on the Slave craton, 1100–140 Ma on the Superior craton; Heaman et al., 2004). Thus, kimberlite magmatism has been repeated in space and time within Canada.

The kimberlites in Canada (Fig. 1) occur in more than thirty discrete comagmatic fields containing $\sim 10-250$ bodies within restricted areas < 100 km across. Where there are sufficient data, single fields appear to result from kimberlite emplacement over a period of approximately 30 Ma (e.g. Lac de Gras, New Liskeard-Kirkland Lake and Attawapiskat; Creaser et al., 2004;

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Fig. 1. Location of Canadian Kimberlites (Mineral Information Map, 2006; Faure, 2006). NT = Northwest Territories, NU = Nunavut, AB = Alberta, SK = Saskatchewan, ON = Ontario, QC = Quebec.

Heaman et al., 2004). Smaller datasets for other fields suggest that emplacement occurs over at least ~10 Ma (e.g. Birch Mountains; Fort à la Corne with additional stratigraphic controls suggesting ~20 Ma). Single kimberlites appear to have formed in <1-2 Ma, the resolution of the age determination techniques (Creaser et al., 2004; Heaman et al., 2004; Lockhart et al., 2004).

Subvolcanic hypabyssal kimberlites indicate the nature of near-surface kimberlite magmas prior to modification during volcanic eruption processes. Hypabyssal kimberlites (HK) occur in most, but not all, fields across Canada. The majority are similar to HKs worldwide being composed of ~25 vol.% olivine macrocrysts (mantle-derived xenocrysts <15 mm), \sim 25 vol.% olivine phenocrysts (<0.5 mm) and 50 vol.% former melt represented now by a finer grained groundmass (<0.2-0.5 mm; monticellite, phlogopite, spinel, perovskite, carbonate, serpentine and apatite). The similarity of the HKs across Canada, and the world, is consistent with suggestions that they are asthenospheric melts (Mitchell, 2008-this volume). The olivine phenocrysts crystallised well before near-surface emplacement, probably within the mantle (Mitchell, 2008-this volume). The presence of ~50 vol.% mantle-derived olivine crystals together with the preservation of diamonds indicates that the mantle to surface ascent of most kimberlite magmas must have been relatively rapid and did not involve long term residence in magma chambers. The rapid ascent is probably a consequence of the abundance of volatiles in the magma as shown by the presence of primary phlogopite, serpentine and carbonate in the HKs (Mitchell, 2008-this volume). The repeated and consistent 50 vol.% abundance of olivine might represent the upper limit of the crystal carrying capacity of most kimberlite magmas. Near-surface en-masse crystallisation of the magma in most HKs is indicated by the consistent fine grain size of the groundmass minerals and the lack of features such as crystal settling.

3. Kimberlite geology

Field and Scott Smith (1998, 1999) showed that many of the kimberlites discovered in Canada in recent years are different to those in southern Africa that were previously examined in detail. New textural types of kimberlite were highlighted and three types of pipes were identified:

- (1) large shallow bowl-shaped pipes infilled mainly with pyroclastic kimberlite (PK),
- (2) small, steep-sided pipes infilled predominantly with resedimented volcaniclastic kimberlite (RVK), and

(3) small, steep-sided pipes that contain tuffisitic kimberlite breccia (TKB) and hypabyssal kimberlite (HK).

Field and Scott Smith (1999) also noted a correlation between the type of pipe and the nature of the country rocks into which they were emplaced. Subsequent to Field and Scott Smith (1999), a decade of further work has resulted in at least 250 new discoveries. Investigations of an estimated ~700 drillcores from each of the three different types of pipes as well as the examination of mining exposures have been undertaken by exploration and mining companies and academic institutions, including the author. Recent data for pipe shapes are presented in Figs. 2 and 3. The overall shared characteristics of kimberlite and country rock geology for each pipe type are summarised in Figs. 4 and 5 and Table 1 and are discussed below (in the order listed above). Although this paper emphasizes the similarities between the pipes of each of the three types, it should be noted that each individual pipe is unique resulting in considerable variation in geology between pipes of any of the types.

3.1. Prairies-type kimberlites

The first kimberlites of this type were found in 1988 in Saskatchewan and ~75 bodies are currently known. Subsequently, in Alberta, the Mountain Lake, Buffalo Hills and Birch Mountains fields were discovered in 1990, 1997 and 1998, and include 2, 36 and 8 pipes, respectively (Wood et al., 1998; Carlson et al., 1999; Skelton and Clements, 2002; Eccles et al., 2004). The emplacement ages of the Prairies kimberlites are 70-104 Ma (Heaman et al., 2004). The immediate country rocks to the Prairies pipes are poorly-consolidated Cretaceous sediments (Fig. 4a). The pipes are infilled with pyroclastic kimberlite (PK) as illustrated in Fig. 4a. The Attawapiskat kimberlite field in Ontario was discovered in 1988, simultaneous with those in Saskatchewan. Within this field, the \sim 170 Ma eroded, steep-sided Victor pipes (see inset in Fig. 2) are infilled with PK similar to that occurring in the Prairies kimberlites (cf. Fig. 4a; Webb et al., 2004). Comparable pipes occur not only in the rest of the Attawapiskat field (Kong et al.,



Fig. 2. Prairies kimberlite pipe shapes. The Prairies kimberlites are large (up to 250 ha), relatively shallow bowl-shaped bodies. A narrow steep-sided feeder vent has been defined at Star. Two feeders occur in FALC 140-141 and FALC 122. Kimberlite to country rock contact dips are ~0–60°, most commonly 15–45°. FALC 169 (shaded) was selected for Fig. 4. The inset shows one example of the steep-sided bowl-shaped bodies that occur outside the Prairies. See Fig. 1 for locations of kimberlite fields. Data are for the Fort à la Corne (FALC) Joint Venture (Scott Smith, 1996; Scott Smith et al., 1996; poster of Scott Smith et al., 1998; Berryman et al., 2004; Kensington Resources Limited, website of June 2005; Jellicoe, 2005; Lefebvre and Kurzlaukis, 2006), the Star Diamond Project adjacent to FALC (Leroux, 2005), Candle Lake C28 north of FALC (Hetman, 2007; Great Western Diamonds Corporation, website www.gwdc.ca, of January 2007), kimberlite BHH-K14 and other pipe sizes in the Buffalo Head Hills field (Carlson et al., 1999; Skelton and Clements, 2002), sizes of the Birch Mountains bodies (Eccles et al., 2004) and for Victor South, Attawapiskat (Kong et al., 1999; Webb et al., 2004, 2006).

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Fig. 3. Lac de Gras kimberlite pipe shapes. The Lac de Gras kimberlites are mainly small, steep-sided pipes ($\leq 2-3$ ha, occasionally up to 20 ha as illustrated by Fox). Pipe contact angles are typically 75–85° but steeper and overhanging contacts also occur. Koala (shaded) was selected for Fig. 4. See Fig. 1 for locations. Data are for the Ekati Diamond Mine (Nowicki et al., 2004; Dyck et al., 2004; unpublished data provided by BHP Billiton Diamonds Inc.) and the Diavik Diamond Mine (A154N and S, A21 and A418, unpublished 2006 Diavik Diamond Mines Inc. geological models).

1999) but also in the Kirkland Lake-New Liskeard area (unpublished information) and the Northern Slave in Nunavut (e.g. Jericho discovered in 1995, unpublished information; Knife Lake found in 2001, Hetman et al., 2004b). All these pre-Cretaceous steep-sided pipes were emplaced into consolidated Paleozoic sediments dominated by carbonates and, thus, appear to represent a variation on the Prairies-type of pipe occurring in competent sediments.

3.2. Lac de Gras kimberlites

The Lac de Gras kimberlite field was discovered in 1991. Since then many new occurrences, but no new fields of comparable kimberlites, have been found. The emplacement ages of the kimberlites are 45–74 Ma (Creaser et al., 2004; Heaman et al., 2004; Lockhart et al., 2004). The geological setting is basement covered by a veneer of poorly-consolidated Cretaceous and younger sediments. The distinctive feature of these pipes is the abundance of resedimented volcaniclastic kimberlite (RVK) as shown in Fig. 4b. The kimberlitic or juvenile constituents in the RVK and the associated pyroclastic kimberlites are notably similar to those of the pyroclastic kimberlites (PK) of the Prairies and other kimberlites discussed in Section 3.1 above (Fig. 4b). One different kimberlite unit (not shown in Fig. 4), which occurs within the deeper parts of the large Fox pipe (Fig. 3), has been suggested to be possible tuffisitic kimberlite (TK; Nowicki et al., 2003, 2004; Porritt et al., 2006, 2008-this volume). Representative samples of this unit examined by the author are composed of abundant discrete olivine grains and less common magmaclasts (term after Field and Scott Smith, 1998) composed of olivine plus former melt set in a serpentine-rich inter-clast matrix. Features similar to TKs include: widespread replacement of olivine by partiallyclay-mineralised serpentine, minor microlitic textures in the inter-clast matrix and common fresh granitic xenoliths and xenocrysts. Features atypical of TKs include: chaotic, clastsupported and close-packed textures; olivine distributions that do not resemble those of HK; paucity of fine-grained olivine grains; some fresh olivine; common olivine grains without selvages; olivine grains with thick relatively well-crystallised kimberlite selvages (spinel, phlogopite, monticellite); some carbonate in the inter-clast matrix; and clasts of shale or mixed shale and olivine. These atypical features show that this rock type is not TK but appears to be a variant on the main RVK-PK rock types found at Lac de Gras (Fig. 4b). Thus, importantly, the author is not aware of any bona fide TK in the Lac de Gras field.

3.3. Tuffisitic kimberlites

The first of the TK-bearing pipes at Gahcho Kue, NWT was discovered in 1995 (Fig. 1). Subsequently, four additional analogous fields have been discovered at Camsell Lake 40 km northwest of Gahcho Kue found in 1997, at Renard, Quebec found in 2001, at Aviat, Nunavut found in 2002 and at Qilalugaq, Nunavut found in 2003 (Fig. 1). Nine pipe-like bodies and numerous sheets occur at Renard, eleven bodies including numerous sheets and at least two pipes have been found at Aviat, and eleven bodies including at least four pipes are currently known at Qilalugaq. Emplacement ages are 542 Ma and 630 Ma (Heaman et al., 2004) for Gahcho Kue and Renard, respectively, and 558 Ma for Aviat (unpublished information courtesy of Stornoway Diamond Corporation). All five of these fields were emplaced into competent basement granitoids with no sedimentary cover. The rock types infilling the pipes in each of these fields are remarkably similar consisting of typical HK and TK and, in many cases, rocks displaying TK-HK textural transitions (Fig. 4c). The textures vary with the pipe zones (Fig. 4c). Other features exclusive to this pipe type are the presence of so-called pelletal lapilli (Fig. 4c), microlitic textures (see TK inset in Fig. 4c), the consistent presence of abundant country rock xenoliths of a wide range of sizes (0.5 cm-5 m), and the occurrence of fractured and pulverized country rock adjacent to the kimberlite.

3.4. Sheets

Most of the known kimberlite sheets occur in the vicinity of TK-bearing pipes (Fig. 4c) which in the southern Slave includes the Snap Lake sheets near Gahcho Kue and Camsell Lake (Fig. 1). Some sheets occur in the vicinity of the Lac de Gras bodies (e.g. Doyle et al., 1999; Fig. 1 of Moss and Russell, 2006), but kimberlite sheets are not known in the Prairies or in the vicinity of Victor, Ontario. Apparent isolated sheets occur at Wemindji, Quebec (Fig. 1). Most sheets occur as multiple, thin (<1-3 m wide), discontinuous or en-echelon, tabular bodies. They have variable dips apparently reflecting jointing in the basement into which they were emplaced. The sheets are composed of typical HK (e.g. Snap Lake) or HK with textural variations resulting from local processes such as flow differentiation within volatile-rich low viscosity magmas (e.g. Wemindji).

4. Emplacement processes

The similarity in the nature of hypabyssal kimberlites across Canada, and the world, suggests that all the pipes form by the emplacement of similar parental magmas. The characteristics of HK, including sheets, and the nature of other emplacement products suggest that the pipes were formed from similar typical kimberlite magmas consisting of 50 vol.% olivine crystals and 50 vol.% melt containing abundant H_2O and CO_2 . The contrasting nature of the three types of pipes discussed above suggests that they formed by different near-surface emplacement processes. Detailed consideration of the processes is beyond the scope of this paper but some discussion is

warranted. This discussion is subdivided into three main aspects: (1) pipe formation processes, (2) pipe infill processes, and (3) the relative timing of (1) and (2). Modifications to the typical magma, particularly to the olivine distribution, provide evidence critical to the understanding of emplacement processes (contrast Figs. 4a, b and c).

4.1. Pipe formation processes

One of the few similarities between most single kimberlite pipes of any of the types is that they have sub-circular plan view shapes, i.e. the surface expression of explosive activity from a point source feeder. The kimberlite infilling pipe types (a) and (b) in Fig. 4 lack high concentrations of xenoliths of the adjacent country rocks and, as shown in Fig. 5, represent sequential units of extrusive infill. This indicates that in these bodies, the volcanic pipes and/or craters were cleared prior to infilling with the products of subsequent eruptions. Both these types of pipe, therefore, formed in two overall stages, pipe excavation and pipe infill. The material resulting from the explosive excavation of each pipe must have formed extracrater deposits that were not readily reworked back into the pipe. The different pipe shapes of Figs. 4a and b probably reflect contrasting competency of country rocks; poorly-consolidated sediments versus competent basement, respectively. An intermediate pipe shape occurs in competent Paleozoic sediments (Fig. 2 inset).

The presence of the nested craters commonly observed in pipe type (a) (Fig. 5), indicates repeated discrete pipe excavation—infill events from the same feeder with all but the initial event occurring within previous PK. More complex body shapes and internal geology result from cross-cutting or coalescing pipes with variable feeder locations. Multiple pipe excavations do not appear to be a common feature of pipe type (b), perhaps a consequence of the small pipe diameters.

Certain features suggest that pipes of type (c) in Fig. 4 are unlikely to have been open holes: the lack of bedding and sorting; the occurrence of in situ magmatic textural transitions (Hetman et al., 2003, 2004a); ubiquitous steep internal contacts (Fig. 5) that indicate apparent intrusive relationships between separate phases of TK, TK-HK and/or HK; the resulting juxtaposition of textures at internal contacts; steeply oriented fabrics; the lack of any remnants of extrusive infill or weathering; and the presence of abundant and large locallyderived country rock xenoliths. Units of massive extrusive volcaniclastic kimberlite (PK and/or RVK; cf. terminology of Sparks et al., 2006) can form by a number of processes but usually display features different from those in TK (as shown in Table 1 of Hetman, 2008-this volume; Fig. 4). A key line of evidence is that the olivine population of TK is similar to that of HK, except for dilution by xenoliths. In contrast, most massive extrusive volcaniclastic kimberlites contain populations of olivine which are both variable and different from that of HK, or the erupting magma, mainly as a consequence of processes such as sorting.

Understanding pipe excavation processes is hampered by the absence of preserved crater rim deposits and, thus, the lack of direct evidence. Phreatomagmatic processes could be involved in the excavation process for the Fort à la Corne and Victor South pipes given the maar-like size and shape of the pipes and the fact that they flare from points that coincide with aquifers. The lack of consistent aquifers across the Lac de Gras or TKbearing fields suggests it is unlikely that all these pipes formed by phreatomagmatic processes. Also, the resedimented kimberlite infilling much of the Lac de Gras pipes contains constituents that are considered to be formed by magmatic processes. For TK-bearing pipes, the textural transitions together with the lack of evidence of deposition into an open hole show that these pipes could have formed by magmatic processes (Hetman et al., 2004a; Skinner, 2008-this volume). The detailed nature of the HK-TK textural transition suggests that devolatilisation was the driving force behind the eruptions forming these types of kimberlite, and thus the pipe formation.

4.2. Pipe infill processes

The kimberlite infill in each of the three pipe types is distinctly different (Figs. 4 and 5). Only the pyroclastic kimberlite (PK) in pipe types (a) and (b) of Fig. 4 displays similarities. PK is the product of hot (>1200 °C) near-surface magmatic eruptions with variable explosiveness from feeder vents at the base of the previously-excavated pipes. Although some of these eruptions are comparable to basaltic fire fountaining, airfall and associated eruption column processes, the juvenile constituents of PK display different characteristics to basaltic pyroclasts. For example, the relatively small, fluidal, vesicle-poor magmatic pyroclasts (olivine+former melt) reflect the lower viscosity of kimberlite magmas. The lack of welding or flattening and only rare occurrence of slight molding show that the magmatic pyroclasts were solid prior to deposition. A high proportion of pyroclastic kimberlite is dominated discrete crystals, mainly olivines. Olivine-dominated pyroclastic rocks (olivine PK) are a consequence of the combination of very low viscosity magmas, the very high inherent crystal content and possibly the high volatile content at the time of eruption. Olivine PK forms the occasional mega-graded bed (right hand side of Fig. 4a), presumably as a result of larger volume, higher energy eruptions compared to fire fountains. The volatile-rich nature of the erupting kimberlites is illustrated by common primary serpentine and carbonate in the quenched base of the magmatic pyroclasts. One possibly significant difference between the magmatic pyroclasts found at FALC and Lac de Gras is that the latter appear to have groundmasses dominated by carbonate (Fig. 4b) in contrast to carbonate and/or serpentine at FALC (Fig. 4a). Further detailed work is required on magmaclasts in the Lac de Gras PK to confirm this.

PK typically completely infilled most of the pipes in the Prairies (and Victor) providing little opportunity for RVK to form. At Lac de Gras, the initial PK seldom completely infilled the pipe. The available evidence suggests various types of RVK, and occasionally some late PK probably from an adjacent pipe, were deposited into the remaining vacant parts of the pipes. The horizontal layers or wedge-like kimberlite units resulted from



discrete periods of diverse resedimentation processes producing a wide range of rock types with contrasting components and textures (Fig. 4b).

The TK-bearing pipes (Fig. 4c, Table 1) are distinctly different. Section 4.1 discusses critical evidence testifying to an origin that is partly intrusive and magmatic rather than entirely extrusive. Numerous features indicate that these pipes are remarkably similar to many southern African pipes: the variation in kimberlite texture with pipe zone, the TK–HK transitions, the root zone, the high xenolith content of TKs, fractured adjacent country rock and association with common HK sheets peripheral to, and in the vicinity of the pipes. The emplacement processes for the southern African pipes suggested by Clement (1982; reviewed by Field and Scott Smith, 1999), Skinner and Marsh (2006a,b) and Skinner (2008-

this volume) appear to explain the observed features of the TKbearing pipes in Canada. Closed system degassing caused breakthrough and pipe development. The substantiated correlation of the country rock geology with the three pipe types could indicate variable constraints on volatile exsolution which, in turn, affected the nature of the magmatic eruptions in the different settings. The more competent rocks resulting in initial closed system degassing.

The pipes were infilled with TK by the textural modification and rapid cooling of the subsurface magma column. There is no evidence that hot magma reached the surface. The lack of depositional breaks between the different textural types (TK, TK–HK, or HK) within individual phases implies that they formed by a continuous process that could not have lasted much longer than the duration of the eruption of that pulse of magma.

Fig. 4. Schematic representation of the geology of the three main types of kimberlite pipes (after Figs. 1–5 in Scott Smith, 2006). PK = pyroclastic kimberlite, RVK = resedimented volcaniclastic kimberlite, TK = tuffisitic kimberlite, HK = hypabyssal kimberlite, PTK = pyroclastic equivalent of TK which is not observed in Canada. Pink dashed line = present surface. Country rock: grey = Cretaceous shale, orange = Cretaceous siltstone, cream = Paleozoic carbonates, pink = basement. The pipes have been reconstructed to the time of emplacement and, therefore, are to some extent speculative. Surface expressions of the crater rims and pipe infills are not known. (a) Prairies kimberlites. The pipe shape is FALC 169 from Fig. 2. The dominant pipe infill is PK. Overall volumetrically minor RVK is not shown. No TK or HK-like rocks have been found. The main constituents of the PK are discrete olivine grains (green, right hand side) and magmatic pyroclasts (left hand side). The fluidal, commonly amoeboid-shaped magmatic pyroclasts are composed of olivine grains and former melt. The latter is composed of isotropic serpentine (dark grey) and/or cryptocrystalline carbonate (stippled white). The inter-clast cement is composed of serpentine and less common carbonate (purple background). The PKs can be broadly subdivided into three groups composed of: (i) predominantly magmatic pyroclasts (left hand side), (ii) mainly discrete olivine grains (right hand side); and (iii) variable mixtures of magmatic pyroclasts and discrete olivines (shown by the arrows and in the feeder vent). Over the Prairies field as a whole, these three groups occur in approximately equal proportions. The nature and distribution of olivine grains within the magmatic pyroclasts are similar to that of HK. The discrete grains of olivine resemble those within the magmatic pyroclasts, both of which are commonly fresh. Clast-supported textures are typical. Normal grading (right hand side) and an overall paucity of fine constituents (<0.5 mm) including both small olivine grains and the former melt, presumably as ash, indicate widespread sorting. Graded units vary from very thin beds (schematically represented on the right hand side if the olivine grains are to scale) to rare mega-graded beds (schematically represented on the right hand side at the scale of the pipe outline). Not shown here are the low proportion of country rock xenoliths which include, in decreasing order of abundance, carbonates (<15 cm), basement (<10 cm), shale (<1 m) and rare siltstone (<5 m). Evidence such as the fluidal pyroclast shapes, the widespread paucity of fines and the bedding suggests that much, but not all, of the pipe infill processes were subaerial. Data are from Scott Smith (1995, 1996), Scott Smith et al. (1994, 1995, 1998), Mitchell (1997), Jellicoe et al. (1998), Carlson et al. (1999), Field and Scott Smith (1999), Berryman et al. (2004), Zonneveld et al. (2004), Eccles et al. (2004), Hetman (2007), Scott Smith and Berryman (2007) and Scott Smith (2008) and unpublished information. (b) Lac de Gras kimberlites. The pipe shape is based on a model for Koala (as illustrated in Fig. 3) reconstructed to the time of emplacement. The pipe infill is dominated by mud-rich RVK with less prevalent but common PK. The RVK is composed of variable mixtures of commonly fresh, frequently angular, discrete olivine grains (green), xenoliths of mudstone (darker grey with lines) and fresh granitoid (red), minor magmatic pyroclasts typically with cryptocrystalline carbonate groundmasses (stippled white), autoliths (fragments of previously deposited RVK; darker grey containing olivines) and wood (brown) set in a matrix of mixed disaggregated shale (paler grey). The RVK infill is characterised by different packages of massive-towell-bedded, poor-to-well-sorted and matrix-to-clast-supported material displaying variations in xenolith size, type and abundance, olivine size and abundance and proportions of wood and matrix. Minor kimberlite-poor sediments are depicted by siltstone (orange) and mudstone (ornamented grey, upper right). Less common PK occurs as early infill. The PK is composed of similar constituents to the PK in (a), with a similar depletion of fines, set in a serpentine inter-clast cement. Rare, late-stage deposits of graded material (upper left) are present and interpreted as pyroclastic kimberlite. Granitoid xenoliths can be more common than shale clasts. A mega-graded unit in the upper part of the pipe (left hand side) is composed mainly of discrete olivines in a serpentine cement (purple). A few partly-digested sub-round kimberlitetransported xenoliths (pale grey) occur in the base of the bed. In the mega-graded bed illustrated on the upper right, discrete olivines are mixed with disaggregated sedimentary material (stippled grey). A few granite (red) and shale (darker grey) xenoliths are present. The diverse rock types shown here represent a composite of deposits observed in a number of pipes. Coherent monticellite-bearing HK-like rocks infill a few pipes (not shown here). See Section 3.2 for discussion on the possible occurrence of TK. As for (a), subaerial pipe infill processes appear to be more common than subaqueous. Data are from T. Nowicki (pers. comm.), McKinlay et al. (1998), Doyle et al. (1999), Field and Scott Smith (1999), Graham et al. (1999), Bryan and Bonner (2003), Crawford et al. (2006), Nowicki et al. (2003, 2004, 2006, 2008-this volume), Dyck et al. (2004), Harder et al. (2006), Moss and Russell (2006), Porritt et al. (2006, 2008-this volume) and unpublished information. (c) TKbearing pipes. The shapes of many of these more recently discovered small, variable and commonly irregular bodies are not well defined. The composite geological model for Gahcho Kue (Fig. 14 of Hetman et al., 2004a) is used and reconstructed to the time of emplacement. The irregular root zone of HK (dark blue) occurs below a simpler-shaped pipe infilled with TK (brown). The latter can be termed diatreme-facies. Pyroclastic material may have formed near surface (dark brown, PTK). Relatively common HK sheets (paler blue lines) occur in the vicinity of TK-bearing pipes. The root zone is typical HK composed of olivine grains (green), which are often fresh, set in a fine-grained but well-crystallised groundmass (dark blue). Granitoid xenoliths are in low abundance (pale grey), sub-rounded and partly-digested. In contrast, the TK contains totally serpentinised olivine (darker green) and commonly includes abundant (>30 vol.%), angular, fresh granitoid xenoliths (red) and is termed TKB (B = breccia, >15 vol.% xenoliths). Most of these constituents have thin, extremely fine-grained selvages considered to represent coatings of rapidly cooled former-kimberlite-melt (orange). These are termed pelletal lapilli to indicate that they are distinct from the magmatic pyroclasts shown in (a) and (b). The inter-pelletal lapilli cement is composed of serpentine which is susceptible to alteration, particularly by clay-mineralisation (brown). Common microlites are a hallmark feature of the cement (white needles shown in the enlarged TK inset). Carbonate is not present. Except for dilution by xenoliths, the distribution of the olivine in the TK is similar to that of the HK. Both the HK and TK are massive with no sorting or bedding. There is a gradational transition between the HK and TK (yellow) with increasing xenolith abundance and size, magmaclastic and microlitic textures, olivine replacement and decreasing degree of crystallinity and xenolith reaction. Data are from Field and Scott Smith (1999), Hetman et al. (2003, 2004a and c), Hetman (2006, 2008-this volume), O'Connor and Lepine (2006) and unpublished information.

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Fig. 5. Schematic representation of the internal geology of the three types of kimberlite pipes shown in Fig. 4 (abbreviations and references as for Fig. 4). The geometry of different kimberlite units within each pipe type is distinct (shown by variable shades of grey separated by dashed lines for internal contacts). (a) Each unit of PK formed from the eruption of a single pulse of magma. Nested craters formed by the sequential eruption of separate pulses of magma from the same feeder vent. Internal contacts typically have dips of $\sim 30-60^\circ$. The internal contacts are either (i) gradational when the earlier PK is unconsolidated and constituents from the two eruptions are mixed (e.g. Webb et al., 2004; van Straaten et al., 2006) or (ii) sharp when the earlier infill was cemented prior to the next eruption (e.g. Webb et al., 2006; Hetman, 2007). Cross-cutting and adjacent craters also occur (not shown here). (b) Initial deep PK formed from the feeder to that pipe but the later upper PK probably originated from a nearby pipe. Horizontal layers or wedge-shaped units of RVK represent distinct resedimentation events. Internal contacts commonly have dips of $\sim 0-45^\circ$, and may be sharp or gradational. Nested units or cross-cutting pipes are not common. (c) Each kimberlite unit is the product of the emplacement of a single pulse of magma. Internal contacts are sharp and steep with dips of $\sim 60-90^\circ$, consistent with the intrusion of multiple pulses of magma. The number of kimberlite units tends to increase within depth, with one late unit dominating a single pipe. The textures can vary within one unit (HK–TK–PTK). Cross-cutting and adjacent pipes occur (not shown here).

Importantly, any extrusive material would be expected to resemble TK as found in the so-called Northern Pyroclastic Kimberlite at Orapa in Botswana (Field et al., 1997; termed PTK in Fig. 4c), and not the PK of Fig. 4a and b.

4.3. Timing of pipe formation and infill

The Prairies and Lac de Gras pipes (Figs. 4a and b) remained open for some time after excavation. In the Prairies, the overall lack of weathering, soil, RVK and country rock material near the pipe contacts or at the edges of nested craters suggest 'rapid' infilling with PK. Timing of the multiple events that formed nested or cross-cutting craters may have been variable as indicated by early deposits that were either unconsolidated or cemented (see legend for Fig. 5). The infilling of some of the Lac de Gras pipes, however, appears to have been longer-lived given overall slower resedimentation processes resulting in diverse units of RVK. Some palynomorphs in the RVK infill are younger than the apparent emplacement age (perhaps up to ~ 10 Ma; Scott Smith, 2002; unpublished palynological information). Age determinations suggest that single kimberlite pipes form in <1-2 Ma (Section 2). The discussion above suggests that the formation and initial infilling of TK-bearing pipes (Fig. 4c) are contemporaneous. Each TK-forming event was probably short-lived but multiple such events form one pipe.

5. Summary and conclusions

Kimberlite magmatism in Canada has been repeated in space and time. More than 770 kimberlites have erupted in diverse tectonic settings over a period of at least 1000 Ma and over an area more than 5000 km across. The kimberlites occur in at least 30 comagmatic fields that formed over periods of 10–30 Ma. Single bodies appear to have formed in <1-2 Ma. Recent information substantiates the proposal by Field and Scott Smith

Table 1 Contrasting generalised characteristics of the three main types of kimberlite pipes shown in Fig. 4

| Pipe type | (a) Prairies | (b) Central Slave | (c) 3 Cratons |
|-----------------------|-----------------|------------------------------|------------------|
| | | | |
| Pre-erosion CR | Soft CRS | Soft CRS | Hard CRG |
| | Hard CRS | Hard CRG | |
| No. of fields | 3-4 | 1 | 5 |
| No. of pipes | ~120 | >250 | 10-20 |
| Max. area (ha) | 250 | 20 | 2 |
| Pipe diameter (m) | <1500 | <300 | <200 |
| Original diameter (m) | <1500 | < 500 | <400 |
| Present depth (m) | <250 | <1000 | <600 |
| Original depth (m) | <300 | <1200 | <1000 |
| Pipe zones | Shallow crater | Steep crater | Diatreme+root |
| PK | Dominant | Common | Absent |
| RVK | Minor | Common | Absent |
| ТК | Absent | Absent | Common |
| Pipe-fill HK | Absent | HK-like present ^a | Common |
| HK sheets | Absent | Present | Common |
| Olivine abundance | 25-80% | 0-80% | <30% |
| Broken olivines | Low | Common | Rare |
| Bedding/sorting | Common | Common | Absent |
| Peripheral CRB | No | No | Common |
| CR xenolith abundance | <5% | <10% | >30% in TK |
| CR xenolith size | <15 cm | <15 cm | <500 cm in TK |

Legend: CR = country rock, CRS = CR sediments, CRG = CR granitoids, CRB = CR breccias, soft = poorly-consolidated, hard = competent. PK, TK, HK and RVK as for Fig. 4. Pipe zones after Field and Scott Smith (1999). Exceptions to some of the generalisations presented here do occur, such as the xenolith abundance and size. The original pipe depths and diameters are based on reconstructions such as in Fig. 4 and are to some extent speculative.

^a HK-like rocks occur in a few Lac de Gras pipes but are unlikely to be hypabyssal in the true sense of the word (possibly pipe-fill lava or lava spatter, Nowicki et al., 2008-this volume).

(1999) that each kimberlite field in Canada, for which there is sufficient information, is dominated by one of the three main types of pipes. The three pipe types show substantial differences with respect to pipe size, shape and infill as well as the nature of the country rocks into which they were emplaced. In fact, most geological characteristics are distinctly different in each of the three types as shown in Figs. 4 and 5 and Table 1. New data show that a variation on the Prairies pipe type (Fig. 4a) occurs when kimberlites were emplaced into competent Paleozoic sediments resulting in steeper-sided pipes (Fig. 2 inset) infilled with PK similar to that observed in the Prairies kimberlites, an interpretation which differs from the preliminary suggestions of Field and Scott Smith (1999, see Fig. 7). Thus, Fig. 1 of Scott Smith (2006, a 2003 update of Fig. 7 of Field and Scott Smith, 1999) remains a valid, albeit simplified, overview that can be used together with the more detailed summaries of the geology of the three pipe types presented in Figs. 4, 5 and Table 1 as evidence for the understanding of emplacement processes. Pipe types (a), (b) and (c) of Fig. 4 correspond to pipe classes (2), (3) and (1) described in other parts of the world by Skinner and Marsh (2004), respectively. Although this paper emphasizes the similarities within each pipe type, it should be noted that each

individual pipe is unique resulting in considerable variation in geology and implied processes within each type or field.

The similarity in the nature of hypabyssal kimberlites across Canada, and the world, suggests that all the pipes form by the emplacement of similar parental magmas consisting of 50 vol.% olivine crystals and 50 vol.% volatile-rich melt. Any hypotheses regarding kimberlite emplacement must be constrained by the characteristic features of the different types of kimberlite pipes. In particular, it is proposed that the consistently different styles of pipe infill preserved in each of the pipe types cannot be explained by a single process. For example, pipe types (a) and (b) in Fig. 4 were initially open volcanic features that were subsequently infilled by relatively rapid pyroclastic and/or probable longer-lived resedimentation processes. In contrast, pipe type (c) in Fig. 4 formed by relatively short-lived intrusive-extrusive processes. Apparently similar near-surface, olivine-rich kimberlite magmas were modified differently during the contrasting emplacement processes resulting in distinct textural rock types, including a range of different types of pyroclastic kimberlite (PK), tuffisitic kimberlite (TK) and associated hypabyssal kimberlite (HK) or resedimented kimberlite (RVK) dominating each type of pipe. The substantiated correlation of pipe type with country rock geology could indicate variable constraints on volatile exsolution which affected the nature of the magmatic eruptions in different settings.

The geological data collated for the summaries presented here derive from investigations relating to the evaluation and mining of kimberlites. Such summaries, or geological models, are important because they provide the basis for successfully applying predictive geology to the development of existing and new mineral resources. Staged project work, therefore, continually tests, modifies and increases the degrees of confidence in the models presented in Figs. 4 and 5 and Table 1.

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References

- Berryman, A.K., Scott Smith, B.H., Jellicoe, B.C., 2004. Geology and diamond distribution of the 140/141 kimberlite, Fort à la Corne, central Saskatchewan, Canada. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 99–114.
- Bryan, D., Bonner, R., 2003. The Diavik Diamond Mine, Lac de Gras, Northwest Territories, Canada. Slave Province and Northern Alberta Field Trip Guidebook. 8th International Kimberlite Conference. Geological Survey of Canada Bookstore, Ottawa, Canada.
- Carlson, S.M., Hillier, W.D., Hood, C.T., Pryde, R.P., Skelton, D.N., 1999. The Buffalo Hills kimberlites: a newly discovered diamondiferous kimberlite province in North-central Alberta, Canada. Proceedings of the 7th International Kimberlite Conference, Cape Town, South Africa, 1998, vol. 1. Red Roof Design, Cape Town, South Africa, pp. 109–118.
- Clement, C.R., 1982. A comparative geological study of some major kimberlite pipes in the Northern Cape and Orange Free State. PhD Thesis, University of Cape Town.
- Crawford, B.B., Porritt, L., Nowicki, T., Carlson, J., 2006. Key geological characteristics of the Koala kimberlite, Ekati Diamond Mine, Canada. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Creaser, R.A., Grutter, H.S., Carlson, J., Crawford, B., 2004. Macrocrystal phlogopite Rb–Sr dates for the Ekati property kimberlites, Slave Province, Canada: evidence for multiple intrusive episodes in the Paleocene and Eocene. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 399–414.
- Doyle, B.J., Kivi, K., Scott Smith, B.H., 1999. The Tli Kwi Cho (DO27 and DO18) diamondiferous kimberlite complex, Northwest Territories, Canada. Proceedings of the 7th International Kimberlite Conference, vol. 1, pp. 194–204.
- Dyck, D.R., Oshust, P.A., Carlson, J.A., Nowicki, T.E., Mullins, M.P., 2004. Effective resource estimates for primary diamond deposits from the Ekati Diamond Mine, Canada. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 317–336.
- Eccles, D.R., Heaman, L.M., Luth, W., Creaser, R., 2004. Petrogenesis of the Late Cretaceous northern Alberta kimberlite province. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 435–459.
- Faure, S., 2006. World Kimberlites and Lamproites CONSOREM Database (Version 2006-1). Consortium de Recherche en Exploration Minérale CONSOREM, Université du Québec à Montréal. Numerical Database on www.consorem.ca.
- Field, M., Scott Smith, B.H., 1998. Textural and genetic classification schemes for kimberlite: a new perspective. Extended Abstracts, 7th International Kimberlite Conference, Cape Town, pp. 214–216.
- Field, M., Scott Smith, B.H., 1999. Contrasting geology and near surface emplacement of kimberlite pipes in southern Africa and Canada. Proceedings of the 7th International Kimberlite Conference, vol. 1, pp. 214–237.
- Field, M., Gibson, J.G., Wilkes, T.S., Gababotse, J., Khujwe, P., 1997. The geology of the Orapa A/K1 kimberlite, Botswana: further insight into the emplacement of kimberlite pipes. Proceedings of the 6th International Kimberlite Conference. Russian Geology and Geophysics, vol. 38 (1), pp. 24–39.
- Graham, I., Burgess, J.L., Bryan, D., Ravenscroft, P.J., Thomas, E., Doyle, B.J., Hopkins, R., Armstrong, K.A., 1999. Exploration history and geology of the Diavik kimberlites, Lac de Gras, NWT, Canada. Proceedings of the 7th International Kimberlite Conference, vol. 1, pp. 262–279.
- Harder, M., Hetman, C.M., Scott Smith, B.H., Pell, J., 2006. Geology of the DO27 pipe: a pyroclastic kimberlite in the Lac de Gras Province, NWT, Canada. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.

- Heaman, L.M., Kjarsgaard, B.A., Creaser, R.A., 2004. The temporal evolution of North American kimberlites. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 377–398.
- Hetman, C.M., 2006. Tuffisitic kimberlite: a Canadian perspective on a distinctive textural variety of kimberlite. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Hetman, C.M., 2007. Kimberlite emplacement 3: class 2 kimberlites. Notes accompanying Short Course Kimberlite Geology: Basics, Advances and Economics. Mineral Exploration Round Up, Vancouver, Canada, January 2007.
- Hetman, C.M., 2008. Tuffisitic kimberlite: a Canadian perspective on a distinctive textural variety of kimberlite. Journal of Volcanology and Geothermal Research 174, 57–67 (this volume). doi:10.1016/j.volgeores.2007.12.039.
- Hetman, C.M., Scott Smith, B.H., Paul, J.L., Winter, F.W., 2003. Geology of the Gahcho Kue kimberlite pipes, NWT, Canada: root to diatreme transition zones. 8th International Kimberlite Conference, Extended Abstract, vol. 352.
- Hetman, C.M., Scott Smith, B.H., Paul, J.L., Winter, F.W., 2004a. Geology of the Gahcho Kué kimberlite pipes, NWT, Canada: root to diatreme magmatic transition zones. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 51–74.
- Hetman, C.M., Holmes, P.K., Paul, J.P., 2004b. Exploration geology of the Knife Lake kimberlite, Nunavut, Canada. www.debeerscanada.com.
- Hetman, C.M., Scott Smith, B.H., Paul, J.P., 2004c. Geology of the Hearne Kimberlite pipe, Northwest Territories, Canada: magmatic kimberlite emplacement. Abstract for the 2nd International Maar Conference, Hungary, 2004.
- Hoffman, P.F., 1988. United plates of America, birth of a craton, early Proterozoic assembly and growth of Laurentia. Annual Review of Earth and Planetary Sciences, 16, 543–603.
- Jellicoe, B.C., 2005. Summary of exploration and evaluation of the Fort à la Corne field, east-central Saskatchewan. A technical report for Shore Gold Inc. dated 9th November 2005. Available on www.sedar.com.
- Jellicoe, B.C., Robertshaw, P., Williamson, P., Murphy, J., 1998. Summary of exploration activities and results for the Fort à la Corne diamond project, Saskatchewan. Summary of Investigations 1998: Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep., vol. 98-4, pp. 144–157.
- Kong, J.M., Boucher, D.R., Scott Smith, B.H., 1999. Exploration and geology of the Attawapiskat kimberlites, James Bay Lowland, Northern Ontario, Canada. The J.B. Dawson Volume, Proceedings of the 7th International Kimberlite Conference, vol. 1, pp. 452–467.
- Lefebvre, N., Kurzlaukis, S., 2006. Contrasting eruption styles of the 147 kimberlite, Fort à la Corne, Saskatchewan, Canada. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Leroux, D.C., 2005. Amended and Restated Technical Review of Shore Gold Inc. Diamond Exploration Project, Fort à la Corne, Saskatchewan, Canada. Dated 15th December 2005. Available on www.sedar.com.
- Levinson, A.A., Gurney, J.J., Kirkley, M.B., 1992. Diamond sources and production: past, present, and future. Gems and Gemology, Winter 1992, 234–254.
- Lockhart, G., Grutter, H., Carlson, J., 2004. Temporal, geomagnetic and related attributes of kimberlite magmatism at Ekati, Northwest Territories, Canada. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 77, pp. 665–682.
- McKinlay, F.T., Scott Smith, B.H., de Gasparis, S., Kong, J., 1998. Geology of the recently discovered Hardy Lake kimberlites, NWT. Extended Abstracts of the 7th International Kimberlite Conference, Cape Town, pp. 564–566.
- Mineral Information Map, 2006. Northern Canada Diamonds: Nunavut and Northwest Territories and Lac de Gras/Slave area. Produced by Mineral Information Maps. Northern Miner (www.minmaps.com), a division of Intierra Ltd.
- Mitchell, R.H., 1997. Kimberlite, Orangeites, Lamproites, Melilitites, and Minettes: a Petrographic Atlas. Almaz Press Inc.. 243 p.
- Mitchell, R.H., 2008. Petrology of hypabyssal kimberlites: relevance to primary magma compositions. Journal of Volcanology and Geothermal Research 174, 1–8 (this volume). doi:10.1016/j.volgeores.2007.12.024.
- Moss, S., Russell, J.K., 2006. Pyroclastic origins of the mega-graded bed at Diavik. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.

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- Nowicki, T.E., Porritt, L., Crawford, B., 2006. Geochemical trends in kimberlites from Ekati, NWT: insights on volcanic and resedimentation processes. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Nowicki, T.E., Porritt, L., Crawford, B., Kjarsgaard, B., 2008. Geochemical trends in kimberlites from Ekati, NWT: insights on volcanic and resedimentation processes. Journal of Volcanology and Geothermal Research 174, 117–127 (this volume). doi:10.1016/j.volgeores.2007.12.030.
- Nowicki, T., Crawford, B., Carlson, J., Crawford, B.B., Lockhart, G.D., Oshust, P., Dyck, D., 2003. Field guide to the Ekati Diamond Mine. Slave Province and Northern Alberta Field Trip Guidebook. 8th International Kimberlite Conference. Geological Survey of Canada Bookstore, Ottawa, Canada.
- Nowicki, T., Crawford, B., Dyck, D., Carlson, J., McElroy, R., Oshust, P., Helmstaedt, H., 2004. The geology of kimberlite pipes of the Ekati property NWT, Canada. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 1–27.
- O'Connor, A., Lepine, I., 2006. Technical report and recommendations. The Otish Mountains, Quebec Project. A Technical Report for Ashton Mining of Canada Inc. Dated 24th February 2006. Available on www.sedar.com.
- Porritt, L.A., Cas, R.A.F., Crawford, B.B., 2006. The origin and implications of the TK-like infill of the Fox kimberlite, Ekati Diamond Mine, NWT, Canada. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Porritt, L.A., Cas, R.A.F., Crawford, B.B., 2008. In-vent column collapse as an alternative model for tuffisitic kimberlite emplacement: an example from the Fox kimberlite, Ekati diamond Mine, NWT, Canada. Journal of Volcanology and Geothermal Research 174, 90–102 (this volume). doi:10.1016/j. volgeores.2007.12.029.
- Scott Smith, B.H., 1995. Geology of the Sturgeon Lake 02 kimberlite block. Saskatchewan: Exploration and Mining Geology C.I.M., vol. 4, pp. 141–151.
- Scott Smith, B.H., 1996. Kimberlites. Chapter 10, Mineralogical Association of Canada Short Course Series. In: Mitchell, R.H. (Ed.), Undersaturated Alkaline Rocks: Mineralogy, Petrogenesis, and Economic Potential. Short Course, vol. 24, pp. 217–243.
- Scott Smith, B.H., 2002. Emplacement of the Hardy Lake kimberlites, NWT, Canada. Short Abstract. GAC/MAC Annual Meeting, Saskatoon, Special Session on Kimberlites.
- Scott Smith, B.H., 2006. Canadian kimberlites: geological characteristics relevant to emplacement. Long abstract for the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. Available on www.8ikc.ca.
- Scott Smith, B.H., 2008. The Fort a la Corne kimberlites, Saskatchewan, Canada: geology, emplacement and economics. Journal of the Geological Society of India 71, 11–55.
- Scott Smith, B.H., Berryman, A.K., 2007. Discussion on "Discussion of "Geology and diamond distribution of the 140/141 kimberlite, Fort à la Corne, central Saskatchewan, Canada" (Lithos 76, 99–114) by B.A. Kjarsgaard, D.A. Leckie and J.P. Zonneveld". Lithos 97, 429–434.
- Scott Smith, B.H., Letendre, J.P., Robison, H.R., 1996. Geology of the Sturgeon Lake 01 kimberlite block, Saskatchewan. Exploration and Mining Geology 5, 251–261.
- Scott Smith, B.H., Orr, R.G., Robertshaw, P., Avery, R.W., 1994. Geology of the Fort à la Corne kimberlites, Saskatchewan. In: Jambor, J.L. (Ed.), Proceedings of Canadian Institute of Mining, Metallurgy and Petroleum, District 6 Annual General Meeting, Vancouver, B.C., Canada, October 1994, 19-24.

- Scott Smith, B.H., Orr, R.G., Robertshaw, P., Avery, R.W., 1995. Geology of the Fort à la Corne kimberlites, Saskatchewan. Extended Abstracts of the 6th International Kimberlite Conference, Novosibirsk, Russia, Siberian Branch of Russian Academy of Sciences, pp. 543–545.
- Scott Smith, B.H., Orr, R.G., Robertshaw, P., Avery, R.W., 1998. Geology of the Fort à la Corne kimberlites, Saskatchewan. Extended Abstracts of the 7th International Kimberlite Conference, Cape Town, pp. 772–774.
- Skelton, D., Clements, B., 2002. Technical Report and Recommendations. The Buffalo Hills area, Alberta Project. Dated 17th May 2002. Available on www.sedar.com and www.ashton.ca.
- Skinner, E.M.W., Marsh, J.S., 2004. Distinct kimberlite pipe classes with contrasting eruption processes. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 183–200.
- Skinner, E.M.W., Marsh, J.S., 2006a. The emplacement of Class 1 kimberlites Part 1, evidence of geological features. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Skinner, E.M.W., Marsh, J.S., 2006b. The emplacement of Class 1 kimberlites Part 2, petrographic evidence. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Skinner, E.M.W., 2008. The emplacement of Class 1 kimberlites. Journal of Volcanology and Geothermal Research 174, 40–48 (this volume). doi:10.1016/ j.volgeores.2007.12.022.
- Sparks, R.S.J., Baker, L., Brown, R.J., Field, M., Schumacher, J., Stripp, G., Walters, A., 2006. Dynamical constraints of kimberlite volcanism. Journal of Volcanology and Geothermal Research 155, 18–48.
- van Straaten, B., Kopylova, M., Russell, K., Webb, K., Scott Smith, B., 2006. Victor North pyroclastic kimberlite: resource versus non-resource distinguished. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Webb, K.J., Scott Smith, B.H., Paul, J.L., Hetman, C.M., 2004. Geology of the Victor kimberlite, Attawapiskat, Northern Ontario, Canada: cross-cutting and nested craters. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 29–50.
- Webb, K.J., Scott Smith, B.H., Paul, J.L., Hetman, C.M., 2006. Geology of the Victor kimberlite, Attawapiskat, Northern Ontario, Canada: cross-cutting and nested craters. Poster. Long abstract, Kimberlite Emplacement Workshop, Saskatoon, Canada, September 2006. Available www.8ikc.ca.
- Wood, B.D., Scott Smith, B.H., De Gasparis, S., 1998. The Mountain Lake kimberlite pipes of N.W. Alberta: exploration, geology and emplacement model. Extended Abstracts of the 7th International Kimberlite Conference, Cape Town, South Africa, 1998, pp. 960–962.
- Zonneveld, J.-P., Kjarsgaard, B.A., Harvey, S.E., Heaman, L.M., McNeil, D.H., Marcia, K.Y., 2004. Sedimentological constraints on the emplacement of the Star kimberlites, east-central Saskatchewan. Proceedings of the 8th International Kimberlite Conference. Lithos, vol. 76, pp. 115–138.