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The internal geology and emplacement history of the Renard 2 kimberlite, Superior Province, Quebec, Canada

C.E. Fitzgerald [a,*], C.M. Hetman [b], I. Lepine [a], D.S. Skelton [a], T.E. McCandless [a]

[a] Stornoway Diamond Corporation 116-980 West 1st St., North Vancouver, BC, Canada V7P 3N4
[b] Mineral Services Canada, 205-930 Harbourside Dr., North Vancouver, BC, Canada V7P 3S7

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ABSTRACT

The Renard 2 kimberlite is located in the Otish Mountains region of Quebec, Canada and is one of the largest pipes in the Renard cluster. The cluster consists of nine kimberlite bodies and was discovered in 2001 by Ashton Mining of Canada Inc. and its joint venture partner SOQUEM Inc. Renard 2 was emplaced into Archean meta-greywacke derived migmatite, gneiss and granite of the Opinaca Subprovince of the eastern Superior Province at approximately 640.5 ± 2.8 Ma. An undetermined amount of erosion has occurred since emplacement with the present surface expression of the pipe estimated to be 0.75 ha. This kimberlite is interpreted as a steep-sided diatreme with minor irregularities in the external shape. The dominant infill is a massive volcaniclastic kimberlite (MVK) that is classified as tuffisitic kimberlite breccia (TKB) and is characterized by a high proportion of granitoid country rock xenoliths. A second dominant infill is a texturally complex, less diluted coherent kimberlite (CK) characterized locally by a transitional textures between CK and TKB. Surrounding the diatreme is a significant zone of variable width comprised of extensively brecciated country rock (+/−kimberlite) and referred to as marginal breccia. In addition to the two main rock types infilling the pipe, a number of hypabyssal kimberlite (HK) dykes and irregular shaped intrusions occur throughout the body, along the pipe contacts, within the marginal breccia and in the surrounding country rock. Geological features displayed by Renard 2 are similar to those described from Class 1 kimberlites of the Kimberley area of South Africa, the Gahcho Kué cluster of Canada and the Pimenta Bueno kimberlite field of Brazil. The economic evaluation of Renard 2 is in progress and to date has included extensive diamond and reverse circulation drilling as well as the collection of an underground bulk sample. Results from material sampled from Renard 2, including a 2449 tonne bulk sample, suggest Renard 2 has an estimated diamond content of 83 cpht (carats per hundred tonnes). A three dimension geology model of the pipe has been developed following the investigation of drill cores, subsurface mapping and petrography combined with diamond studies and geophysics. The model produced is being used to guide and direct the evaluation of the kimberlite and unravel the emplacement history of the pipe.

1. Introduction

1.1. Geologic setting

The Renard cluster consists of nine kimberlite bodies discovered in 2001 by Ashton Mining of Canada Inc. (now a wholly owned subsidiary of Stornoway Diamond Corporation) and its joint venture partner SOQUEM Inc. These are named Renards 1 through 10, with Renards 5 and 6 considered to be one body (Renard 65). The kimberlites were emplaced into the Archean meta-greywacke derived migmatite, gneiss and granite of the Opinaca Subprovince (Percival, 2007) in the James Bay region of Quebec, Canada (Fig. 1). The cluster is located in the northeast portion of the Superior structural province, which is bordered by Proterozoic rocks of the Labrador Trough in the east and the Grenville Province in the south. Northern portions of the project area are comprised of north–northwest trending plutonic and gneissic terranes. Based on metamorphic grade, mineralogy, lithology and aeromagnetics, the terranes appear to vary in width from 70 to 150 km. Granite–gneiss and retrograde granulite gneiss are the predominant lithologies in the region with lesser amounts of granite and granodiorite. Metamorphic grade is primarily amphibolite facies with local granulite (Percival et al., 1994). The Renard cluster is located at the southern end of the structural feature known as the Mistassini–Lemoyne Tectonic Zone (MLZ) that is defined by north–northeast lineaments and faults (Portella, 1980; Thériault and Chevé, 2001). Moorhead et al. (2003) believe this may have had some control on the emplacement of the Renards. The larger kimberlites in the cluster are elongate in a north–northwest orientation, aligned parallel to late faults and diabase dykes of the 2475 Ma Mistassini swarm (Heaman,

* Corresponding author. Tel.: +1 604 983 7761; fax: +1 604 987 7107.
E-mail address: cfitzgerald@stornowaydiamonds.com (C.E. Fitzgerald).

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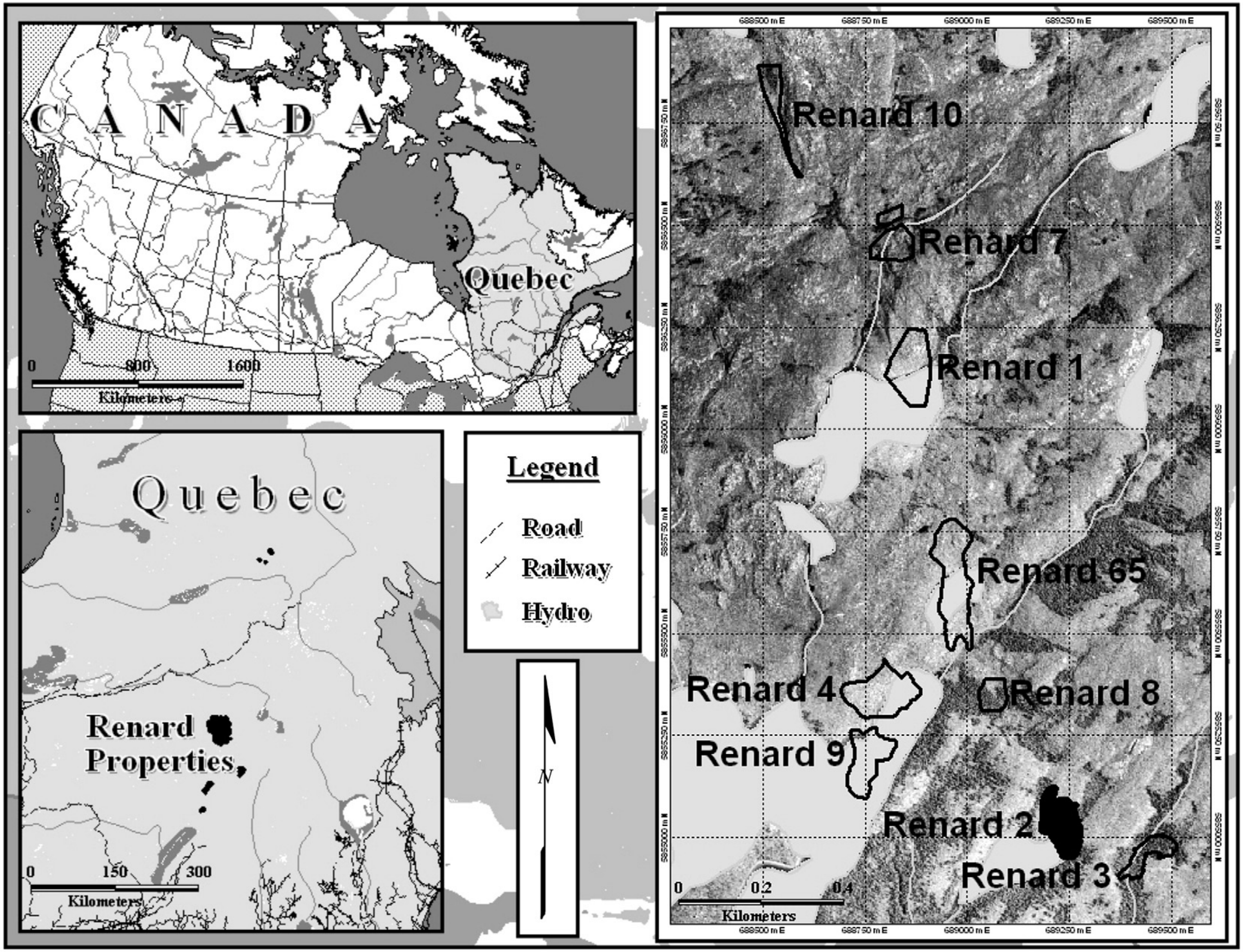


Fig. 1. The Renard kimberlite cluster, in Quebec, Canada. On the right are the plan view outlines (black outline) of the Renard bodies and the location of Renard 2 (filled with black) relative to these.

1994). Most of the Renard kimberlites occur as magnetic highs and electromagnetic conductors in geophysical survey data. Post-glacial deposits up to 20 m thick cover the Renard kimberlites.

Whole rock trace element compositions suggest that the Renards have a close affinity to Group I kimberlite (after Skinner, 1989), with some overlap with melnoite likely due to contamination by country rock (Birkett et al., 2004). Petrographic investigation of these kimberlites indicates that they are archetypal Group I kimberlites. Most of the pipes are infilled by more than one type of kimberlite, with at least one type of massive volcaniclastic kimberlite (MVK) and multiple phases of hypabyssal kimberlite (HK) dykes and irregular intrusions present throughout. In addition, all of the pipes are surrounded by significant zones of extensively brecciated country rock referred to as marginal breccia, which may or may not contain kimberlite.

Previous U–Pb dating of groundmass perovskite in HK dykes within Renard 1 suggested an emplacement age of 631.6 ± 3.5 Ma (Birkett et al., 2004). Recent data obtained for the main rock types in Renards 2 and 3 using the same method (L. Heaman, pers. comm.) suggest an emplacement age of 640.5 ± 2.8 Ma.

1.2. The Renard core area

The joint venture partners have completed significant work since discovery of the Renard kimberlites, including: geophysical surveys, core and reverse circulation drilling, comprehensive core logging and underground mapping, modal analysis, petrographic and geochemical studies and diamond analysis. Of the nine bodies in the cluster, four are of economic interest due to their high diamond contents: Renards 2, 3, 4 and 9 (the core area) are the focus of an economic evaluation program. The surface expressions and three-dimensional subsurface shapes of these bodies have been modeled using information from detailed drill core logging and mapping from underground excavations. The models suggest that all four bodies are generally elliptical in plan view at surface and occur as steep-sided pipes that taper with depth.

Renard 2 is one of the largest kimberlites in the cluster and, as such, has been the focus of extensive evaluation work, which culminated in the release of a NI 43-101 compliant mineral resource estimate which classifies it as an indicated resource to 250 m (Lecuyer et al., 2008). Renard 2 is an elliptical, north trending diatreme that has been drilled to 564 m below the present surface and has a surface expression of 0.75 ha based on total magnetic intensity ground geophysics and drilling. Renard 2 has an average diamond content of 83 cpht (carats per hundred tonnes) as determined from a total of 2697 tonnes processed to date (Note: The diamond content of the Renard bodies, as discussed below, are based on a lower diamond recovery cutoff using a 1.1 mm circular screen or ~0.01 ct, unless noted otherwise). As detailed below, it is infilled predominantly by an MVK and a texturally complex coherent kimberlite (CK). Renard 3 is the smallest body in the cluster having a surface expression of 0.3 ha, but has the highest diamond content with an average grade of 118 cpht based on 2319 tonnes processed. It is irregularly shaped and is dominated by multiple types of texturally complex CK and has one MVK rock type. Renard 4 is the second largest body (behind the low grade Renard 65) with an elliptical, east–west trending surface expression of 1.2 ha and a drill-confirmed depth of 360 m below present surface. It has an average diamond grade of 34 cpht based on 2296 tonnes processed. It is also dominated by one MVK and one CK. Renard 9 is the second smallest body with a surface expression of 0.5 ha. It is irregularly shaped, dips towards the east with depth and is infilled by petrographically distinct MVK and CK rock types. It has an inferred diamond content of 40 cpht based on 100 tonnes processed (with a lower cutoff of +1.18 mm Tyler screen).

Here we present the geology of the Renard 2 body and offer an interpretation of how the kimberlite was emplaced. Terminology used to describe the textural classification of the rocks is taken from Field and Scott Smith (1999), Sparks et al. (2006) and Cas et al. (this issue). Terminology for the mineralogical classification is from Skinner and Clement (1979).

2. Geology of Renard 2

2.1. External pipe shape

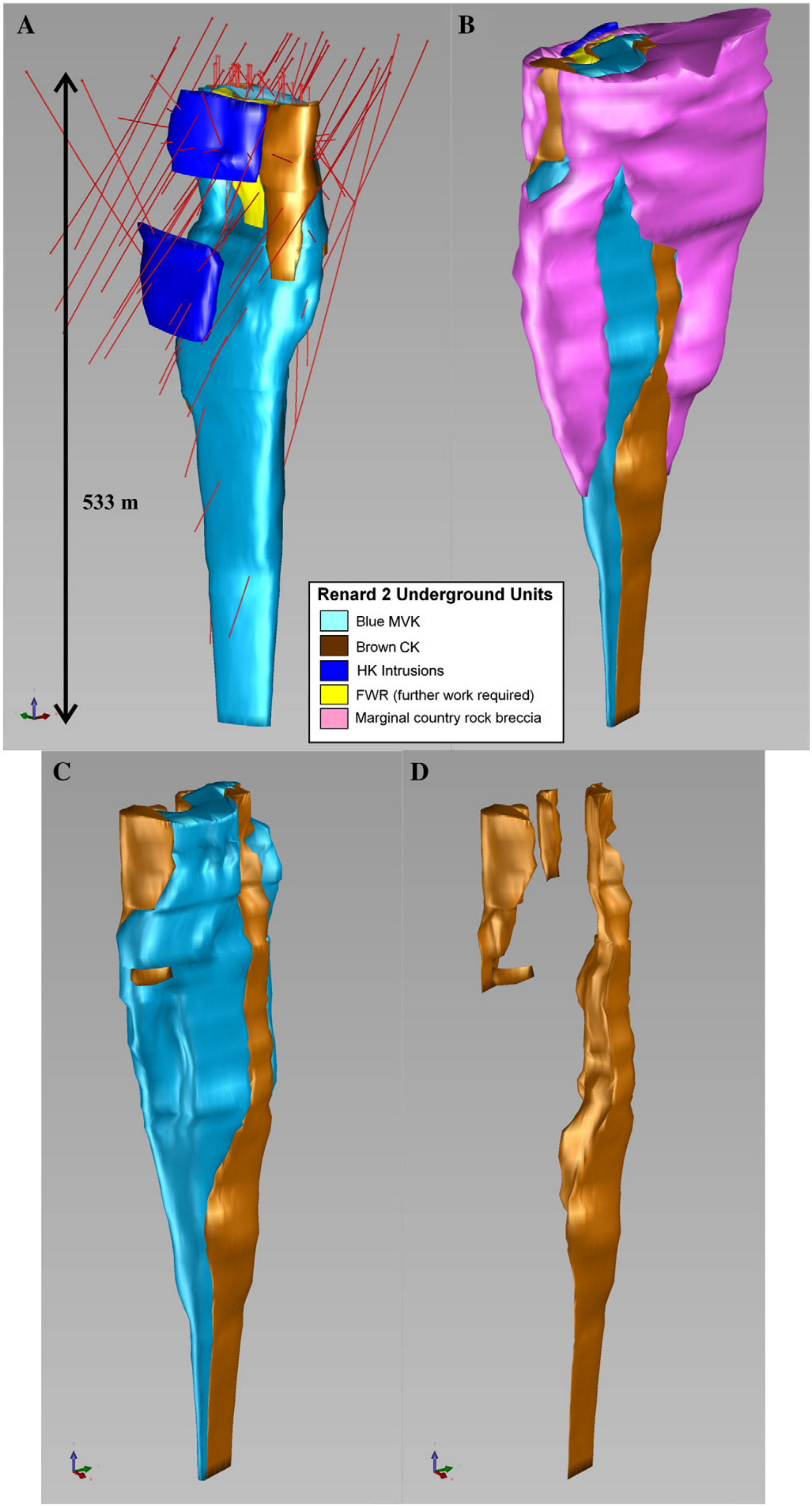
The Renard 2 external pipe shape was modeled in three dimensions using the results of geophysical surveys, comprehensive logging of 35 drill cores and mapping of underground exposures (Fig. 2). Field logs of an additional 40 drill cores and 9 reverse circulation holes were also examined, for a total of 84 holes used. The Renard body is a steep sided pipe with a number of irregularities close to surface. However, more data are available close to surface, particularly at the level of the underground decline (50 m below surface), increasing the number of pierce points available to delineate the shape near surface. With fewer pierce points with depth in the body, more extrapolation between points was required and assumption of a straight and steep-sided shape in the deeper zone was made. Confidence in the pipe shape is lowest below 250 m below surface due to the limited number of pierce points.

2.2. Internal geology: main pipe infills

The internal geology of Renard 2 was established using geological logs of both core and reverse circulation drill holes combined with detailed mapping of the underground drift (Fig. 3). This work revealed that the pipe infill is comprised predominantly of two main kimberlite rock types: an MVK type informally known as the Blue MVK and a coherent CK type that displays textures transitional to an MVK, informally known as the Brown CK. Also present throughout the body are HK dykes and irregular shaped HK intrusions. The two main infills exhibit contrasting primary textures, olivine and country rock xenolith abundances and populations and diamond contents.

2.2.1. Blue MVK

The Blue MVK is volumetrically the most significant rock type infilling the pipe, accounting for 81% of the body by volume. It is extensively altered, generally massive and can be classified as TKB (sensu stricto: Clement and Skinner, 1979; Clement, 1982; Clement and Reid, 1989; Field and Scott Smith, 1999; and Hetman, 2008). The majority of features observed underground were consistent with those observed in drill core. Macroscopically this blue to blue–green rock is comprised of olivine, juvenile clasts and country rock xenoliths that are poorly sorted, typically loosely packed and less commonly clast supported and set within a highly altered interclast matrix (Fig. 4A). Two generations of olivine are observed: the olivine macrocrysts are medium to coarse grained (3–6 mm), anhedral to subhedral, whereas the olivine phenocrysts are fine grained (<1 mm), euhedral to subhedral. Olivine comprises 10–20% of the rock. They are typically whole crystals and are completely pseudomorphed by serpentine and clay with rare carbonate. Juvenile clasts include both uncored and cored varieties (terminology after Webb, 2006). Cored varieties typically have a kernel of an olivine macrocryst, phenocryst, or a country rock xenolith. Country rock xenoliths are comprised of locally derived granite and gneiss that are fresh to moderately altered. Granite xenoliths may appear dark pink to orange in areas of strong alteration whereas gneissic xenoliths are white to grey and generally fresher. Most of the country rock fragments are angular to rounded and range in size from <1 cm xenocrysts to xenoliths up to 1.5 m, however the typical maximum is 50 cm. The shape of xenoliths is variable, with common shards and angular shapes observed close to pipe walls and extending into the marginal breccia, whereas more rounded varieties are observed within the centre of the diatreme. A


A
B
C
D
533 m
Renard 2 Underground Units
Blue MVK
Brown CK
HK Intrusions
FWR (further work required)
Marginal country rock breccia

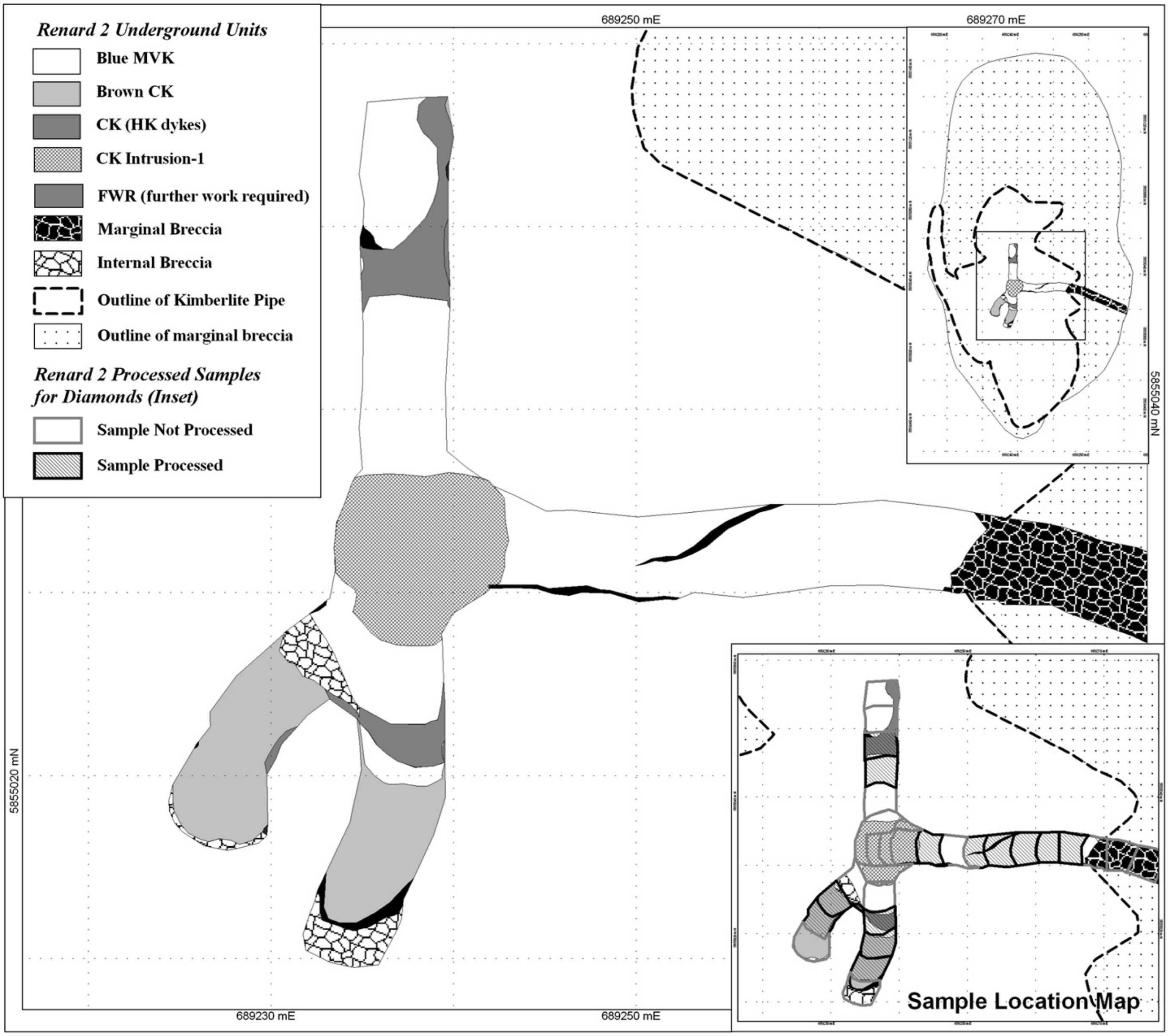


Fig. 3. Detailed map of the underground exposure highlighting geological units observed underground. Illustrated here are the two main rock types in Renard 2: the Blue MVK (white) and the Brown CK (light grey), as are several HK dykes (black) (intruding mostly Blue MVK) and the internal and marginal country rock breccias (patterned).

number of large country rock blocks up to 3 m in diameter have been observed in the Blue MVK in the underground exposure. Xenoliths may comprise 30% to 90% of the rock, however the most common range observed is 40% to 65% (Fig. 4B). Detailed line scan data from mapping of the walls in the underground drift show an average country rock xenolith content of 46% for the Blue MVK in this area of the body.

Textural features and dilution within the drill cores and underground exposures are similar; however, vertical fabrics defined by changes in country rock xenolith size and abundance, and the preferred orientation of elongate country rock xenoliths are more conspicuous within the underground exposures. These vertical fabrics occur as localized, metre-scale, vertically oriented zones in the Blue MVK (Fig. 4C) and they are generally associated with internal and pipe wall contacts. In addition, alteration zones associated with late-stage HK intrusions are much easier to identify in the underground exposures.

Thin section investigation of this rock has revealed that microscopically, the Blue MVK is characterized by good textural preservation however it displays poor mineralogical preservation in that extensive alteration has occurred. Olivine macrocrysts are medium to coarse grained and anhedral to subhedral and fine grained while olivine phenocrysts are fine grained and euhedral to subhedral. Olivine comprises 10–35% of the rock and is pervasively altered to serpentine, clays and carbonate and commonly display thick rims of microlitic clinopyroxene (Fig. 4D and E). The olivine morphology (predominance of unbroken crystals) and distribution (uniform) is comparable to that of a texturally unmodified HK (e.g. Snap Lake (Kirkley et al., 2003)); however, the total olivine abundance is lower

Fig. 2. Three-dimensional geological model of the Renard 2 kimberlite. (A) Looking northeast, showing the Blue MVK, Brown CK, two HK intrusions peripheral to the body and drill holes completed to date. (B) Looking northwest, showing the marginal breccia surrounding the pipe. (C) Looking northwest, marginal breccia removed. (D) Looking northwest, Brown CK only.

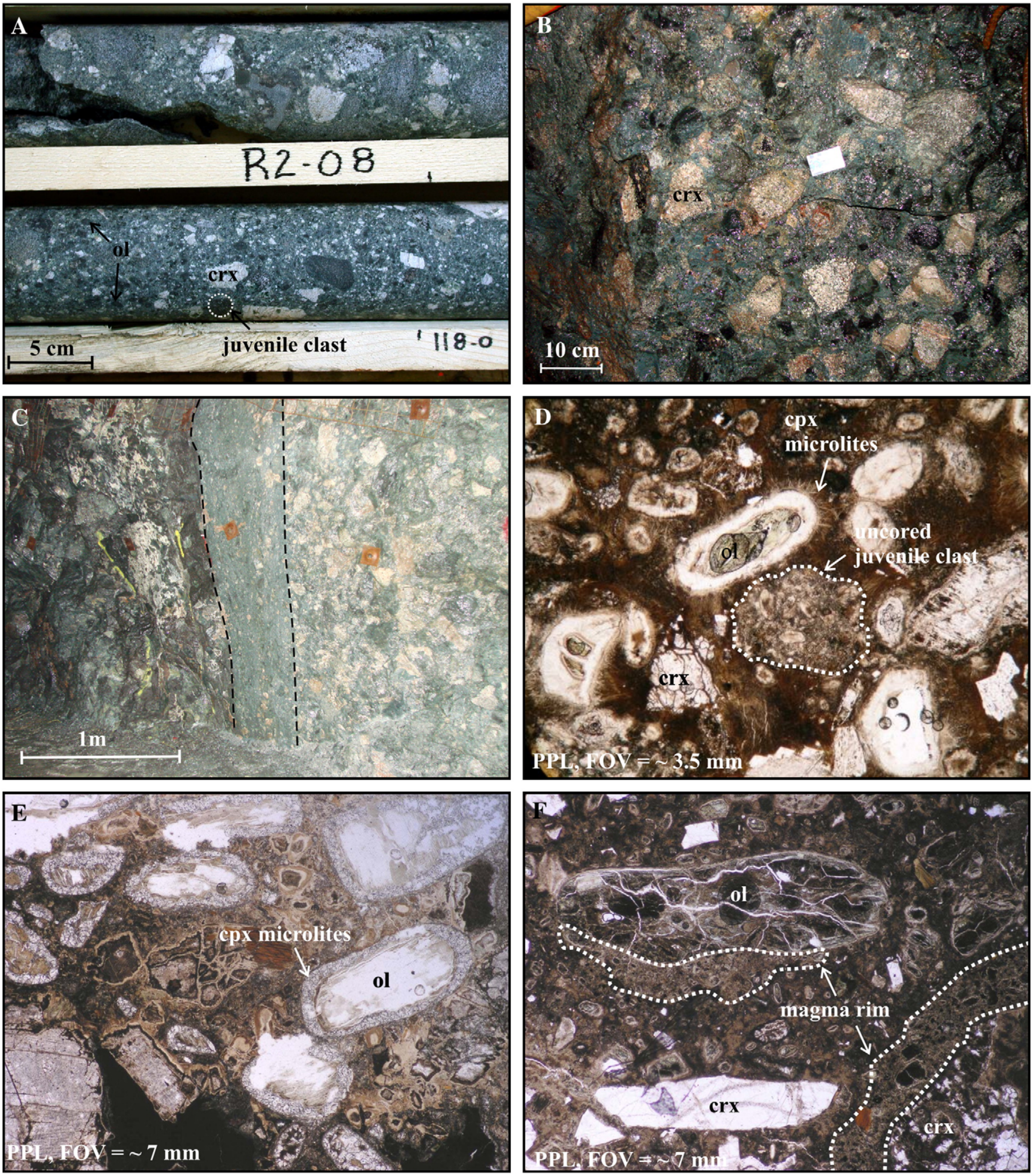


Fig. 4. The Blue MVK as observed in drill core: (A) Typical Blue MVK core consisting of light blue–green interclast matrix, white fresh country rock xenoliths and xenocrysts, medium- to coarse-grained serpentinized olivine macrocrysts and rare uncored juvenile clasts; and as observed in underground exposure showing: (B) the typical high abundance of country rock xenoliths and (C) the nature of the contact between the Brown CK (left) and Blue MVK (right) which is sharp, and marked by the localized metre-scale vertically oriented zone that is characterized by an absence of country rock xenoliths >1 mm in size (outline in black stippled lines); and as observed in thin section: (D) Pervasively altered olivine and juvenile clasts and commonly fresh country rock xenoliths (crx) are typically poorly sorted and loosely packed in a highly altered interclast matrix; (E) Serpentinized olivine macrocrysts and phenocrysts display microlitic clinopyroxene (cpx) replacement rims; (F) Cored juvenile clasts consist of either a serpentinized olivine macrocryst (ol) or fresh country rock xenolith (crx) and a single incomplete or complete coherent juvenile rim.

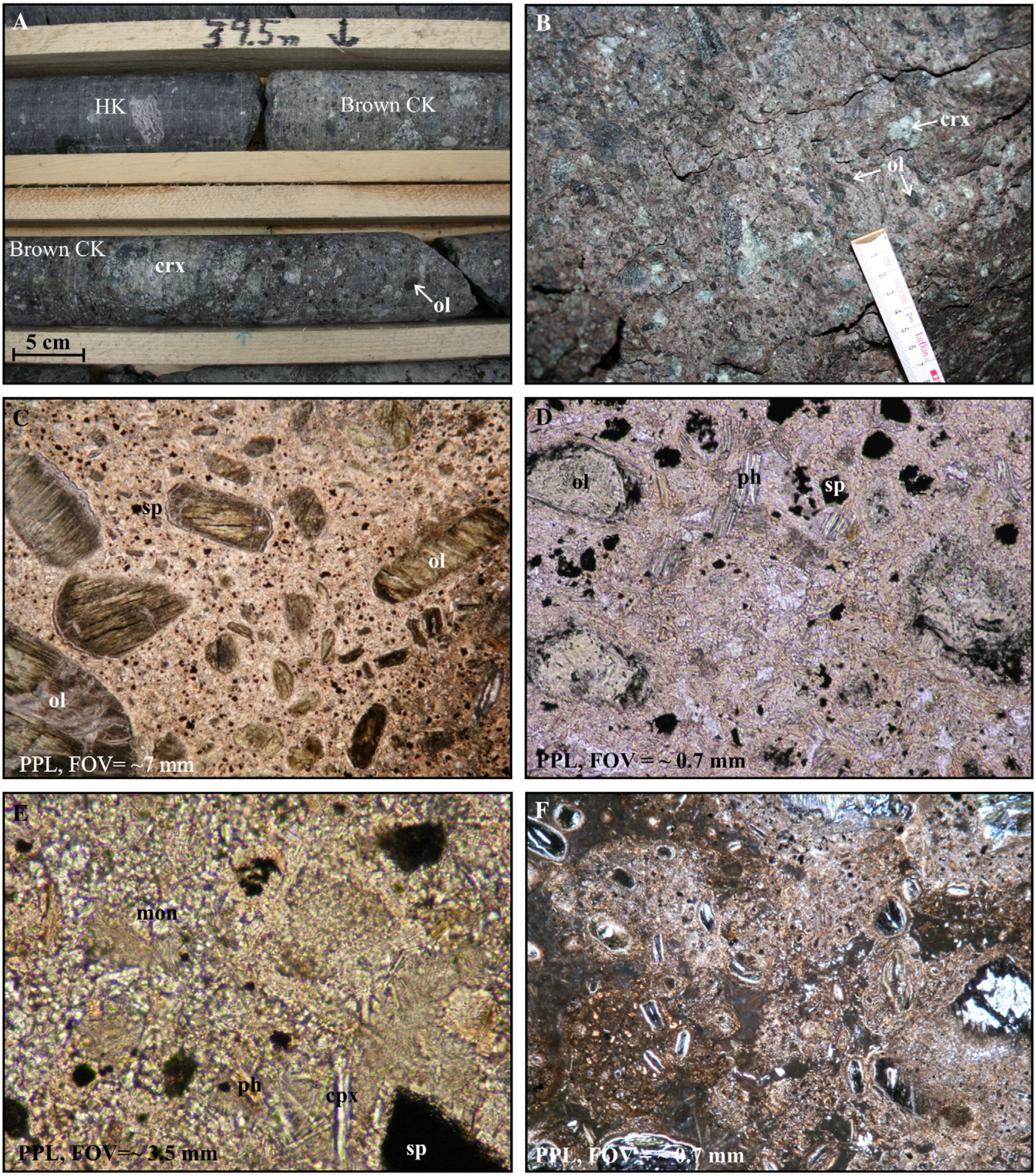


Fig. 5. The Brown CK, as observed in drill core: (A) Typical Brown CK core consisting of medium to coarse (with rare very coarse) grained serpentinized olivine macrocrysts and moderately to highly altered country rock xenoliths. Texture is like that of a CK, with evenly distributed olivines and a crystalline groundmass; and as observed in underground exposure showing (B) the typical light brown interclast matrix/groundmass with coarse sized olivine macrocrysts (dark brown) and lack of country rock xenoliths >5 cm in size (pale green); and as observed in thin section: (C) Highly serpentinized olivine (ol) macrocrysts and phenocrysts occur in a uniform crystalline groundmass containing spinel (sp); (D) Characteristic fine laths of phlogopite (ph) in the groundmass; (E) Close-up of groundmass monticellite (mon) (small, colourless euhedral to subhedral grains on left side of image) as associated groundmass minerals such as clinopyroxene (cpx), spinel (sp) and pale brown phlogopite (ph). (F) Close-up of a transitional–textured zone showing uncored partially developed juvenile clasts set in an inhomogeneous interclast matrix.

due to the high proportion of country rock xenoliths and the texture of the Blue MVK is clearly volcaniclastic. Mantle derived indicator minerals and mantle xenoliths are extremely rare. When observed, mantle indicator minerals include red to purple peridotitic garnet and mantle xenoliths are peridotitic. The interclast matrix is comprised of serpentine, clinopyroxene microlites and clay minerals and includes minor carbonate. Locally derived granitoid and lesser gneissic xenoliths and xenocrysts are fresh to moderately altered and angular to rounded. Juvenile clasts are both single rim uncored (refer to Fig. 4D) and cored varieties (Fig. 4F). Groundmass minerals present within the juvenile clast rims include phlogopite, perovskite and spinel. The Blue MVK is classified as a phlogopite kimberlite based on the mineralogy of the juvenile clasts and texturally this rock can be further classified as a TKB.

2.2.2. Brown CK

The second most volumetrically signficant rock type is Brown CK, accounting for 19% of the body by volume. The Brown CK is a moderately altered, massive and texturally variable unit that displays both coherent and less common volcaniclastic (i.e. TKB) textures. Characteristics of this rock were more easily discerned in drill core than underground due to limited light conditions underground combined with the dark colour of this rock type. Macroscopically, the Brown CK is pale brown to black and is comprised of two generations of olivine set within a crystalline groundmass with common country rock xenoliths that typically show significant reaction to the host kimberlite (Fig. 5A and B). Juvenile clasts are rarely encountered and more easily discerned within drill core compared to the underground exposures. In general, the Brown CK exhibits a CK texture with evenly distributed olivine and a dominantly crystalline groundmass, however there are relatively rare zones of diffuse juvenile clasts. The word transitional is used to describe minor subunits within the Brown CK as there are areas that display textures of both coherent and volcaniclastic rocks within the same interval.

Olivine macrocrysts are medium to coarse grained with sporadic very coarse grains (>10 mm). These are subhedral, fresh to extensively pseudomorphed by serpentine and comprise 25–30% of the rock. Olivine phenocrysts are fine grained, euhedral to subhedral and pseudomorphed by serpentine. Juvenile clasts have diffuse margins. In parts of the rock where the juvenile clasts are visible, the rock is lighter brown and groundmass appears less crystalline. The olivine morphology (predominance of unbroken crystals) and distribution (uniform) is similar to that of a texturally unmodified HK (e.g. Snap Lake (Kirkley et al., 2003)).

Visual estimates of country rock xenoliths in drill core show they comprise 20–50% of the kimberlite. Detailed line scan data from mapping of the walls in the underground drift show an average country rock xenolith content of 22% for the Brown CK in this area of the body. Country rock xenoliths include both granitoid and gneiss, although the latter predominates. The xenoliths are sub-angular to rounded and typically <10 cm in size in drill core and underground, however much larger xenoliths are sporadically distributed and are up to 50 cm in size. Xenoliths are variably altered, showing a range of reaction with the host that can include complete replacement of some xenoliths. Gneissic xenoliths commonly have dark green reaction rims when altered.

Thin section investigation of this rock has revealed that the Brown CK displays good textural and mineralogical preservation. Microscopically, olivine macrocrysts are medium to coarse grained with common very coarse grains that are anhedral to subhedral. Olivine phenocrysts are fine grained and euhedral to subhedral. Olivine comprises 25–50% of the rock (Fig. 5C). Mantle derived indicators and mantle xenoliths are extremely rare and include peridotitic garnets and extremely rare chrome diopside. Mantle xenoliths include extensively altered peridotites. The crystalline groundmass consists of phlogopite, perovskite, spinel, carbonate and rare monticellite (Fig. 5D). The monticellite is observed as euhedral, extensively altered crystals smaller than 1 mm (Fig. 5E). Microlitic clinopyroxene can be abundant in the groundmass; however, it is generally associated with areas of digested country rock xenoliths and is considered secondary in origin. Localized areas displaying a more complex texture are characterized by the presence of diffuse juvenile clasts set in an inhomogeneous variably crystallized groundmass and/or and interclast matrix dominated by microlitic clinopyroxene and probable clay. These clasts are partially to completely cored to uncored with less common uncored varieties (Fig. 5F) and are commonly tightly packed and have boundaries that touch one another. Texturally this rock is classified as a CK and mineralogically as a monticellite phlogopite kimberlite.

2.2.3. Blue MVK VS. Brown CK

The two main infills, the Blue MVK and the Brown CK, display contrasting textures and primary mineralogy and also differ in terms

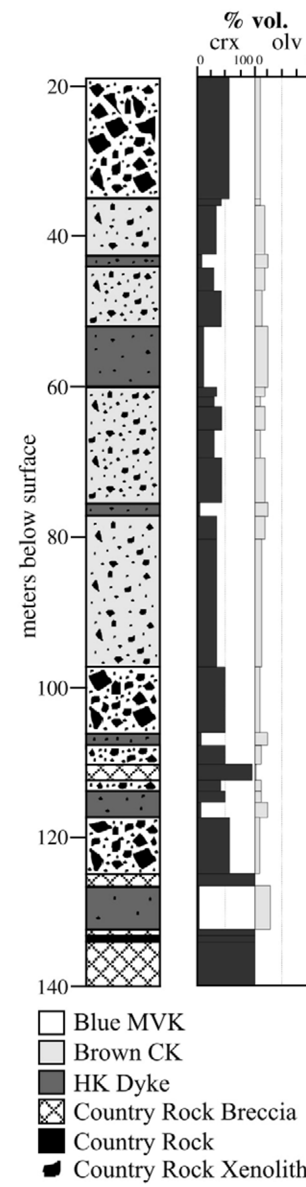


Fig. 6. Schematic illustration of a portion of vertical core drill hole R2-47. This hole illustrates the general features that characterize the Blue MVK, Brown CK and HK dykes. Highlighted are the visual estimates of country rock xenolith and olivine content adjacent to the geology. This data illustrates the variabilty observed in the Brown CK, as compared to the general homogeneity in the Blue MVK. HK dykes are common, less than 1 m thick and intrude both the Blue MVK and the Brown CK.

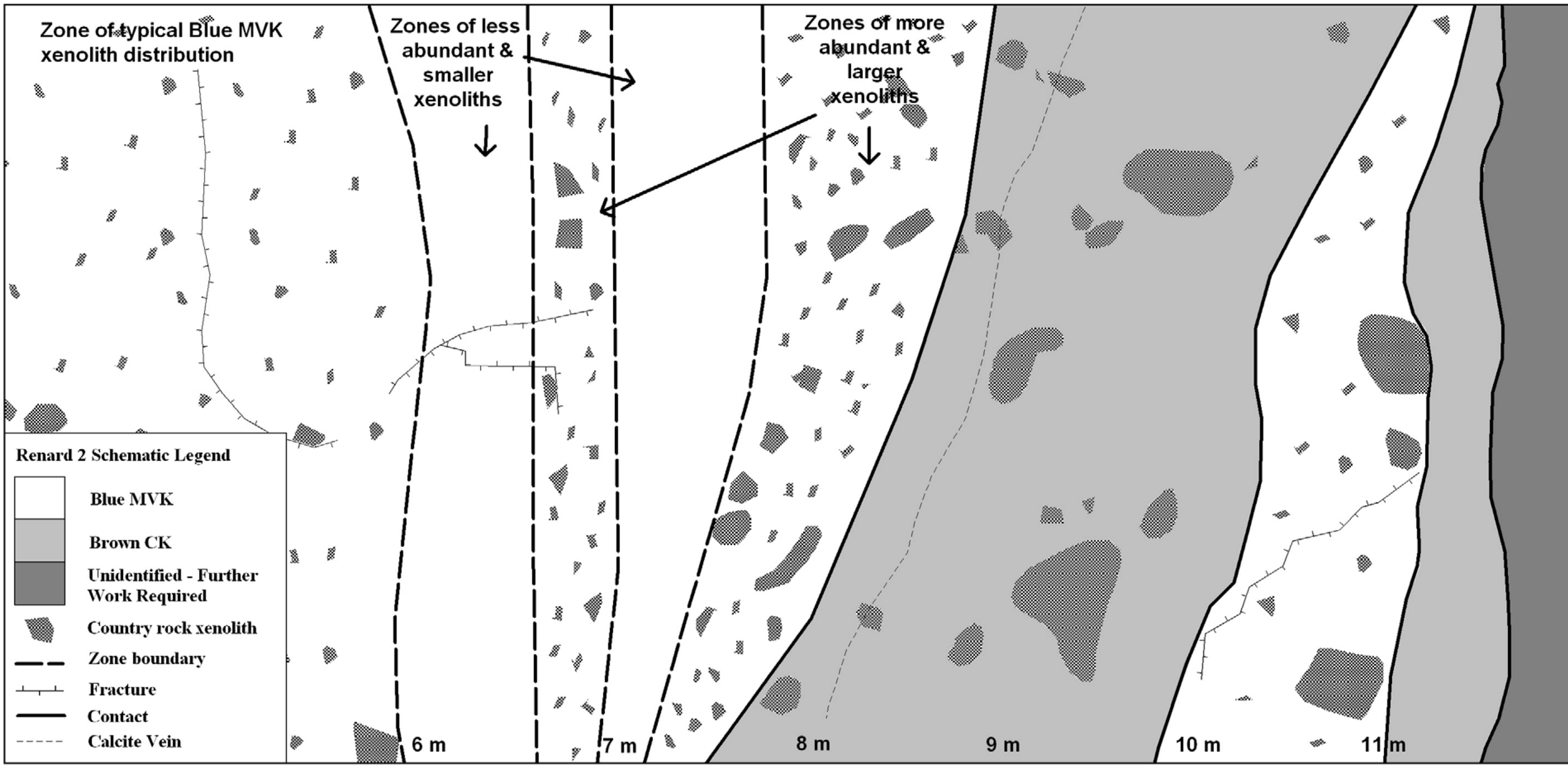


Fig. 7. Sketch of the west wall in the north drift of the Renard 2 underground exposure. This highlights the sharp nature of the contact between the Blue MVK (white) and Brown CK (light grey) units and the variation in country rock xenolith distribution in the Blue MVK adjacent to this contact. Note the subtle vertical orientation of xenoliths in this zone.

of their olivine content (specifically conspicuous coarse olivine macrocrysts in the Brown CK) and country rock xenolith abundances and population, and most significantly the diamond grade. A schematic of a representative portion of a core hole illustrates the differences in country rock xenolith and olivine content in the two main pipe infills and the variability within the Brown CK itself (Fig. 6).

The Blue MVK is classified mineralogically as phlogopite kimberlite and the Brown CK as monticellite phlogopite kimberlite. The Brown CK is characterized by a higher proportion of coarser-grained olivine macrocrysts; the olivine macrocrysts in the Blue MVK are typically finer-grained and less abundant. Country rock xenoliths in the Brown CK are generally less abundant, smaller and more altered and show greater reaction to the host kimberlite as compared to those in the Blue MVK and the population is dominated by gneissic rather than granitoid xenoliths. Contacts between the two contrasting rock types are sharp and in places highlighted by HK dyke intrusions, as well as changes in the proportion of country rock xenoliths in the Blue MVK (Fig. 7 and refer to Fig. 4C). Bulk sampling results clearly indicate a higher diamond grade for the Brown CK than the Blue MVK. The contrasting textural and component features described above and sharp nature of the contacts, combined with the difference in diamond grade, supports interpretation of the two pipe infills as two distinct rock types emplaced during two separate volcanic events.

2.3. Country rock breccia

Country rock breccia in the Renard kimberlite cluster is defined as a rock type that consists of more than 95% country rock fragments with <5% to no kimberlite component. Two types of country rock breccia are documented in Renard 2: an extensive "archetypal" country rock breccia that surrounds the upper half of the body, referred to as the marginal breccia due to its location relative to the pipe; and an internal country rock breccia that may be related to the Blue MVK.

The marginal breccia is both vertically and horizontally extensive, reaching a maximum width of 100 m adjacent to the body near surface and extending almost 370 m vertically (refer to Fig. 2). The breccia has been observed in both drill core and in the underground exposure. It consists of angular to sub-angular and elongate, clast supported country rock fragments and blocks ranging in size from <1 cm up to 1 m and displays common jig-saw fit textures (Fig. 8A). Clasts are typically granitoid with less common gneiss. The granitoids are generally highly altered and dark pink to orange, whereas gneissic clasts are less altered, more rounded and a pale grey colour. The relative proportion of granitoids to gneissic clasts is generally 60% to 40%, respectively. Matrix-supported zones, consisting of dark grey sand-sized pulverized country rock material, are found throughout this unit but are more common adjacent to the body. In the underground exposure, rotated country rock blocks (25–30 cm) were observed to dip inwards gently toward the centre of the diatreme, suggesting that they were not formed in situ (Fig. 8B). The marginal breccia at Renard 2 includes zones that do not contain any kimberlite and others that contain up to 5% juvenile kimberlite components (excluding HK sheets) mixed within matrix-supported zones. Kimberlitic constituents, when encountered, are often found adjacent to the main diatreme zone and consist of fine to rarely medium grained, completely serpentinized and/or carbonatized olivine, very rare uncored juvenile clasts and rare autoliths of HK. Kimberlite also occurs in the marginal breccia as HK dykes and irregular intrusions of varying thickness. Most HK dykes are <1 m thick, however a few intrusions are >10 m and are described as irregular intrusions, due to their extreme size (compared to the HK dykes), and more complex morphology. Contacts between the marginal breccia and surrounding un-brecciated country rock are sharp, observed both in drill core and underground. Contacts between the marginal breccia and the two main pipe infills differ: they are sharp between the marginal breccia and the Brown CK, but variable with the Blue MVK. In drill core contacts between the marginal breccia and Blue MVK are commonly diffuse or gradational, whereas underground it is sharp.

The marginal breccia is similar to those described from the Kimberley area (De Beers, Wesselton and Dutoitspan mines) (Clement, 1982; Clement and Reid, 1989) and at Venetia (Barnett, 2002; Brown et al., 2009), in that crude layering and large jig-saw fit angular blocks are documented.

The internal country rock breccia was identified during mapping of the underground exposure. This breccia consists of large fresh blocks of white granitoid and gneiss with a minor matrix component manifested as <2 cm wide veins. This unit is associated spatially with the Brown CK and contacts are sharp between these rock types (refer to Fig. 3).

2.4. Hypabyssal dykes and irregular intrusions

Coherent kimberlite (CK) in Renard 2 occurs in the form of late-stage dykes and irregular intrusions and both are classified as HK (Fig. 8C and D). HK dykes are found throughout the body and typically occur along contacts between types of main pipe infills, along the pipe walls and throughout the marginal breccia. Dykes range in thickness from a few centimetres to 1 m and contacts are often characterized by flow alignment of elongated minerals and carbonate veining. The HK is dark green to black and is comprised of two generations of olivine (macrocrysts and phenocrysts) that are evenly distributed and set within a homogeneous, crystalline groundmass. The abundance of medium- to coarse-grained olivine macrocrysts ranges from 25–30%. The olivine is generally completely serpentinized with minor carbonate replacement (Fig. 8E), but is overall less altered than olivine in the main pipe infills. The various HK intrusions include a spectrum of primary groundmass mineral assemblages, ranging from monticellite-dominated to phlogopite-dominated, each additionally consisting of common carbonate, spinel and perovskite (Fig. 8F). Disseminated biotite xenocrysts and rare, highly altered, country rock xenoliths may also be present. Although this rock type is commonly uncontaminated by country rock, dykes and irregular intrusions emplaced within the marginal breccia can have elevated country rock xenolith contents and thus superficially appear volcaniclastic in texture. Country rock xenoliths in the HK dykes are typically <5 cm in size, irregular in shape and highly altered. In addition to the differences in primary mineralogy, variations in alteration state, size and abundance of olivine macrocrysts and size of groundmass constituents also exist within and between the HK dykes. Most of the HK dykes contain very few mantle indicator minerals and appear to lack ilmenite, however there are rare ilmenite rich dikes that have been identified which contain abundant indicators.

In the underground exposure, HK dykes are more commonly observed within the Blue MVK more often than within the Brown CK. These are typically sub-vertical and less than 1 m in width. Dykes are also emplaced along contacts between rock types. Typically these were too dark in colour to observe olivine macrocrysts underground and were generally uncontaminated with country rock xenoliths. In addition to these, a large, irregular, coherent kimberlite intrusion was observed in the centre of the drift that has a width of approximately 10 m (refer to Figs. 3 and 8D). This unit was dark in colour and was characterized by highly altered, rounded, white country rock xenoliths that comprised 10–15% of the rock.

3. Diamonds

Underground excavation on the Renard 2 body was undertaken in 2006 in order to to aquire a macrodiamond parcel for valuation purposes. Processing of the kimberlite focused on subsamples that consisted of dominantly one rock type, but also representing different

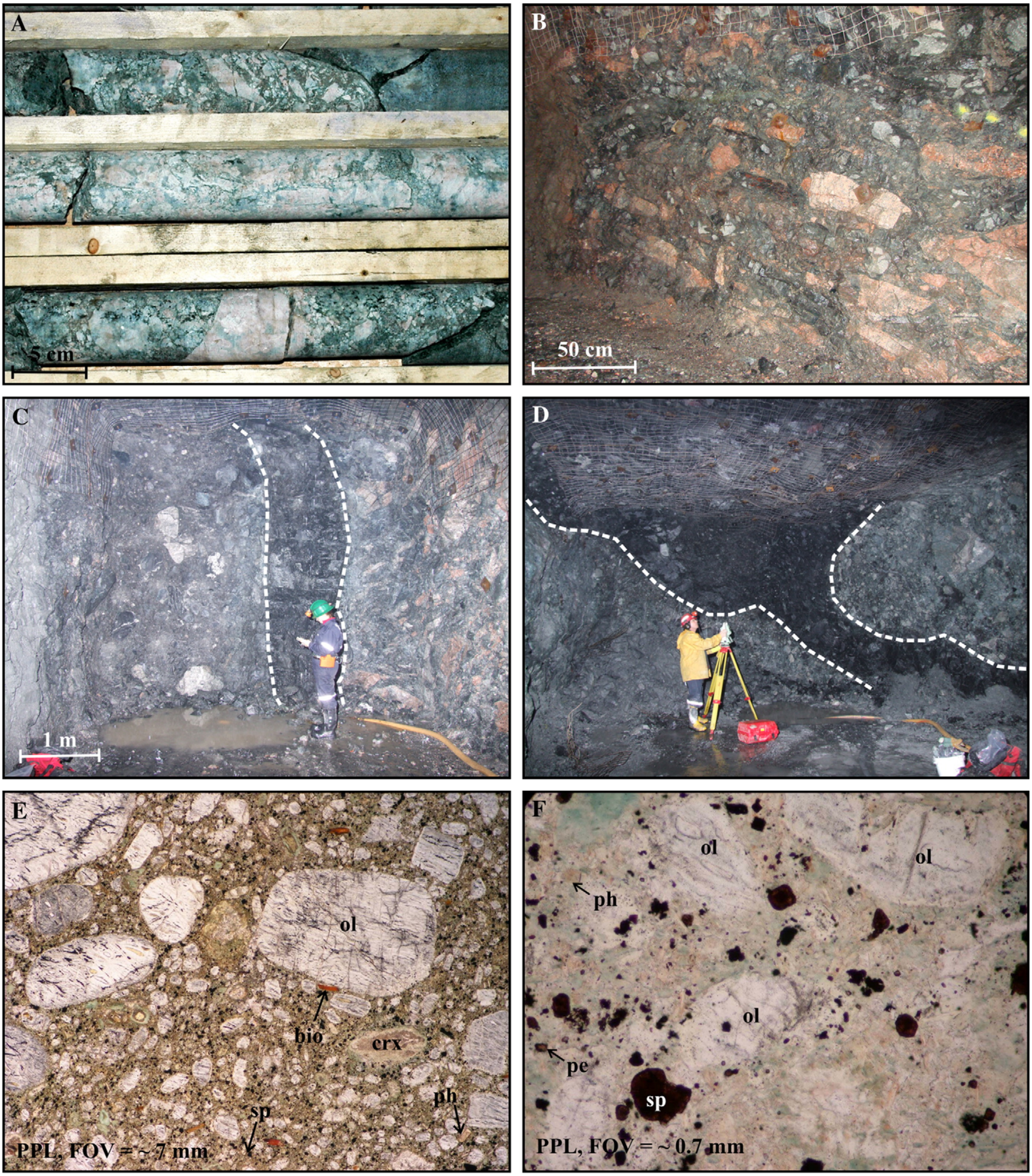


Fig. 8. Typical marginal breccia as observed in: (A) drill core showing the jig-saw fit texture and (B) underground, which is characterized by angular clast supported country rock blocks that are rotated and dip inwards toward the centre of the pipe. Hypabyssal kimberlite (HK), as observed in underground exposure showing: (C) a vertical HK dyke (dashed white lines) emplaced along a contact between two country rock breccia domains, and (D) an irregular HK intrusion (outline in dashed white lines) in the centre of the body (50 m below surface) emplaced within the Blue MVK; and as observed in thin section: (E) Variably serpentinized medium-grained olivine (ol) macrocrysts and very fine phenocrysts are set in a uniform crystalline groundmass dominated by carbonate and phlogopite (ph) with minor spinel (sp). Note disseminated biotite xenocrysts and rare highly altered country rock xenoliths; (F) Close-up of the subhedral olivine phenocrysts set in a uniform crystalline groundmass of carbonate and phlogopite (pale brown) with disseminated spinel (sp) and perovskite (pe).

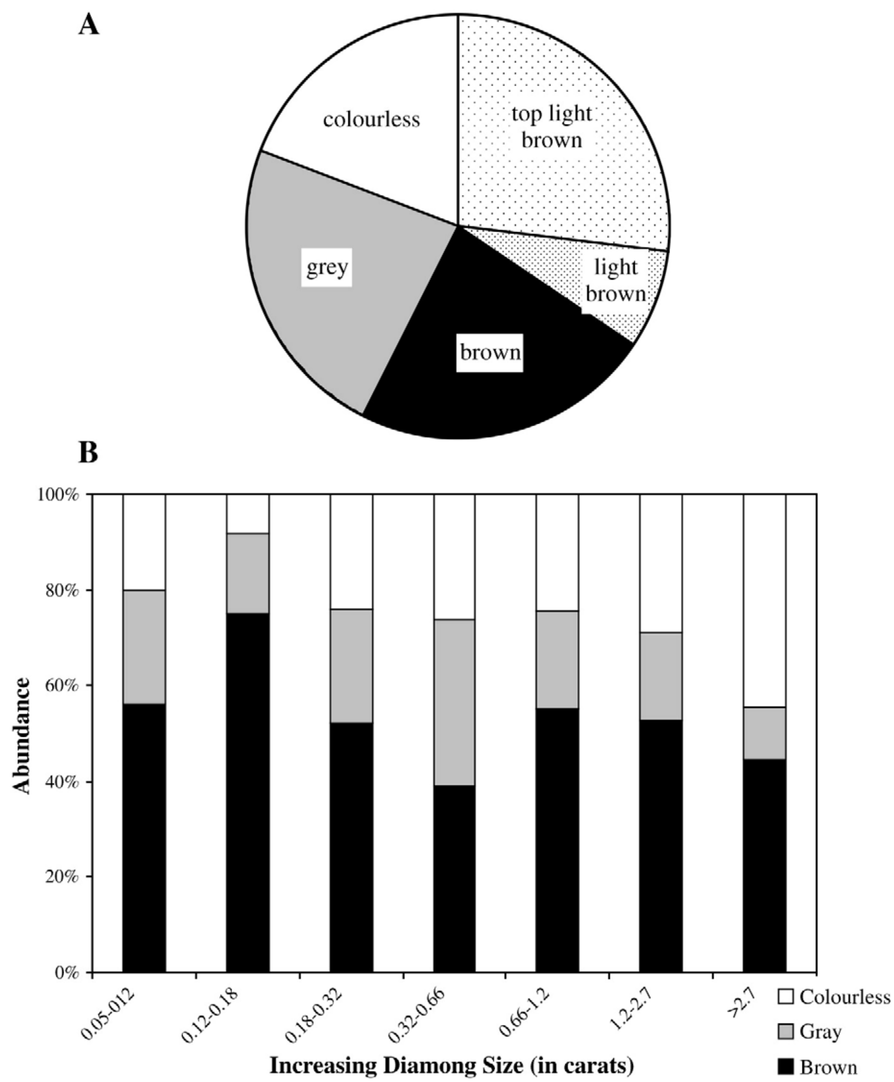


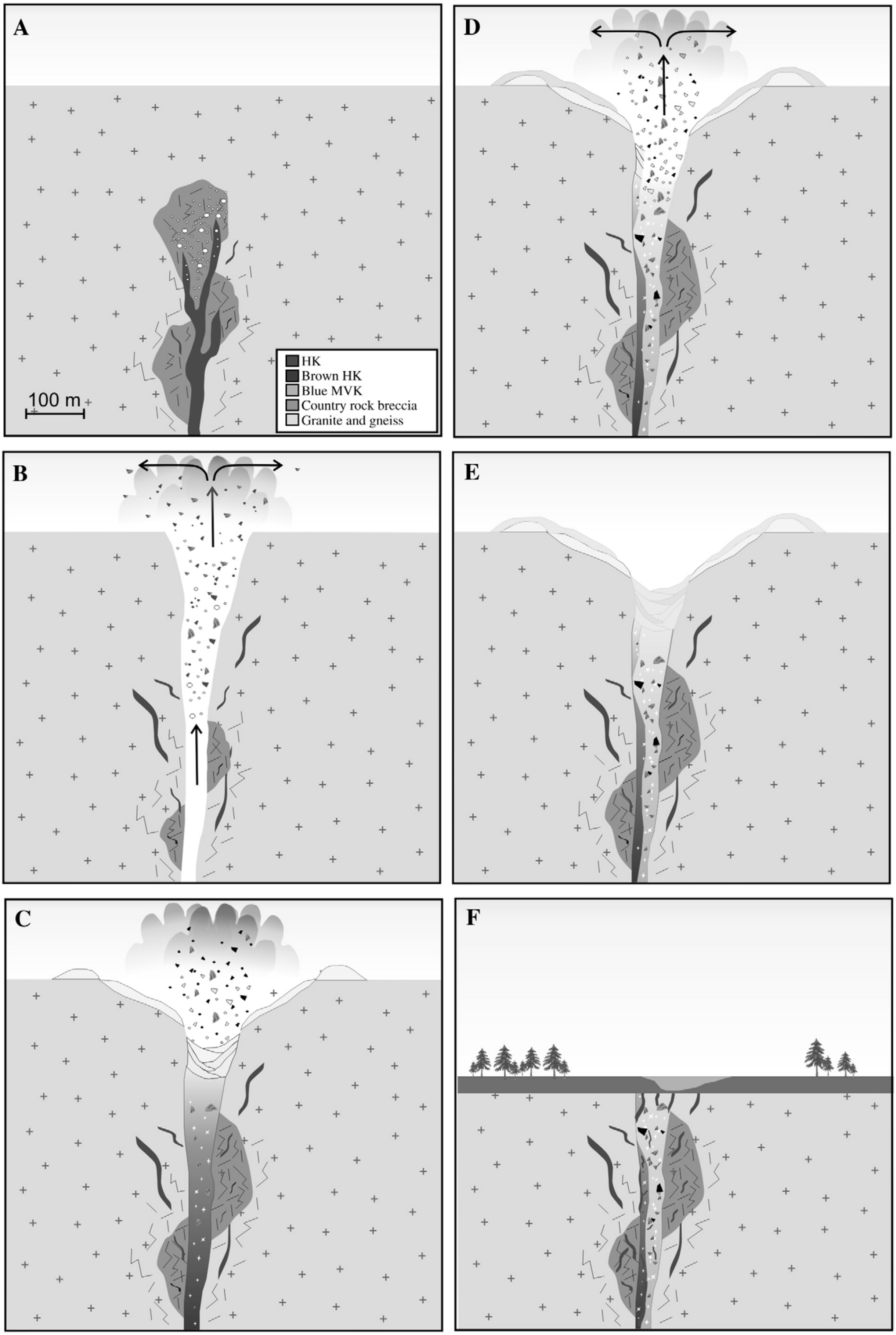
Fig. 9. (A) Detailed colour divisions for diamonds from Renard 2, for stones exceeding 0.05 ct. (B) Correlation between colourless crystal abundance and increasing diamond size (in carats) for the diamonds in Renard 2. For clarity, brown diamonds are combined in (B).

areas across the pipe. A total of 1600 ct was recovered from 2449 tonnes of kimberlite during this excavation. Subsamples that were dominantly Brown CK (>90%) have diamond contents ranging from 63–144 cpht, whereas those that were dominantly Blue MVK (>90%) have sample grades ranging from 26–78 cpht (minimum recovery size ~0.01 ct). The largest stone recovered from the Brown CK is 15.46 ct and the largest from the Blue MVK is 4.9 ct (refer to online Annexes A and B).

A morphological assessment was completed on Renard 2 diamonds from this bulk sample for stones greater than 0.05 ct, with a total of 9830 diamonds being examined. Significant physical differences were not detected when comparing diamonds from subsamples dominated by Brown CK versus those dominated by Blue MVK. The population was first assessed for colour, with divisions approximating those used in commercial diamond valuation exercises, in particular the top light brown division. In Renard 2, colourless and top light brown diamonds comprise 19% and 27% of the population, respectively. Light brown stones contribute 8%, with brown and grey colours each contributing 23% of the total (Fig. 9A). In both the brown and grey groups, colouration is due in part to the presence of small opaque inclusions that give the stones a darker translucent appearance with increasing abundance, rather than from deformation.

Genetic grouping of the diamonds was approached using the concept of Sunagawa (1984) that multiple crystal forms reflect increasing carbon saturation during diamond genesis. In this respect the Renard 2 diamonds are distinctive in having a near absence of fine diamond aggregates (<1 mm crystallites; after McCandless et al., 1989), amounting to less than a percent of the population even when broken diamonds and fragments are considered. Multiple diamond crystals in Renard 2 are dominated by coarse diamond aggregates and dominate the genetic forms in the brown (74%) and grey groups (67%). In contrast, single crystals dominate the light brown (99%), top light brown (84%), and colourless groups (79%). Colourless crystals also increase in abundance with increasing size (Fig. 9B). With respect to resorption, 88% of all diamonds are tetrahexahedroida (terminology after Robinson, 1979; Robinson et al., 1989), with a variety of hillock

Fig. 10. Schematic illustration of the emplacement of the Renard 2 kimberlite. (A) Pre-conditioning of the country rock by rising volatiles, leading to development of marginal breccia due to depressurization and movement of country rock towards the diatreme. (B) Breaching of the surface, explosive degassing of magma followed by marginal breccias falling into the pipe. Further failure of walls may occur creating more country rock breccia. (C) Infilling of the pipe by the Brown CK. (D) Partial excavation of the Brown CK during the explosive emplacement of the Blue MVK. (E) Late-stage emplacement of hypabyssal sheets and irregular intrusions. (F) Hydrothermal alteration of the kimberlite followed by an undetermined amount of erosion.


A
B
C
D
E
F
HK
Brown HK
Blue MVK
Country rock breccia
Granite and gneiss
100 m

types defining the tetrahexahedroidal surface textures. Octahedra form a minor component regardless of genetic form or size. The most common octahedral surface textures are shield laminae, consistent with the advanced state of resorption for the Renard 2 diamonds. A late, low-temperature corrosion texture that overprints octahedral and tetrahexahedroidal surfaces on many stones in a non-systematic manner, indicates that diamond-resorbing fluids were still active after emplacement of the body into the crust.

The correlations between diamond colour and primary genetic form suggest that at least two genetic groups could be present in the Renard 2 diamond population. Preliminary analysis of inclusions in select diamonds has indicated that at least two diamond lineages are present in the Renard 2 diamonds. A peridotitic (harzburgitic) parentage has been confirmed by the presence of chromian Mg-spinel, subcalcic Cr-pyrope and forsterite, and a second parentage is represented by SiO_2 inclusions (Hunt et al., 2008). This silica assemblage is unusual and could not have coexisted with a peridotitic mineralogy, and may represent an eclogitic silica-rich source (Hunt et al., 2008). Further work on inclusions in the diamonds is scheduled to better resolve these uncertainties.

4. Emplacement history of Renard 2

Based on the investigations completed to date, the emplacement of Renard 2 can be outlined in five main stages that include at least two major pipe excavation and infilling events.

(i) Pre-conditioning of the country rock by ascending kimberlite fluids leading to the development of country rock breccia.

During this process, high-pressure fluids rising ahead of the ascending magma act to fracture country rock (Wilson and Head, 2007), which may create weak zones from which a pipe may develop (Fig. 10A). In extreme cases the country rock has been reduced to clasts set in a matrix of sand-sized particles. The distribution of the country rock breccia in the area of the pipe and the extent of brecciation is irregular, as revealed within the core holes, and is likely related to the position of local joints and faults and the interconnectedness of these structures at the time of emplacement. The country rock breccia that envelops the diatreme zone, referred to as the marginal breccia, is interpreted to have formed initially prior to breaching of the surface (Clement, 1982; Clement and Reid, 1989; Field and Scott Smith, 1999; Kirkley et al., 2003; Wilson and Head, 2007) and then further developed (during stage ii) as the excavation of the pipe progressed (Sparks et al., 2006, Brown et al., 2009). Following explosive breaching of the surface, the excavation of the diatreme would have allowed for additional brecciation and rock bursts due depressurization of the country rock along the pipe margins (Sparks et al., 2006), as well as movement of this material toward the free space of the active diatreme. Evidence for this process can be observed along the underground ramp leading into the Blue MVK, where a significant zone of rotated country rocks can be seen dipping inwards toward the centre of the pipe. Volcaniclastic kimberlite is only present within the marginal breccia closest to the diatreme. The nature of the contact between the marginal breccia and main pipe infills differs: the Blue MVK contact is dominantly gradational, whereas the Brown CK contact is sharp. The mixed nature of the contact between the marginal breccia and the Blue MVK suggests that the diatreme development was ongoing as this kimberlite was infilling the diatreme.

(ii) Breaching of the surface and consequent explosive degassing of kimberlite magma leading to pipe excavation and infilling of the pipe with the Brown CK.

Following explosive breaching of the surface and excavation of the diatreme (Fig. 10B), the diatreme was first infilled with Brown CK (Fig. 10C). The lower abundance of country rock xenoliths in this rock compared to the Blue MVK indicates that much of the diatreme had been excavated and the country rock was almost completely removed from the pipe prior to the infilling of the Brown CK. This suggests that the initial eruption/s involved must have been highly explosive in order to develop the pipe and remove the majority of the country rock from the system. The texture of the Brown CK (i.e. absent to rare juvenile clasts and shardy country rock xenoliths) suggests subsequent emplacement by less explosive processes. It is possible that the Brown CK represents a welded volcaniclastic kimberlite deposit formed by processes such as those described by Sparks et al. (2006) or Brown et al. (2009). Because of the depth in the pipe, it is likely that pyroclasts would have welded together, however, the predominantly unbroken morphology and uniform distribution of the olivine macrocrysts and lack of fabric in the rock is inconsistent with textures observed in clastogenic coherent kimberlites studied by Webb et al. (2008). The Brown CK exhibits features of both clastogenic (welded pyroclasts) and intrusive rocks (magma fragmentation). A combined petrographic and geochemical approach as used by Nowicki et al. (2006) and Webb et al. (2008); in addition to systematic logging and description as described by Brown et al. (2009), may serve to determine whether the Brown CK experienced an explosive fragmentation event by determining if there was a loss of fines. Emplacement of the Brown CK is thought to have preceded formation of the Blue MVK based on the relative distribution of these rock types within the pipe, the cross-cutting relationship of the Blue MVK and the presence of remnant blocks of Brown CK within the Blue MVK.

(iii) A second pipe excavation and kimberlite emplacement event resulting in the removal of a significant volume of the Brown CK and infilling of the diatreme by the Blue MVK.

The Blue MVK was the second major rock type to erupt and infill the diatreme. This is evidenced by the sharp sub-vertical contacts between the two, suggesting that the Brown CK was lithified when the Blue MVK was emplaced. The Blue MVK cored out a significant volume of the Brown CK, leaving continuous Brown CK only in the southern portion of the body and as remnant blocks in the upper portion of the pipe (Fig. 10D). The high abundance of country rock xenoliths, the mixing of the Blue MVK with marginal breccias, abundant, well formed juvenile clasts and volcaniclastic texture of the Blue MVK suggest that this rock was being deposited as the pipe was being further excavated and that it was emplaced by more explosive processes than those involved in the formation of the Brown CK. Based on the presence of subtle vertical to sub-vertical fabrics defined by elongated country rock clasts and the lack of a horizontal fabric (i.e. bedding that is more typical of upper diatreme to crater settings), this rock type is interpreted to represent a deep in-vent pyroclastic deposit. In-vent vertical fabrics such as these have been discussed by Ross et al., 2008 and sub-vertical fabrics have also been described by Gernon et al. (this issue) at Venetia, where they are thought to be produced by fluidisation following emplacement.

(iv) Emplacement of late-stage hypabyssal kimberlite dykes and irregular intrusions.

Following the infilling of the pipe by the Brown CK and subsequently by the Blue MVK, a variety of HK dykes and irregular intrusions were emplaced along zones of weakness, such as geological contacts within the pipe and in the marginal breccia (Fig. 10E). Many of the dykes are vertical in orientation. Dyke morphology within the marginal breccia is more complex than within the pipe. In some cases, mixing between the pulverized country rock material and the HK suggest that the country rock breccia was unconsolidated when the HK intruded. In general, the thin dykes are uncontaminated due to emplacement along pre-existing zones of weakness; however, the larger, more irregular intrusions are characterized by common country rock xenoliths suggesting that their emplacement was much more dynamic.

(v) Post-emplacement alteration of the kimberlites and erosion.

Erosion of the pipe that included glaciation has removed the extra crater deposits, the crater and likely much of the upper diatreme zone of the pipe (Fig. 10f). No material from the crater has been encountered within the pipe. In addition to erosion, the main pipe infills have been extensively altered; particularly the Blue MVK. Secondary minerals present include diopside, serpentine, carbonate minerals, mica and clays. The secondary minerals have not only completely pseudomorphed many of the juvenile and country rock constituents, but they have also masked many of the primary features of the rock, particularly the original character and constituents of interclast matrix.

5. Conclusions

The Renard 2 kimberlite is classified as a Class 1 or Kimberley-type body as defined by Skinner and Marsh (2004). It is considered to have undergone extensive erosion since emplacement and displays geological features consistent with a lower diatreme setting similar to kimberlites described by Clement (1982), Hetman et al. (2004), Skinner and Marsh (2004) and Masun and Scott Smith (2006). The features that support a lower diatreme setting for Renard 2 include the emplacement age, the present surface expression of the pipe (0.75 ha), the low degree of textural modification displayed by the main pipe infills, the extensive marginal breccia preserved around the pipe, the sub-vertical orientation of the contacts between the main pipe infills and the vertical to sub-vertical fabrics present within the volcaniclastic infill.

The diamond grade difference between the two main pipe infills, the Brown CK and the Blue MVK, is not thought to be simply a function of variable dilution, but rather the result of these being two separate rock types characterized by a different mantle sample. This interpretation is supported by the contrasting textural and component characteristics, including different olivine and country rock xenolith abundances and populations and groundmass mineralogy. The higher grade Brown CK is characterized by a higher total olivine abundance and coarser olivine macrocryst population compared to the Blue MVK.

The emplacement history presented here includes two major volcanic events, each involving pipe excavation and infilling stages. The Brown CK is interpreted to have been emplaced first, based on its geometry and distribution in the diatreme relative to the Blue MVK, and the nature of the contact with this rock type. The low country rock xenolith abundance of the Brown CK suggests it was emplaced within a well-developed diatreme where the majority of country rock was removed and pipe development had ceased. The coherent and locally transitional texture of the Brown CK suggests it may represent a clastogenic deposit, however, the uniform distribution and lack of broken olivine crystals is not consistent with an explosive emplacement process. The texture and country rock xenolith content of the Blue MVK is consistent with a more dynamic and explosive emplacement origin compared to the Brown CK, where there was simultaneous infilling and excavation of the pipe. Based on the low degree of textural modification and the presence of subtle vertical to sub-vertical fabrics, the Blue MVK is interpreted to represent an in-vent pyroclastic deposit.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.lithos.2009.05.036.

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