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The Fort à la Corne Kimberlites, Saskatchewan, Canada: Geology, Emplacement and Economics

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Abstract: The Cretaceous Fort à la Corne kimberlite province includes at least seventy well preserved bodies ranging up to 200 hectares in size. Kimberlite volcanism spanned at least 20 Ma. The main bodies formed by a two stage process: (i) excavation of shallow craters into Cretaceous sediments, and (ii) crater infilling by subaerial magmatic pyroclastic processes, both during regressions of the Western Interior Seaway. Each of the twenty-five bodies investigated is different but dominated by a few volumetrically significant phases of kimberlite. Subsequent eruptions formed nested craters within earlier indurated kimberlites. Eruption styles varied from Hawaiian and Strombolian to a probable kimberlite-specific type of eruption which formed unique mega-graded beds. Separation of olivine grains from the low viscosity melts was a widespread process that resulted in discrete olivine grains forming approximately half of the pyroclasts across the province. Ash-sized clasts are not common indicating removal by a large scale sorting process. No diatremes, root zones, dykes, hypabyssal or tuffisitic kimberlite or significant amounts of resedimented material were found. The contrast in geology of the Fort à la Corne bodies supports, rather than negates, the 'classic' kimberlite pipe model. The Fort à la Corne mode of emplacement comprises a second style of eruption or model which is applicable to kimberlites. The new models have been an important foundation of the ongoing economic evaluation of the Fort à la Corne bodies. Applying predictive geology based on knowledge obtained from other kimberlite bodies would have been misleading.

Keywords: Kimberlites, Pyroclastic, Volcanology, Crater, Juvenile lapilli, Olivine, Canada.

INTRODUCTION

The Fort à la Corne (FALC) kimberlite province (Fig. 1) comprises more than 70 bodies which range in size up to approximately 200 hectares (Berryman et al. 2004). The FALC bodies occur in a NNW-SSE trending zone 45 km long and 30 km wide approximately 80 km east of Prince Albert, Saskatchewan (Fig. 1). The province was discovered in 1988 by Uranerz Exploration and Mining Limited (Lehnert-Thiel et al. 1992). Since their discovery, exploration of the FALC bodies has been ongoing (e.g. 1992-1998 update by Jellicoe et al. 1998; 2000-2003 update by Berryman et al. 2004) with joint venture partners Cameco Corporation (since 1989) and Monopros Limited (since 1992), now called De Beers Canada Inc., and Kensington Resources Ltd. (since 1995), now a wholly owned subsidiary of Shore Gold Inc. (since 2005). Significant amounts of diamonds have been recovered from a number of the kimberlites and evaluation of some of these bodies by the FALC joint venture is ongoing. The 2005-2007 program includes an extensive core drilling programme.

This paper presents the results of the investigation of the geology of the FALC kimberlite province based on the first two main phases of core drilling which included many discovery holes. The details of the investigation have been presented only in unpublished reports. The results have been summarised in Scott Smith et al. (1994, 1995, 1996, 1998) and Scott Smith (2002). A number of publications by other workers not available during this study are discussed later (Other Work). At the time of this investigation, very different published and unpublished hypotheses on the nature of the FALC kimberlites were being proposed, for example globular segregationary-hypabyssal kimberlites, epiclastic kimberlites, autolithic volcaniclastic breccias, pyroclastic tephra cones with no underlying crater, submarine lahars, debris flows or Surtseyan phreatomagmatic eruptions.

The kimberlite forming the FALC bodies is extremely similar to that forming the Sturgeon Lake glacially transported mega-blocks (Fig. 1) found shortly before FALC (Scott Smith, 1995b; Scott Smith et al. 1996). The textures of all these Saskatchewan kimberlites are unlike

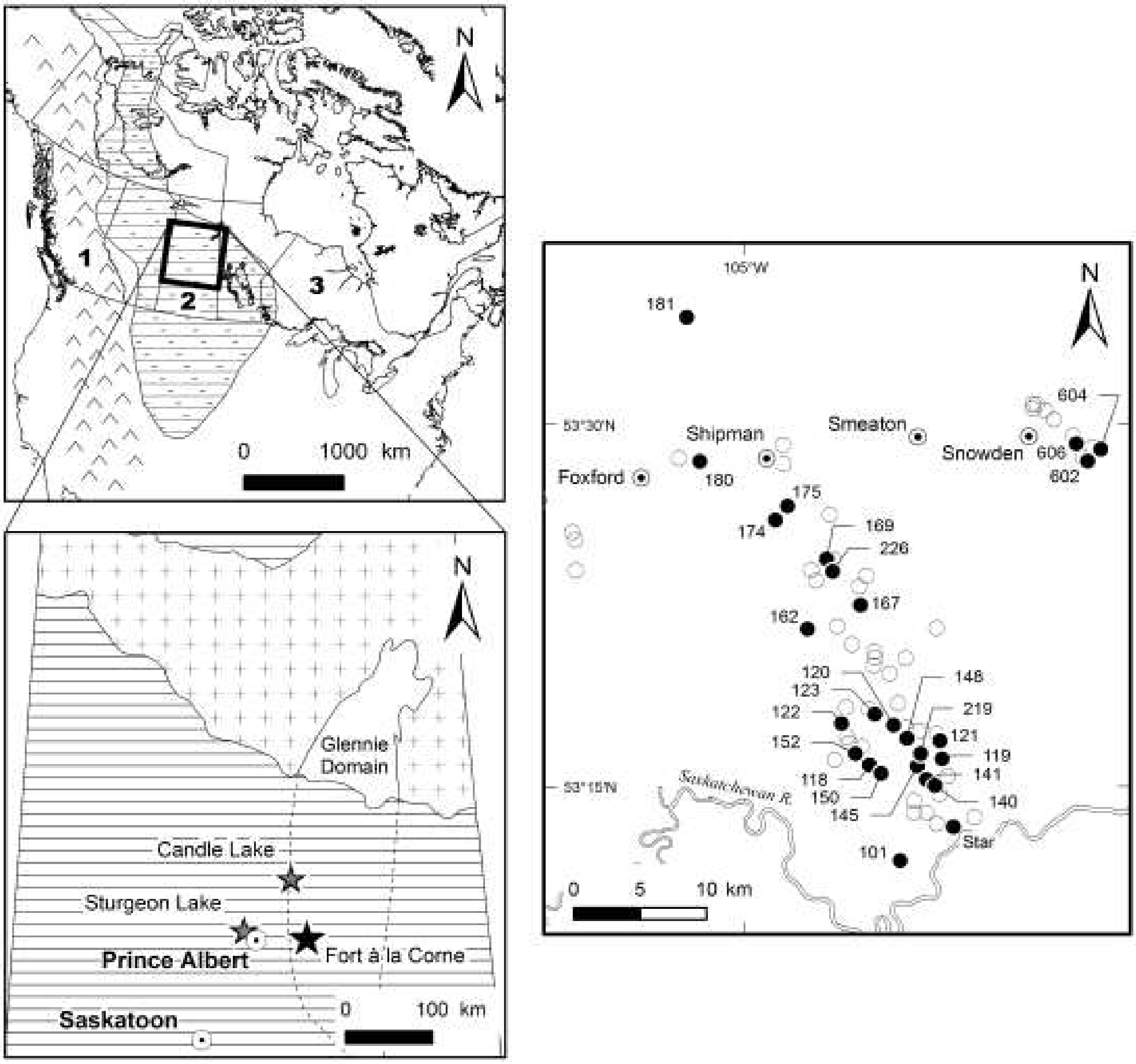

Fig. 1. The Fort à la Corne kimberlites: location and geological setting. The Western Interior Seaway (2) is shown for a Cretaceous lowstand during the late late Albian, ~100-98.5 Ma, at about the time of the main kimberlite emplacement (from Fig. 1 of Kauffman and Caldwell, 1993). The Seaway occurs between the Cordillera or Rockies (1) to the west and the Canadian Shield or Superior Craton (3) to the east. Crosses = basement; solid lines = sediments. Labelled bodies (solid circles) were investigated in this study. Towns are shown by half filled circles.

other kimberlites documented prior to their discovery, notably many of the kimberlite pipes of southern Africa (e.g. Clement, 1982). The unusual features include vesicular and amoeboid-shaped juvenile lapilli and extensive rocks composed predominantly of discrete olivine grains, showing that the kimberlites of Saskatchewan at the time were "One of a Kind" (Scott Smith, 1995a). This investigation showed that the Saskatchewan kimberlites are more similar to some common basaltic subaerial eruption styles than the tuffisitic kimberlites of southern Africa.

METHODS

Buried below ~100 m of glacial overburden, the FALC kimberlites were investigated by drilling. This study was undertaken during 1992-1994 on 5.8 km of 1992-1993 drillcore including ~5 km of kimberlite from 44 vertical holes drilled into 25 different anomalies distributed across the province (shown in Fig. 1; eleven of which are illustrated in Figs. 3-17). A few of the studied bodies no longer remain within claims that continue to be held by the FALC joint venture. Most anomalies were investigated by single drillcores but some had two or more (118, 120, 121, 122, 140, 141, 145, 169, 174). The drillcores (except for 900-1 on 140) are located towards the centre of the bodies based on interpretations of the geophysical data and limited prior drilling. Each body, originally defined as a discrete geophysical anomaly, is identified with a three digit number (e.g. 120 as shown in Fig. 1) to which the drillhole number is added (e.g. 120-11, Lehnert-Theil et al. 1992) and then the sample number (e.g. 120-11-4). Depths from surface presented in this paper have not been adjusted for differences in elevation between drill collars but relief in the project area is limited. One of the three drillcores investigated from body 169 was obtained, and studied, by the Geological Survey of Canada (Kjarsgaard et al. 1995; Leckie et al. 1997a).

The primary aim of this work was to develop geological and emplacement models and determine the consequent economic implications. This study included megascopic core logging, augmented with macroscopic examinations undertaken with a binocular microscope, of all the drillcores. These results were integrated with the subsequent macroscopic examination of 1143 representative samples of the drillcores (7 to 58 per hole) and the petrographic investigation of polished slabs and thin sections of 207 selected samples (including those illustrated in Figs. 8, 9 and 10 of Jellicoe et al. 1998; Figs. 7 and 8 of Berryman et al. 2004; Figs. 2b, c in Sparks et al. 2006). Petrographic work was also undertaken in 1991 on samples from one of the few initial 1989 drillcores, 120-11. Standard igneous or volcanological size classes proved to be insufficient to meaningfully sub-divide the FALC rocks. A new size classification was developed for this investigation (Table 1, *see* Clast Shape and Size, below for details). This paper is based on the results as presented in the unpublished 1991-1994 reports prepared for Uranerz Exploration and Mining Limited. Subsequent modifications to that investigation are clearly indicated. The opinions presented in this paper are that of the author and not necessarily that of the FALC joint venture or any of the joint venture partners.

Table 1. Clast Size Classification

Descriptor	Code	Size
(A) Juvenile lapilli and discrete olivines		
Very Coarse	VC	>10 mm
Coarse	C	5-10 mm
Medium	M	2-5 mm
Fine	F	0.5-2 mm
Very Fine	VF	0.2-0.5 mm
Very Very Fine	VVF	<0.2 mm
(B) Xenoliths (VC)		
Breccia	B	>15%, >10 mm in size

OVERVIEW OF THE GEOLOGY OF THE DRILLCORES

The drillcores (e.g. Table 2 which presents five summary logs from four bodies 118, 119, 140 and 219 selected to show significant and diverse FALC features many of which are illustrated in Figs. 3-17; Table 1 of Scott Smith and Berryman, 2007 which presents two summary logs from body 169) comprise two main rock types:

(i) Kimberlite (Petrological Classification, below), and
(ii) Country rock sediments.

All the drillcores include (i) a significant continuous intersection of kimberlite (~65 to 275 m long; e.g. <173.2 m in 118-3, <227 m in 118-4, <159.9 m in 119-2, <300.5 m in 140-5 and <241.3 m in 219-3, Table 2; <189.6 m in 169-6 and <245.1 m in 169-7 in Table 1 of Scott Smith and Berryman, 2007) and below that (ii) different lengths of sediments were recovered (<1 m to 131 m) in all except one drillhole (101-1). The major kimberlite intersections are the main subject of this paper and are termed the “Main Kimberlites”. The main kimberlite to country rock contacts were found at ~160-500 m below the present surface. Thus, the sediments below the contacts derive from different depths from surface and together vertically span approximately 340 m. Twenty of the sediment intersections exceeded 10 m in length (e.g. Table 2a) and they range up to over 50 m. Together, the sediment intersections indicate the nature of the Cretaceous sediments hosting the FALC kimberlites (Geological Setting). In addition to the main kimberlite intersections, much smaller intersections of kimberlite (<5-10 m thick) occur within the sediments occurring below, and in rare cases above, the main kimberlite. It is important to note that these minor kimberlites are described separately (Minor Kimberlites within the Adjacent Sediments).

AGE

Lehnert-Theil et al. (1992) reported that the FALC kimberlites formed in the Lower Cretaceous with initial ages of 94-96 Ma based on both Rb-Sr isotopic data and palynology on enclosing sediments. The Rb-Sr mica isotopic age for body 122 is 94±3 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.709 and for body 120 is 96±1 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.705 (determined by E. Barton and C.B. Smith of the Bernard Price Institute of Geophysics,

Table 2. Simplified Summaries of the Geology of Selected Drillcores

Based on logging augmented with petrography. Presented in drillhole number order. Body location shown in Fig. 1. Depths in meters. Size classification given in Clast Shape and Size and Table 1. Similar summary logs for 169-6 and 169-7 are given in Table 1 of Scott Smith and Berryman (2007).

(a) DRILLCORE 118-3

General comments: The main kimberlite intersection (<173.3 m) is a single phase of kimberlite with sub-divisions given below are based on variations in clast size and bedding. The pale grey kimberlite is composed of clast-supported, fluidal, vesicle-bearing juvenile lapilli which range from VF to C in size. The juvenile lapilli have groundmasses containing spinel and carbonate laths (Fig. 5b) in a base composed of cryptocrystalline carbonate and serpentine (Fig. 7c). The juvenile lapilli are very similar to those forming drillcore 118-4 (Table 2b). The main kimberlite comprises sharply-bounded normally-graded beds mostly <2 m thick with dips of 10-20º (Figs. 13a, b). Finer clasts, or VVF-VF, predominate and are mainly discrete olivine phenocrysts. These rocks are usually laminated. The coarser areas, M-C, are composed of mixed discrete olivine macrocrysts (up to 5 mm) and juvenile lapilli. VC clasts are xenoliths, and some occur in the fine tops of beds suggesting ballistic impact by airfall. Garnet and ilmenite are common. Mantle xenoliths are present in the coarser areas. Black shale xenoliths occur, particularly below 145 m (Fig. 11). The interclast material can change with the bedding. Contrast the clast sizes with the coarser main kimberlite in 118-4 in Table 2b. Below 173.3 m are three different phases of kimberlite which are probably concordant beds of kimberlite within in situ Cretaceous sediments.

FROM	TO	DESCRIPTION
106	109.3	Thinly (<0.12 m) bedded FK.
109.3	123.65	Medium to thickly bedded (0.1-1.5 m) VF-M-CK dominated by M-CK. Fig. 13a.
123.65	139.0	Thickly bedded (0.2-0.5 m, up to 1 m) VF-F-M-CK, dominated by VF-FK. Fig. 13b.
139.0	148.0	Thickly bedded (up to 0.8 m) VF-FK, with some CK.
148.0	167.5	Thickly to very thickly bedded (0.4-2.7 m, one of 4.15 m) VF-FK with some MK. Common shale xenoliths (<14 cm) include poorly-consolidated types (Fig. 11).
167.5	173.2	Bedded mixed FK and M-CK. Irregular lower contact which dips at ~70°.
173.2	180.0	Dark grey shale presumed to be Lower Colorado.
180.0	180.6	Light brown carbonatised F-MK which contains clast-supported small discrete olivine grains and juvenile lapilli <3 mm in size. Different to main kimberlite above. Upper and lower contacts dip at ~15º. A 2 cm sub-horizontal layer or possible bed of shale occurs just above the lower contact.
180.6	181.4	Shale.
181.4	184.7	Green MK composed of just matrix-supported abundant irregular juvenile lapilli (<5 mm) which contain only fine grained olivine (<3 mm). A few ilmenite macrocrysts occur but are less common than above 173.3 m. The upper and lower contacts dip at ~45 and 0º respectively.
184.7	186.5	Poorly-consolidated fissile black shale, probably Lower Colorado.
186.5	214.0	Varied brown Mannville sediments with bedding mainly 0-10º.
214.0	214.55	Pale buff coloured, carbonatised, normally graded unit of VF to CK composed of discrete olivines (up to 6 mm) and common juvenile lapilli (up to 10 mm). A few basement xenoliths are present (<3 cm). The upper contact is sharp and horizontal. Bottom contact is irregular. Fig. 16b.
214.55	229.0	Varied brown Mannville sediments.

(b) DRILLCORE 118-4

General comments: The drillcore comprises a single phase of macrocrystic kimberlite. The sub-divisions given below are based mainly on variations in clast size and bedding. The grey kimberlite is dominated by clast-supported, fluidal, vesicle-bearing juvenile lapilli (Fig. 3a) ranging from VF to VC in size. The juvenile lapilli are composed of carbonate laths set in base of cryptocrystalline carbonate and serpentine. The lapilli are very similar to those <173.3 m in 118-3 (Fig. 5b, Table 2a). Sharply bounded normal graded beds are common. The VVF-VFK is dominated by discrete phenocrystal olivines and is commonly laminated. Overall the proportion of fines appears to increase with depth. Contrast the clast sizes with the coarser main kimberlite in 118-3 in Table 2a. Garnet and ilmenite are common. Mantle xenoliths are present in the coarser areas. Minor country rock xenoliths include basement and diverse types of shale, particularly >154 m. The interclast material is composed mainly of serpentine (Fig. 3a), carbonate and magnetite. The interclast cement appears to result from three phases of crystallization, two of serpentine and one of less common carbonate.

FROM	TO	DESCRIPTION
118.0	144.9	M+CK. Minor FK. Graded beds 1.7-5.2 m thick. Horizontal bedding. Fig. 3a.
144.9	172.2	Mixed F+M+CK. More FK than above. Horizontal graded beds 1-4.9 m. Some shale xenoliths, occasionally up to 70 cm in size.
172.2	182.5	FK, minor VFK which was not observed above here.
182.5	195.1	Mixed VF-F-M-C-VCK with abundant C constituents. Graded beds 0.3-2.1 m, most <1.2 m. Variable dips <10 to 60-70º.
195.1	213.4	Mixed VFK, FK, M-CK, with VF, F and F-MK more common. Graded beds up to 4.7 m. Variable dips up to 50º.
213.4	227.0	Mixed VFK and FK. Bedding commonly at 45º. Concentrations of shale occur within some thin beds.
227.0	230.0	Mannville sediments.

Table 2 Contd...

(c) DRILLCORE 119-2

General comments: The drillcore comprises two main phases of kimberlite (<149 m and 149-159.9 m) which are composed of similar common irregular juvenile lapilli and discrete olivines (<5 mm in size). The juvenile lapilli are composed of olivine and perovskite set in a 'glassy' serpentine-like base. Carbonate is absent. The olivine grains commonly have thin selvages of kimberlite. Rare small sediment xenoliths. Common well defined thickly laminated (<1 cm) to thinly bedded (<10 cm) normally graded beds. With increasing clast size, the proportion of discrete olivine phenocrysts decreases and the proportion of discrete olivine macrocrysts and juvenile lapilli increases. The interclast material is composed of serpentine and carbonate. Patches of secondary magnetite are common.

FROM	TO	DESCRIPTION
118.0	118.7	Shale. Lower contact is horizontal.
118.7	149.0	F-MK. Well bedded with dips of 20-35º. Garnet and ilmenite are common. Plane parallel bedding.
149.0	159.9	F-MK. Well bedded with dips of 45-70º. Garnet and ilmenite are rare. Disturbed bedding with undulating bedding planes and small scale faulting.
159.9	160.9	Black shale. Difficult to determine if in situ.
160.9	161.2	FK which contains more common xenolithic material than above and some quartz grains. Indicator minerals and mica common.
161.2	162.9	Shale.

(d) DRILLCORE 140-5

General comments: The drillcore is dominated by one phase of kimberlite which comprises a relatively well-sorted mega-graded bed. Below this is different, complex and includes poorly-sorted matrix-supported kimberlites.

FROM	TO	DESCRIPTION	
127.1	243.6	Mega-graded bed illustrated in Fig. 7 and 8 of Berryman et al. (2004). The kimberlite is dominated by clast-supported discrete grains. Some juvenile lapilli are present within the coarser areas. With depth, the proportion of fine olivine phenocrysts and mica decreases and the proportion of olivine, garnet and ilmenite macrocrysts, juvenile lapilli and clast size increases. Garnet is more common than ilmenite. Somewhat arbitrary sub-divisions are:	
		126-127.1 m	VF-FK.
		127.1-157 m	VFK-FK (<1 mm). Abundant olivine phenocrysts. Mica present.
		157-192 m	FK (<2 mm). Garnet appears more common.
		192-216.4 m	F-MK to MK. Garnet is more abundant.
		216.4-224.7 m	Multiple graded beds <2.8 m thick composed of minor FK and mainly CK-CKB. Xenoliths are dominated by basement with less common carbonates. Garnet abundant.
		224.7-243.6 m	Mixed FK, MK and CK with common xenoliths and common CKB. Likely part of the mega-graded bed.
243.6	255.5	Mixed F to MK, M-CKB.	
255.5	271.7	FK to MK and CK. Ilmenite>garnet indicating a different phase of kimberlite.	
271.7	299.4	VF+FK with some M and C olivines. Indicator minerals are not common. Complex sediment xenoliths include black shale.	
299.4	300.5	MKB. Xenoliths are mainly carbonates and varied poorly-consolidated shales.	
300.5	305.3	Mannville sediments with steep and complex contacts. Possibly not in situ.	
305.3	307.7	F-MK. Abundant VF olivines. Indicator minerals rare.	
307.7	315.6	Different kimberlite containing common fluidal juvenile lapilli up to C in size (rarely VC, < 6 cm). VF-M olivines. Indicator minerals are in low abundance.	
315.6	323	Mannville sediments.	

(e) DRILLCORE 219-3

FROM	TO	DESCRIPTION
108	241.3	Uniform, massive CK composed of approximately equal proportions of clast-supported juvenile lapilli and discrete olivines dominated by anhedral macrocrysts. These constituents range up to 10 mm in size, rarely 2 cm. The juvenile lapilli have smooth fluidal shapes and are composed of olivines set in a groundmass containing variable but overall high contents of very fine grained carbonate and less common spinel, apatite and serpentine. Throughout there is a reduced amount of fine grained discrete olivines and former melt relative to the erupting magma (cf. Plate 6a). Macrocrysts of garnet, ilmenite and mica are abundant. Xenoliths include (i) rare mantle, (ii) carbonates which are frequent zonally altered and occasionally have kimberlite selvages, (iii) minor shale, (iv) rare basement and (v) frequent autoliths that include volcaniclastic kimberlites. The interclast material is composed of serpentine and carbonate.
241.3	244	Mannville sediments.

University of Witwatersrand). Subsequent to this investigation, older ages have been reported. Kjarsgaard et al. (1995) refer to an unpublished age of 99.1±1 Ma for 120 and Leckie et al. (1997a) present an age of 101.1±2.2 Ma from the main kimberlite in body 169 (both U-Pb perovskite). Berryman et al. (2004) refer to ages determined on two samples from 140 and 141 of 99.8±2.4 and 99.5±1.8 Ma respectively (U-Pb perovskite; Kjarsgaard and Heaman, *pers. comm*.). In summary, the isotopic ages determined for the FALC kimberlites span 7 Ma (94-101 Ma). More detailed work is warranted, for example, to investigate the difference in ages, 96.1 and 99.1 Ma from one body (120).

The Sturgeon Lake kimberlite glacial mega-blocks (Fig. 1) have yielded comparable ages of 98±1 Ma (Rb-Sr mica; Hegner et al. 1995) and 98.9±0.2 Ma (U-Pb zircon; Leckie et al. 1997a) with similar unpublished data cited by Scott Smith et al. (1996). Palynological results for the sediments forming juxtaposed glacial mega-blocks and one xenolith within the kimberlite indicated that they are marine shales deposited at 105-98, 99-97 and 99-93 Ma (Scott Smith, 1995b; Scott Smith et al. 1996). Thus, the kimberlites at both FALC and Sturgeon Lake appeared to be broadly similar in age to the Lower Cretaceous sediments. Given the importance to the kimberlite emplacement, the nature of the sediments is considered in some detail in the next section.

GEOLOGICAL SETTING

The FALC bodies, which are overlain by ~100 m Quaternary glacial overburden, occur near the northeastern edge of the Phanerozoic sedimentary cover of the Northern Interior Platform of North America which unconformably overlies the Precambrian basement (Fig. 1). The geological setting of these kimberlites has been discussed by a number of authors such as Lehnert-Theil et al. (1992) and since this investigation by Kjarsgaard et al. (1995), Jellicoe et al. (1998), Berryman et al. (2004) and Zonneveld et al. (2004). The sub-glacial bedrock comprises variably-consolidated Lower Cretaceous sediments which are approximately 200 m thick and unconformably overlie approximately 400 m of indurated Paleozoic sediments below which is the basement. The basement is part of the Glennie Domain considered to be a buried Archaean microcontinent, now known as the Sask Craton. The Cretaceous sediments were deposited towards the northeastern edge of the Western Interior Seaway, a broad shallow epicontinental sea between the Cordillera and the Superior craton (Fig. 1; Caldwell and Kaufmann, 1993). The boundaries of the basin were seldom static with oscillating sea levels and migrating shorelines, moving up to 100 km in 1 Ma or less (Kauffman and Caldwell et al. 1993). The Cretaceous in this area, therefore, was a dynamic environment marked by cyclic transgressive-regressive sequences with the deposition of transgressive sediments with little topographic relief between the units. Some of these sediments remain poorly-consolidated, as observed in the FALC drillcores.

The drillcores indicate (i) that the Lower Cretaceous stratigraphy is consistent with that expected in this area of Saskatchewan (Fig. 3 of Kjarsgaard et al. 1995 presents the geology for a nearby drillhole into sediments only) and (ii) that the stratigraphy is relatively uniform through the FALC area (Fig. 2). The country rock sediments, therefore, are in situ and in most instances were not significantly disturbed before, or by, the main kimberlite emplacement. The Lower Cretaceous sediments at FALC comprise

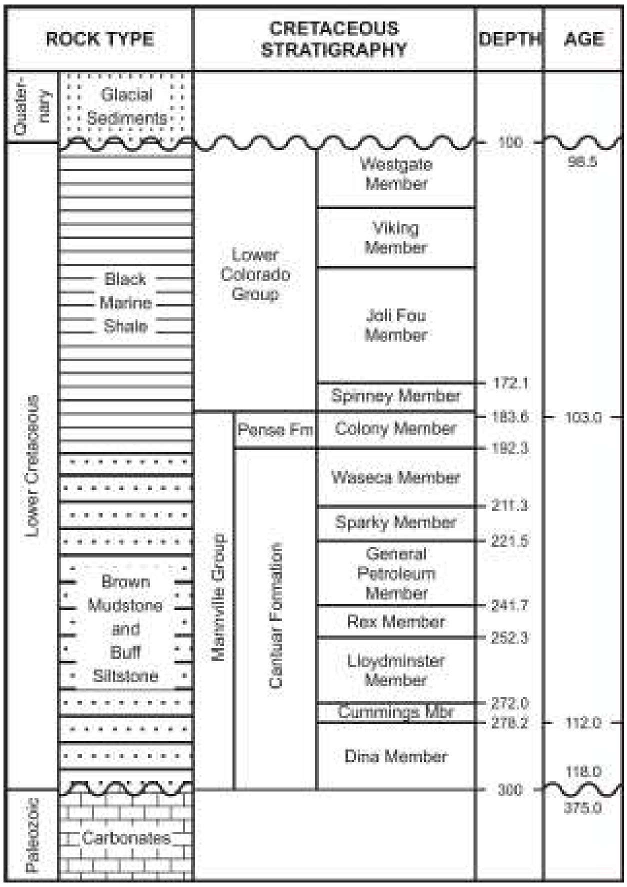

Fig.2. Stratigraphy in the Fort à la Corne area. Left hand depth is from surface. Middle column depths are based on core logging and geophysical logs for hole 900-1 on body 140 by Christopher (1993; see Fig. 4 of Berryman et al. 2004 for location). Ages are from Caldwell and Kauffmann (1993, Fig. 3).

~100 m dark grey to black-coloured, marine, laminated shales mainly of the Joli Fou Formation of Lower Colorado Group which conformably overlie ~110 m of distinctly different Mannville Formation sediments including medium to dark brown clay-rich mudstone and paler buff-coloured siltstone and fine sandstone with minor black organic-rich horizons (Fig. 2).

The Lower Colorado shales were observed only in a few holes (e.g. Tables 2a, c). In one hole (900-1 in body 140), the shale underlying the kimberlite at 60 m below the sub-glacial surface was identified as the Joli Fou Formation (Christopher, 1993). Although comprising mainly marine shales, there is evidence for lower sea levels and terrestrial conditions during the Lower Colorado (Fig. 3 of Kauffman and Caldwell, 1993; Fig. 5 of Jellicoe et al. 1998). The deepest intersection of the black shales which contains silty layers is the Pense Formation that forms the uppermost Mannville (Fig. 2).

Below the Pense Formation, the contrasting terrestrial sediments of the Cantuar Formation of the Mannville were observed in many drillcores (~thirty). Walker (1993) noted mudstone, and less common sandstones which display varied sedimentary features including flat bedding, lenticular bedding, trough cross bedding, convoluted laminations, ripple lamination and bioturbation. Coal horizons and in situ roots are indicative of subaerial conditions. The sediments are interpreted as being formed in subaerial flood plain, estuarine, fluviatile and/or lacustrine or coastal marine environments (Walker, 1993; Christopher, 1993, 2003). Given the wide-ranging environments of deposition of the Mannville, compared to the Lower Colorado, the rock types are laterally variable. The Mannville sediments are striking in the lack of faunal remains which contrasts with the Lower Colorado in which there are well developed faunal assemblages. Kjarsgaard et al. (1995) found pollen and spore assemblages in the sediments below the main 169 kimberlite suggestive of non-marine coal swamp and near-shore environments of deposition.

The marked change in lithology within the Lower Cretaceous sediments between the brown-buff coloured Cantuar Formation and overlying black shales of the Pense and Lower Colorado marks a significant change in the environment, essentially representing a major marine transgression which is a regional unconformity (Fig. 2). The transgression is encountered in one drillcore (900-1) by a 10 cm thick lag of quartz grit and granules. The observed obvious lithological change from black shale to brown mud-rich sediments was observed at approximately 185-190 m below the present surface in four bodies (bodies 121, 123, 140, 145 and probably at 186.5 m in drillcore 118-3 shown in Table 2a). Overall this boundary shows little topographic relief except in body 604 in the northeast of the province, where the Cantuar was observed at 164 m from surface suggesting that there may be some variability (or a result of topography).

The Mannville sediments overlie approximately ~400 m of Paleozoic rocks, separated by a ~250 Ma unconformity. Rare examples of the Mannville to Paleozoic carbonate contact occurred, as expected, at ~300 m below present surface in the main cluster of bodies. Four limited drillcore intersections as well as the xenoliths in the kimberlites, show that the carbonates are varied in appearance. The indurated Paleozoic rocks apparently consist of Devonian, Silurian and Ordovician sediments dominated by carbonates and Cambrian clastic sedimentary rocks.

Based on the general geology of this area of Saskatchewan (e.g. Caldwell and Kaufmann, 1993), further sedimentation would have been expected to have buried the FALC kimberlites. Definite shale above the main kimberlite was recovered in only three bodies (119 as shown in Table 2c; 169 as shown in Fig. 3 of Berryman et al. 2004); 181) and possibly two others (101 and in drill chips from 611). Unfortunately little further investigation has been undertaken on these shales. Palynology reported by Kjarsgaard et al. (1995) and Leckie et al. (1997a) shows that the sediments overlying the kimberlite in 169-8 (Fig. 3 of Berryman et al. 2004) are fully marine shales of the Late Albian Westgate Formation (Fig. 2).

ROCK CLASSIFICATION

Petrological Classification

All the FALC rocks have magmaclastic textures (term after Field and Scott Smith, 1998). The magmaclasts (clasts *sensu lato* or discrete bodies of former plastic molten or liquid kimberlite magma) are composed of abundant olivine set in a fine grained groundmass (Figs. 3a and b). The olivine grains include coarse anhedral and often subround macrocrysts (commonly up to 10 mm, sometimes up to 15 mm, rarely up to 30 mm in size). The olivine is commonly fresh and the macrocrysts can be determined to be mantle-derived xenocrysts because they display features such as polycrystalline and/or deformation textures and garnet intergrowths or inclusions. Other mantle-derived xenocrysts include magnesian ilmenite sometimes with perovskite mantles, abundant garnet with a range of colours typical of kimberlites (such as burgundy, cerise, pink, purple, red, orange indicating the presence of both

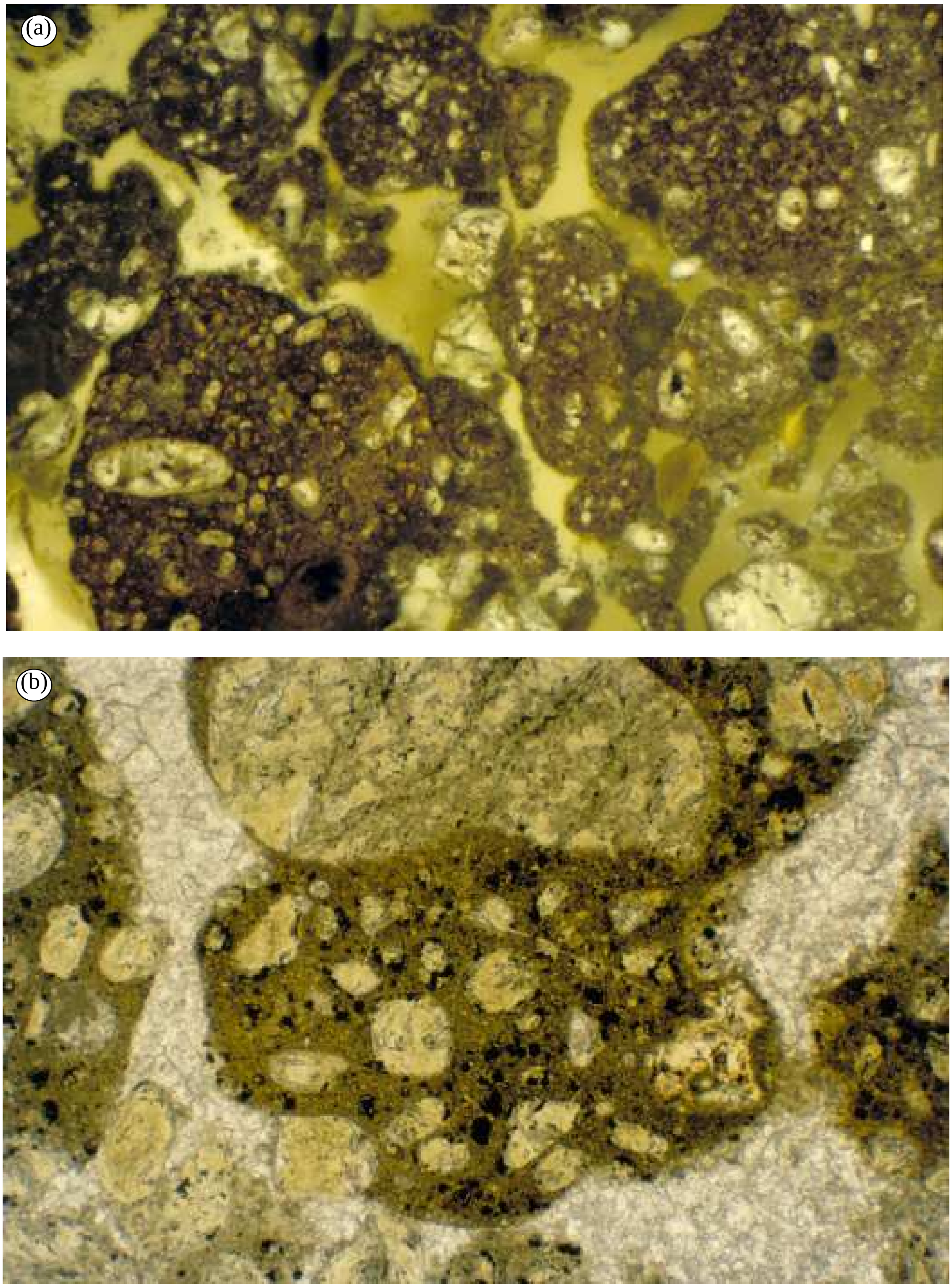

Fig.3. FALC magmaclastic textures. Typical scalloped to amoeboid-shaped fluidal magmaclasts which are juvenile lapilli (see Textural Classification). The lapilli are composed of anhedral olivine macrocrysts and smaller olivine phenocrysts set in a fine grained groundmass, features typical of kimberlite magmas. The samples are juvenile lapilli PK. (**a**) Sample 118-4-44. 120.1 m. See Table 2b for summary log. Polished slab. Field of view = 13 mm. Clast-supported dark-coloured juvenile lapilli containing light-coloured olivine pseudomorphs. The interclast material is composed of pale milky green serpentine. (**b**) Sample 175-1-1. 153.7 m. Thin section. Plane polarised light. Field of view = 4 mm. Dark juvenile lapilli which have groundmasses composed of spinel set in base of serpentine. One olivine protrudes from the main lapillus (bottom left). White, relatively coarse-grained carbonate forms the interclast material.

peridotitic and eclogitic varieties), mica and rare chrome diopside. Analysis of many grains recovered from heavy mineral concentrates confirmed the mantle-derived compositions and also found chrome spinel. The mantle-derived xenocrysts also have compositions typical of kimberlites, including grains similar to diamond inclusions (Jellicoe et al. 1998). Diamonds have also been recovered (e.g. Berryman et al. 2004). Mantle-derived peridotites, eclogites and megacrysts are also present (Fig. 4). The olivine phenocrysts which are mainly <0.5 mm in size usually have simple euhedral shapes (Fig. 3b). Some grains may contain brown needles of rutile (Fig. 5a).

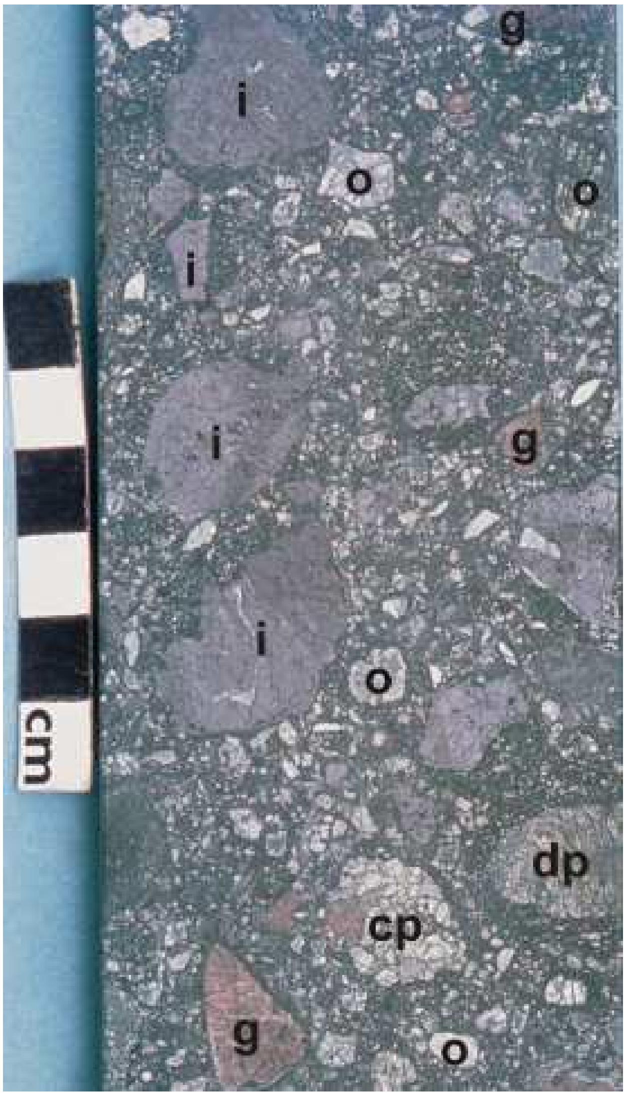

Fig.4. Sample 120-19-99. 143.3 m. Polished slab. VCK. Unusually abundant mantle constituents which include megacrysts of black ilmenite (i), red garnet (g) and olivine (o), as well as one deformed (dp) and one coarse garnet-bearing (cp) peridotite. Note the angular shapes of these constituents.

The groundmasses within the magmaclasts are not well crystallised but a variety of primary fine grained groundmass minerals were observed: brown perovskite, spinel commonly with atoll-like textures (Figs. 3b, 5a), monticellite (Fig. 5a), orange-brown phlogopite, apatite and laths of carbonate (Fig. 5b). The base of the groundmasses is typically composed of serpentine and/or carbonate (Figs. 3b, 5b, 6). The latter usually has a cryptocrystalline texture.

The features described above are all characteristic of kimberlite (Group 1, cf. Skinner, 1989) and consistent with the classification as kimberlites sensu stricto (archetypal or Group 1, after Woolley et al. 1996). Although the whole rock geochemistry of magmaclastic rocks must be treated with caution, the data presented by Lehnert-Thiel et al. (1992, Table 2) are similar to kimberlites in general. A variety of kimberlite magmas were present at FALC with some groundmasses dominated by either phlogopite, monticellite or carbonate. The lack of well crystallised groundmasses precludes meaningful mineralogical classification. Some rocks display features less characteristic of kimberlites (e.g. macrocryst-poor, larger olivine phenocrysts, different groundmasses). Such features probably reflect different pre-eruption petrogenetic processes. Interestingly, the most atypical or marginal type of kimberlites seem to occur at the northern and southern extremities of the province (e.g. bodies 101, 181 and 604; Fig. 7a).

Textural Classification

The FALC kimberlites are composed of two main constituents: (i) magmaclasts composed of one or more olivine grains set in a very fine grained groundmass (Fig. 6, described above) and (ii) discrete crystals which are dominated by olivine. The magmaclasts display a number of features which show that they were formed during pyroclastic eruption processes. These features include the fluidal shapes (Figs. 3, 6), rapidly cooled groundmasses (Figs. 6d, 7b-c), rare more glassy-like textures and the presence of vesicles (Figs. 5b, 7a). Some variation in the nature of different magmaclasts in a single rock indicates slightly different histories during eruption. These features, and the occasional occurrence of composite magmaclasts, (Fig. 7a) all suggest a pyroclastic origin. In addition, the lack of certain constituents known to occur in the erupting magma is also indicative of an extrusive origin. The paucity of olivine phenocrysts and material representing the former melt hosting the now discrete olivine grains must reflect loss through large scale sorting (Fig. 6a). The conclusion that the FALC kimberlites are composed of pyroclastic constituents based on the nature of the magmaclasts is consistent with clast-supported textures (Figs. 3a, 4, 6a, 6c)

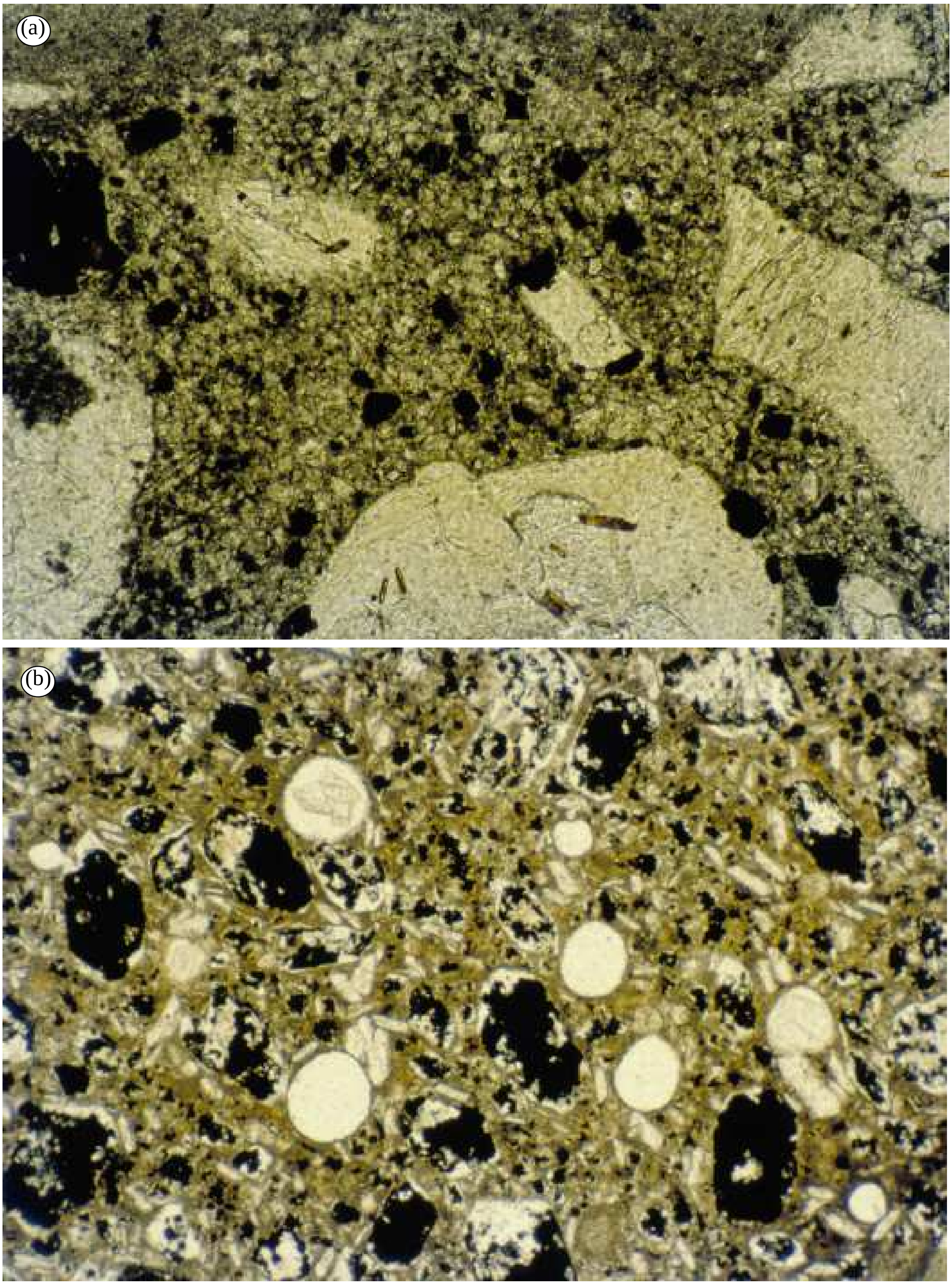

Fig. 5. Primary groundmass minerals within *rare* better crystallised juvenile lapilli. (**a**) Sample 120-12-31. 184.1 m. Thin section. Plane polarised light. Field of view = 0.6 mm. The groundmass is composed of black spinel and abundant sugary textured probable monticellite. Brown rutile needles occur within the light-coloured olivine grains. (**b**) Sample 118-3-26. See Table 2a for summary log. Thin section. Plane polarised light. Field of view = 1.6 mm. The olivine phenocrysts are largely replaced by opaque material. The groundmass minerals include light-coloured carbonate laths which are set in a base of cryptocrystalline carbonate. Spherical light-coloured vesicles infilled with carbonate and serpentine-like material indicate a pyroclastic origin.

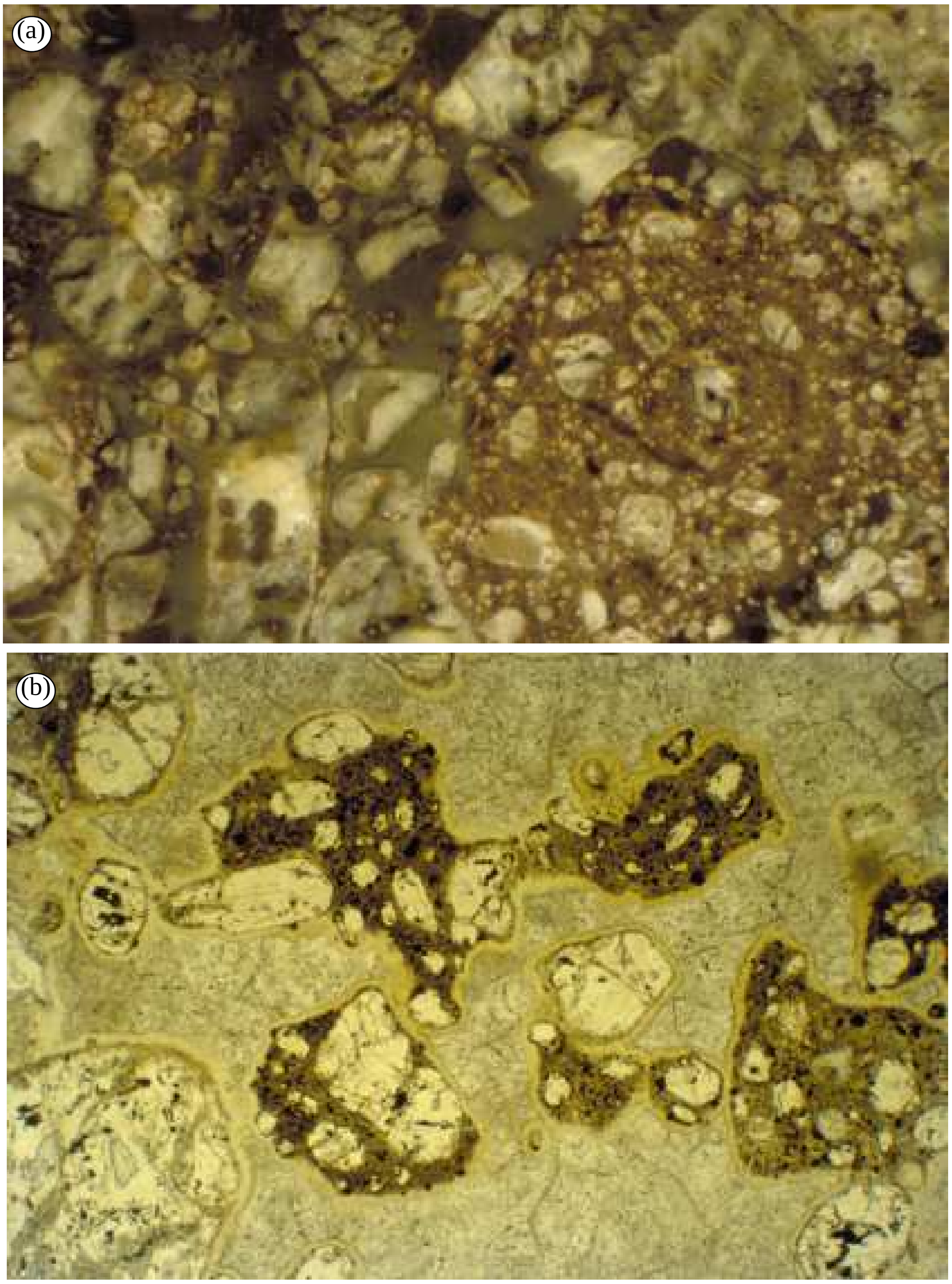

Fig. 6a-b. Dominant constituents of the FALC kimberlites: clast-supported amoeboid-shaped juvenile lapilli composed of olivine set in a fine grained groundmass, discrete olivine grains and interclast material. Note the clast-supported textures, lack of modification to the clast shapes by brittle fracture or abrasion, range of clast sizes and paucity of fine constituents. (**a**) Sample 145-3-99. 134.7 m. Polished slab. Field of view = 13 mm. Full slab is shown in Fig. 8a. Discrete olivine grains and one sub-round juvenile lapillus are set in a dark green interclast material. The juvenile lapillus contains common VVF-VF olivines. The equivalent grains are lacking among the coarser discrete olivines and thus must have been removed. This feature is common across FALC and is important evidence to show that these are extrusive rocks. (**b**) Sample 152-1-5. 155.8 m. Thin section. Plane polarised light. Field of view = 4 mm. The sample is composed of discrete olivines and some juvenile lapilli. Olivine, both within the juvenile lapilli and the discrete grains, are similar and partly fresh. Olivine grains commonly protrude from the juvenile lapilli resulting in a more irregular shape. The occasional grain has almost separated from the lapilli. The juvenile lapilli are composed of olivine set in a base of some cryptocrystalline carbonate set in an isotropic serpentine-like base. The interclast material is a void-filling cement formed by the sequential crystallisation of brown serpentine around the clasts and later white coarse grained carbonate forms the main areas.

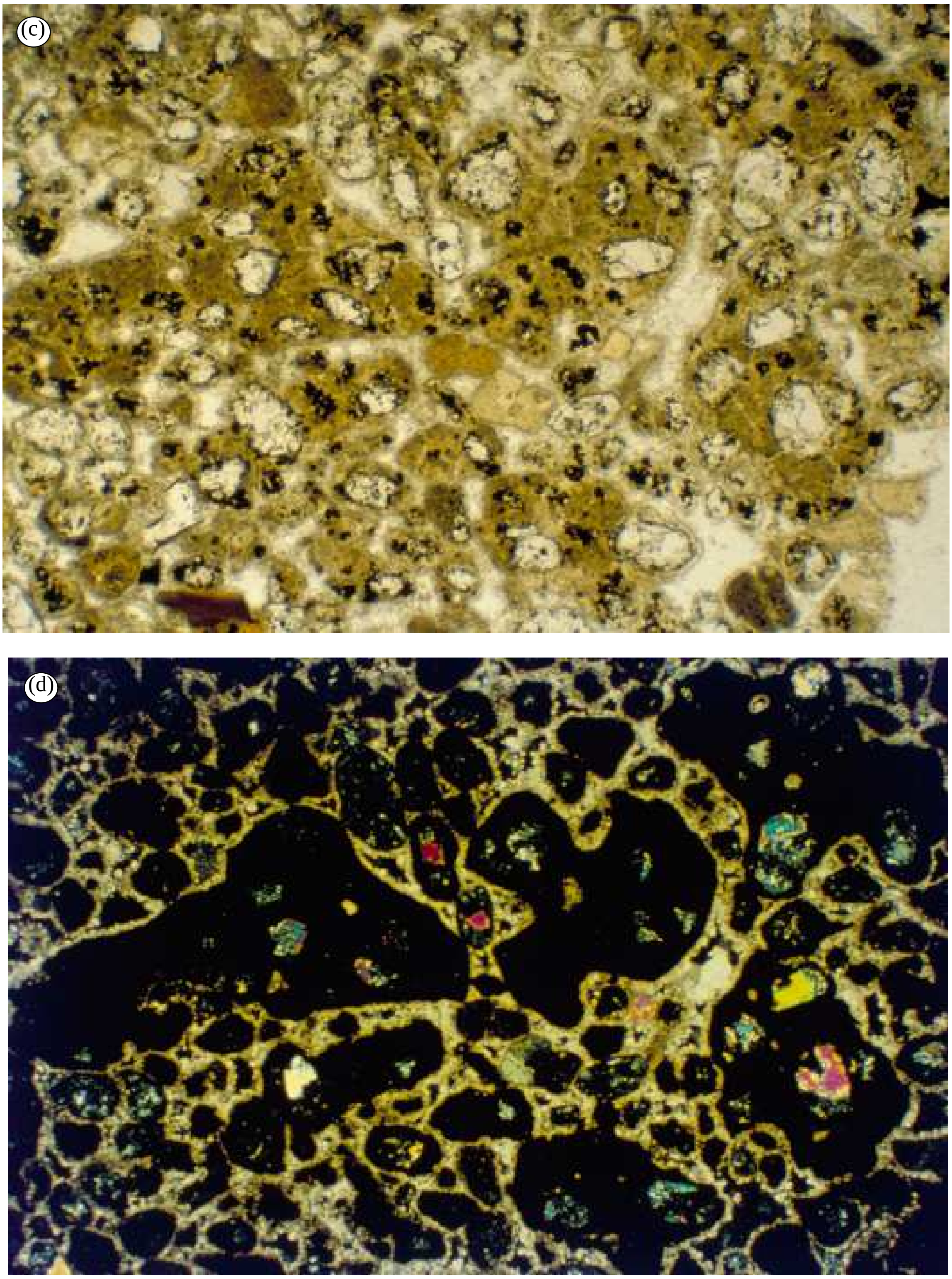

Fig.6c-d. (**c**). Sample 145-2-51. 114.2 m. Thin section. Plane polarised light. Field of view = 4 mm. The material between the partly fresh olivines is composed of brown serpentine and white carbonate. This texture resembles a segregationary hypabyssal kimberlite. (**d**) As (c) but under crossed nicols which shows that the rock is dominated by juvenile lapilli composed of olivine set in a base of isotopic serpentine. The latter has a 'glassy' or quenched appearance. The interclast material formed by sequential crystallisation of carbonate around the clasts and later serpentine, the opposite to (b). The rock is termed a juvenile lapilli PK.

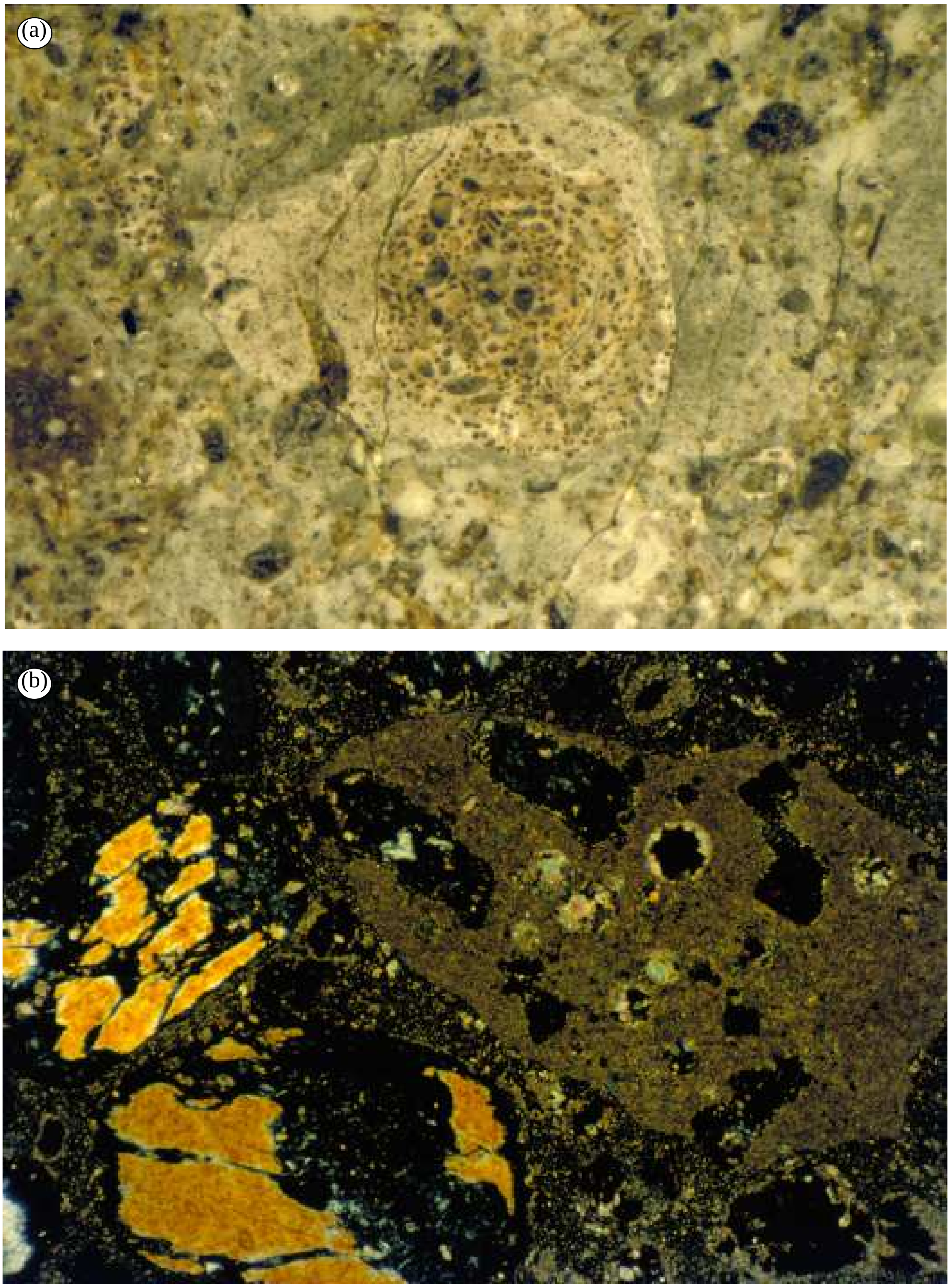

Fig.7a-b. Juvenile lapilli. (**a**) Sample 604-1-3. 103.9 m. Polished slab. Field of view = 13 mm. A composite lapillus composed of three concentric layers of contrasting magma types resulting from pyroclastic recycling. The core is distinct because it contains abundant small dark olivines. The intermediate layer has a lighter colour and the outer layer a grey colour. (**b**) Sample 101-2-4. 167.4 m. Thin section. Field of view = 1.6 mm. Crossed nicols. The juvenile lapillus (right hand side) is composed of serpentinised olivines set in a groundmass composed predominantly of cryptocrystalline carbonate. The larger discrete olivines are partly fresh. The interclast material is composed of isotropic serpentine with small amounts of fine grained carbonate. The juvenile lapillus contains some spherical vesicles composed of coarser carbonate and isotropic serpentine.

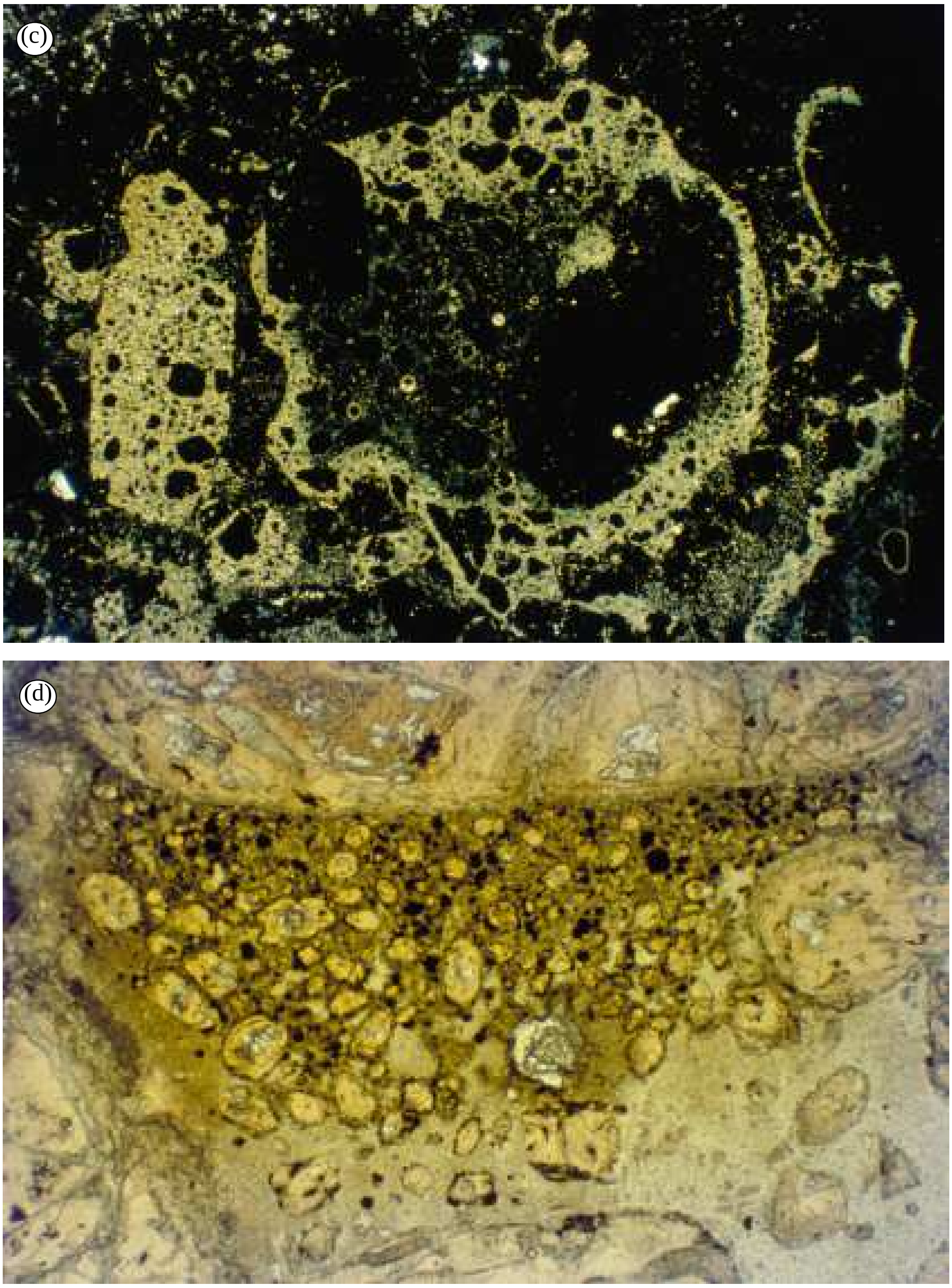

Fig.7c-d. (**c**) Sample 118-3-6. 120.9 m. See Table 2a for summary log. Thin section. Crossed nicols. Field of view = 4 mm. Two smooth outlined juvenile lapilli are highlighted by the presence of cryptocrystalline groundmass carbonate which contrasts with the isotopic serpentine interclast material. Olivines have been replaced by isotropic serpentine. The lapilli have ovoid (left hand side) and sub-round shapes (centre). The small lapillus has a uniform groundmass composed of cryptocrystalline carbonate. Similar carbonate occurs only along the margin of the larger lapillus. The central part of the lapillus has isotropic serpentine as a base. (**d**) Sample 141-1-49. 209.7 m. Thin section. Plane polarised light. Field of view = 4 mm. Parts of a single juvenile lapillus (upper) and two discrete olivines (bottom) are shown. The olivines have been replaced by serpentine. The kimberlite selvage around the large olivine macrocryst (top) has a variable texture. From the macrocryst outwards it appears to be uniform magmatic, then segregationary magmatic then magmaclastic. The magma appears to be disrupting, possibly by a degassing process. It appears that juvenile lapilli with thin selvages were being generated.

and common bedding (Clast Sorting and Structure, below).

The FALC rocks can be termed extrusive volcaniclastic kimberlites composed of juvenile constituents which have formed by pyroclastic eruption processes. The FALC rocks occur in crater-like bodies (next section), therefore, the rocks can also be termed crater-facies kimberlites (cf. Field and Scott Smith, 1998). Similar discussion for comparable rocks from Sturgeon Lake are presented in more detail by Scott Smith (1995b) and Scott Smith et al. (1996). The latter noted that shale xenoliths and organic material within the kimberlite had not been exposed to temperatures greater than 50ºC strongly consistent with an extrusive origin. These conclusions were also supported by contemporaneous work on comparable rocks from the Attawapiskat kimberlites in Ontario (Kong et al. 1999).

Both the Sturgeon Lake and FALC crater-facies kimberlites are very different from many other kimberlites, in particular those forming the basis of the hallmark textural-genetic classification of Clement and Skinner (1985). Importantly, ***no*** diatreme-facies tuffisitic kimberlites (*sensu* Clement and Skinner, 1985; Field and Scott Smith, 1998, 1999), effusive or intrusive magmatic rocks have been observed in the FALC bodies. Diatreme-facies kimberlites typically contain common large xenoliths, thin selvage pelletal lapilli, microlitic clinopyroxene in the inter-lapilli matrices and lack of sorting, none of which are found at FALC.

MAIN KIMBERLITE BODY SHAPE AND SIZE

The FALC bodies are shallow bowl-shaped craters (Fig. 18g). Based on geophysical data, the bodies appear to have sub-circular plan view shapes with areas up to 80 hectares (Fig. 7 of Lehnert-Theil et al. 1992) or 100 hectares (Scott Smith et al. 1994). The bodies which form the basis of this investigation are mainly some of the larger anomalies. Adjacent bodies may coalesce to form larger composite bodies with more complex shapes (e.g. Figs. 3 and 4 of Lehnert-Theil et al. 1992). Sometimes it can be difficult to determine what represents a single body. This investigation showed that the geology of each body is distinct (e.g. contrast the summary logs in Table 2 of this paper and Table 1 of Scott Smith and Berryman, 2007) consequently, the nature of the kimberlite can be used together with the geophysical and drilling data to resolve a single body. This approach was applied to the initial five drillholes from two separate, but adjacent, irregular-shaped anomalies (140 and 141; Fig. 4 of Berryman et al. 2004) to show that they represented a single sub-circular body at least 180 hectares in size. This proposal was confirmed by subsequent drilling and more recent estimates for 140-141 shows that it is at least 200 hectares in size (~2000 m in diameter), one of the larger bodies in the province (Berryman et al. 2004). This interpretation is supported by the similar ages for 140 and 141 (Age, above). Thus, the FALC province includes not only a large number of bodies but also bodies with substantial plan view areas.

Drilling, both RC and core, undertaken by the FALC joint venture up to the end of 1993 included a total of 127 holes with up to 20 per body (on 120). Body 169 had 13 holes and several bodies had 4-6 holes. The thicker kimberlite intersections occur nearer the centre of each geophysical anomaly and the thinner intersections towards the margins. These data from across the province show that most of the drilled bodies display overall similar shapes. The interpretation of the shapes of the three most drilled bodies are given in Fig. 5 of Lehnert-Theil et al. (1992), Fig. 4 of Scott Smith (1996) and Fig. 5 of Field and Scott Smith (1999) for body 120 and by Figs. 3 and 4 of Berryman et al. (2004) for body 169 and the updated shape of the 140-141 body. The data show that the main FALC kimberlites are large shallow bowl-shaped bodies with depths ranging up to at least 200 m from the sub-glacial surface (or 300 m from the present surface). The body shapes, flaring towards surface, have low depth to diameter ratios. The modeled body shapes based on variable amounts of drilling at the time of this study suggested contacts that vary from 5 to 55°. One drillcore showed that the main kimberlite reaches greater depths of at least 375 m (below the sub-glacial surface) where the contact must have much steeper dips. Otherwise feeders were not located during this drilling and presumed to be narrow. Subsequent drilling has intersected apparently narrow feeders (e.g. Zonneveld et al. 2004; Berryman et al. 2004). Models depicting the general shape of the FALC bodies are given in Fig. 18g, as well as Fig. 10 of Lehnert-Theil et al. (1992) and Fig. 5 of Field and Scott Smith (1999). Most of the bodies appear to flare within the Cretaceous sediments. The bodies are commonly symmetrical.

The measured dips of approximately twenty-two main kimberlite to country rock contacts are variable, ranging from 0 to 60°. Three, and possibly another two, contacts appear to dip at 0°. The observed contacts are thus similar to the overall modeled contacts discussed above. Some contacts cross-cut the bedding in the adjacent sediments. The kimberlite to country rock contacts are sharp.

Bedding dips suggest that the poorly-consolidated Cretaceous sediments were mainly undeformed adjacent to the main crater margin. The sediments encountered below the main kimberlite intersections in eleven drillcores display the regional ~0º bedding. In another eleven holes dips of <10-20º were observed. Only two instances of sediments with steeper bedding up to 30-40º were found. The dip of the bedding decreases away from the main kimberlite contact; for example in different holes the dips vary from 30º to 10-20º over 40 m, from 10-15º to 0º over 15 m and from 20º to 10º over <10 m and then to 0º within the next 5 m. In some cases, it is difficult to determine if small intersections of sediments below the main continuous kimberlite intersection are in situ or may be xenolithic (e.g. 173.2-180 m and 180.6-181.4 m in 118-3, 159.9-160.9 m in 119-2 and 300.5-305.3 m in 140-5, Table 2). These uncertainties do not change the large scale shape of the body discussed above.

Overall, the sediments across the FALC province are *in situ* and were not significantly disturbed before, or by, the kimberlite emplacement. This shows that the shallow bowl-shaped bodies represent pipes cut into pre-existing country rocks. The shapes of the FALC bodies strongly resemble subaerial, explosively excavated, shallow volcanic craters. The FALC bodies are comparable in plan view size to the craters of other kimberlites (up to 200 hectares, e.g. Scott Smith, 1992), and in plan view and cross section shape and size to lamproites (up to 124 hectares, <400 m deep, e.g. Scott Smith, 1992) and to maars (e.g. Fig. 9-27 in Fisher and Schmincke, 1984; Fig. 13.18 in Cas and Wright, 1987). Further, the FALC bodies are infilled with extrusively formed volcaniclastic kimberlite (Textural Classification, above). No resedimentation or soil development occurred at the country rock to main kimberlite contacts showing that there was limited time between crater excavation and infilling.

In summary, the FALC bodies are shallow bowl-shaped craters which are different from most southern African kimberlites that comprise three pipe zones: crater, diatreme and root zone with contrasting infills (Hawthorne, 1975; Clement and Skinner, 1985). At FALC there is no deep carrot-shaped diatreme infilled with tuffisitic kimberlite breccia and no underlying hypabyssal root zone. The FALC pipes are clearly different from the southern African pipes in both shape and infill. In addition, no tabular hypabyssal kimberlite sheets have been encountered at FALC.

NATURE OF THE MAIN KIMBERLITES

Terminology

The FALC rocks are texturally different to previously documented kimberlites and the established kimberlite terminology of Clement and Skinner (1985) is insufficient to describe these rocks. The FALC rocks are described using a blend of kimberlite (Field and Scott Smith, 1998) and volcanological terminology (Fisher and Schminke, 1984). The term clast is used to describe a discrete body or particle. Exotic clasts (e.g. sediment or basement) are termed ***xenoliths*** irrespective of the presence or absence of adhered former melt. Melt describes the liquid part of the magma. An ***autolith*** is a fragment of previously-consolidated kimberlite (usually angular in shape). Since all the exotic clasts are termed xenoliths, the term juvenile pyroclast refers to products derived from the magma excluding any entrained xenoliths. The mantle-derived olivine macrocrysts and associated constituents are considered cognate for considerations of emplacement. The term juvenile thus can be applied to any clast derived from the magma except xenoliths. The term ***juvenile lapilli is used to describe pyroclasts composed of former melt and any entrained cognate or primary mineral grains***. The clasts described as juvenile lapilli are mainly 2-10 mm in size, thus the term conforms with standard volcanological size classification for lapilli of 2-64 mm. The term juvenile **coarse ash** describes finer material (0.06-2 mm). The cognate olivine and other crystals that do not have any adhered former melt are referred to as ***discrete crystals or grains. The term juvenile lapilli, as used in this paper, does not encompass such discrete crystals.*** The term "***breccia***" is used as defined in kimberlite terminology: a rock containing more than 15 volume % of xenolithic fragments >10 mm in size (after Clement and Skinner, 1985; not >64 mm as used for pyroclastic breccia in volcanology, e.g. Table 5.2 in Fisher and Schminke, 1984). At FALC most clasts >10 mm and all >64 mm are xenoliths. With respect to the xenoliths, the Lower Colorado and Pense are referred to as (marine) shale (not mudstone), the parts of the mixed Mannville sediments as mudstone (not shale).

Dominant Constituents

The main rock-forming constituents of the FALC kimberlites are (i) juvenile lapilli (olivine plus former melt), (ii) discrete olivine grains (free of former melt) and (iii) interclast material (Fig. 6; cf. Plate 7 of Scott Smith, 1995b and Plates 6 and 7 of Scott Smith et al. 1996, Plates 7 and 9 of Leckie et al. 1997a). Most of the kimberlites are relatively fresh and in most drillcores original features can be readily discerned. Some secondary minerals which mask original features include clay minerals, sporadic irregular patches of magnetite (Fig. 15a; Plate 7E of Leckie et al. 1997a) and a vermiform mineral very similar to that reported by Scott Smith et al. (1996; Fig. 7d) which was thought to be clinochrysotile but Nixon et al. (1993) consider an optically similar mineral to be antigorite. This mineral appears to form preferentially in areas adjacent to shale occurring either at contacts or around xenoliths.

Juvenile Lapilli: The juvenile lapilli (olivine plus former melt) are mostly less than 10 mm in size (Figs. 3a-b, 6). Larger examples up to 30 mm are unusual and only rare examples reach 50 mm in size. They are composed of olivine grains and former melt. The olivine grains may be partly, or totally, pseudomorphed but, notably, are commonly fresh (Figs. 6b-c). A single lapillus, when large enough, contains a number of olivine grains possibly including both macrocrysts and phenocrysts (Fig. 3). Other juvenile lapilli are too small to contain a macrocryst. Some juvenile lapilli are composed of a single olivine grain, especially the larger grains, with a partial or complete selvage of kimberlite magma. Occasionally the selvages may be thin and difficult to observe macroscopically (Fig. 7d). Sometimes the former melt within the lapilli crystallised monticellite, phlogopite, perovskite and spinel (Fig. 5). Most groundmasses, however, were rapidly cooled without the crystallisation of these minerals when the base is composed of serpentine (Fig. 3b), typically isotropic (Fig. 6d), and less abundant cryptocrystalline carbonate (Figs. 7b-c). Some glassy-textured groundmasses occur but no true glass is present.

The shapes of the juvenile lapilli are variable: from common amoeboid to curviplanar (Figs. 3a-b, 6b-d, Fig. 2c of Sparks et al. 2006) to less common sub-spherical or ovoid types (Fig. 6a). Spherical or more irregular vesicles occur but are not common and they are not exposed at the surface of the lapilli (Figs. 5b, 7b; Figs. 2b-c of Sparks et al. 2006). The FALC juvenile lapilli are clearly different to those formed in other rock types such as the common pyroclastic scoria and associated clast shapes such as cuspate shards of basaltic eruptions. Achneliths would be the closest basaltic equivalent of the FALC juvenile lapilli. The smooth surfaces indicate that the pyroclasts were shaped by surface tension processes on low viscosity or fluidal clasts ejected in the molten condition during subaerial eruptions. The final shapes probably partly depend on the cooling time between magma disruption and solidification. More irregular shapes can result from protruding olivine grains (Figs. 3b, 6b). Other irregular lapilli may have formed from more viscous or partly cooled magmas.

Most of the FALC juvenile lapilli are pyroclasts (Textural Classification) formed during subaerial magmatic eruptions by the disruption of very fluidal magmas. The apparent low viscosity is consistent with the high MgO and volatile contents of kimberlite magmas. The lack of angular, blocky or accretionary lapilli, which require fines and moisture to form, are features consistent with this suggestion. Much of the magma disruption likely resulted from fire fountain type processes, with fragmentation possibly enhanced by rapid uprise, high exit velocities, small diameter feeder vents as well as the low viscosities. Rare examples of molding of adjacent lapilli occur in three bodies (121, 175 and 180) which shows some pyroclastic deposition from low eruption columns was more like lava spatter. The absence of flattened lapilli or welding is notable, suggesting that most pyroclasts solidified in flight prior to final deposition possibly indicating low mass eruption rates. The lack of armoured or accretionary lapilli indicates dry eruption columns and may also indicate that water did not exsolve easily from the magmas and rather quenched in the juvenile lapilli upon eruption. In contrast the carbon dioxide which exsolves more easily, escaped and thus is less common than serpentine or if there is no opportunity for degassing it quenched to cryptocrystalline carbonate. These features are consistent with the suggestion of serpentine and carbonate being important primary quench products.

Modification of the solid juvenile lapilli is not common, either by brittle fracture, abrasion or replacement (Figs. 3, 6b-d, 7c). One type of juvenile lapilli dominates most single rocks indicating derivation from a single overall eruption (Figs. 3a, 6b-d). In a few instances, two contrasting types of juvenile lapilli represent different phases of eruption and rare composite lapilli (Fig. 7a) suggest mixing by pyroclastic recycling. Fine and coarse ash-sized equivalent clasts are in low abundance in most parts of FALC. All these features provide evidence for subaerial pyroclastic deposition and the lack of reworking.

Discrete Olivines: The discrete olivine grains (devoid of former kimberlite melt) are similar to those which occur within the associated juvenile lapilli described above with respect to size (<10 mm, occasionally larger), shape and degree and nature of any replacement (by serpentine, carbonate, magnetite and sulphides) as shown in Figs. 6a-b and 8c. The similarity suggests that any replacement process is deuteric, or pre-eruption, and that most grains have not been modified by post-deposition processes. The olivine grains are commonly fresh (Fig. 7b). Discrete olivine grains are a volumetrically important constituent of the FALC kimberlite province (Fig. 8). The separation of discrete grains of olivine, therefore, is a characteristic feature of the FALC eruptions. Discrete olivine grains could be separated from solid juvenile lapilli by reworking but there are many features which indicate that this was not an important process in the final deposition of most of the FALC kimberlites. The most pertinent evidence includes the lack of modification to the associated juvenile lapilli shapes by breakage or abrasion and an absence of fines (Figs. 3, 4, 6, 8).

The discrete olivine grains clearly derive from the same kimberlite magma as the associated juvenile lapilli. Most of the FALC bodies are composed of 'typical' kimberlite magma containing approximately 25% phenocrysts and 25% macrocrysts (Fig. 3, Petrological Classification, above). Both types of olivine were present in the kimberlite magma within the mantle, well before near surface emplacement. As noted above (Juvenile Lapilli, above), olivine crystals commonly protrude from the margins of the fluidal juvenile lapilli (Figs. 3b, 6b, 8c). A spectrum of textures from partial protrusion to near, and then complete, release from the magma are evident when a large number of samples are examined. These textures suggest that olivine liberation resulted from the simple separation of high specific gravity grains from extremely fluidal magmas. Some of the erupting liquids could have had viscosities similar to carbonatites. Degassing or cooling contraction granulation could also have aided this process (Fig. 7d). The separation of olivine from the magma presumably occurred during magma disruption and eruption.

Interclast Material: The juvenile lapilli and discrete olivine grains have loosely-packed, clast-supported textures. Ash or coarse-ash sized constituents are in low abundance. As a result, most rocks contain volumetrically significant proportions of interclast material (Fig. 6). The interclast material is divided into two main types (a) magmatic cement and (b) non-magmatic fine grained matrix. Type (a) is dominant and is composed of mainly serpentine (Figs. 3a, 6a) and carbonate (Figs. 3b, 6d, 9) with much less common magnetite (Figs. 8b, 9; mineralogies confirmed by microbeam analysis). These minerals form open space fill cement between the pyroclasts and display some cockade and other infilling textures are present (Figs. 6, 9). Serpentine and carbonate can both occur in one sample and appear to have formed by sequential crystallisation from a single fluid (Figs. 6b, d). Across the province macroscopically clear dark or light to milky green serpentine appears to be the main interclast mineral. In one sample from body 219, the interclast serpentine (e.g. 31.33 wt% SiO_2, 30.21 wt% MgO, 6.78 wt.% FeO, 7.37 wt% CaO, 2.11 wt% Al_2O_3, likely not pure serpentine) is different in composition to the serpentine in partly altered olivines (e.g. 41.07 wt% SiO_2, 40.89 wt% MgO, 2.57 wt.% FeO after olivine phenocryst with 40.96 wt% SiO_2, 50.91 wt% MgO and 8.12 wt% FeO) indicating they formed by separate processes. Carbonate, shown to be calcite (<0.3 wt% MgO) in the same sample from 219, occurs in some areas but seldom throughout a drillcore or body. The interclast carbonate can be either very fine or coarse grained (Figs. 6b, 9). The latter contrasts with the carbonate occurring within the lapilli (Fig. 7b).

The mineral assemblage of serpentine, carbonate and magnetite is similar to the late stage crystallisation of residual fluids in hypabyssal kimberlites. The interclast material is a post-depositional cement which crystallised in the pore spaces to the pyroclasts from hydrothermal-like kimberlitic fluids that moved upwards through the permeable deposits. The fluids derived from the feeder vent from a boiling event of one or more subsequent eruptions. It is less likely that the fluids derive from the same eruption given that the kimberlite clasts appear to be solid prior to deposition. Occasionally different generations of serpentine are noted, such as light coloured serpentine replacing darker coloured serpentine. Remnants of the first serpentine only survived above larger clasts. In rare cases, three phases of interclast material were noted. Similar minerals to the interclast cement also form post-consolidation cross-cutting veins. The cementation processes consolidated the pyroclastic deposits to form hard indurated rocks. This aspect contrasts with the poorly-consolidated adjacent country rocks showing that the kimberlite lithification processes had little effect on the country rocks.

Cementation and consolidation soon after deposition from each successive eruption would explain the lack of significant secondary alteration, weathering, reworking and deformation caused by percolating groundwater, subsequent eruptions and/or compaction. Rapid and sequential cementation is indicated by the occurrence of previously cemented autoliths of volcaniclastic kimberlite (Fig. 10 and Autoliths, below) and by textures within the kimberlite (e.g. general comments for 118-3 in Table 2b). It is important to note that the fluids forming the interclast cement only rarely appear to replace any of the clasts forming the deposits. Importantly, the mineralogy and mode of occurrence of the interclast minerals contrast with that in the juvenile lapilli (Figs. 3b, 6b, 6c-d, 7b-c).

The type (b) or non-magmatic matrix is not common. A fine apparently clastic grey or brown coloured material occurs in limited areas, seldom throughout a single drillcore. The most likely options for the nature of this material are kimberlitic ash or disseminated mudstone/shale. The matrix can contain apparent single grains of groundmass minerals such as perovskite, spinel and mica suggesting ash. This type of interclast matrix is presumably syn-depositional and appears to occur mainly in the early deep or late upper, but not the main, crater infill. Some matrix-supported textures seemingly had undergone less sorting with the retention of abundant fines. These

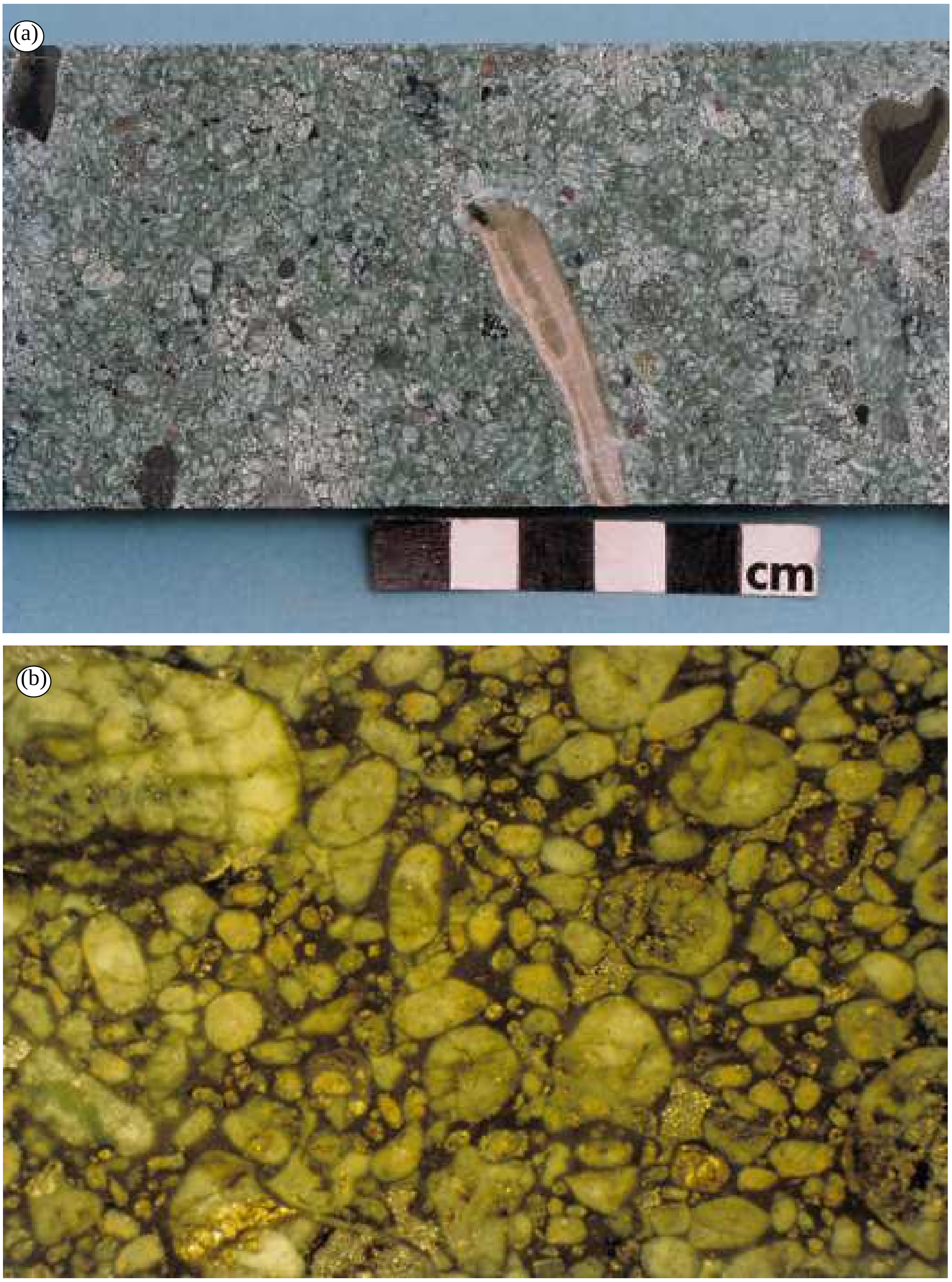

Fig.8a-b. Discrete olivine grains forming olivine PK. Note the clast-supported textures and the lack of fine grains. (**a**) Sample 145-3-99. 134.7 m. M+ColPK. Polished slab. Same sample as Fig. 6a. This rock is composed of clast-supported serpentinised olivine macrocrysts (up to 10 mm). Fines are uncommon. The few xenoliths are Paleozoic carbonates with different colours and some display zonal alteration. The latter indicates residence in the hot kimberlite magma. (**b**) Sample 101-2-35. 326.4 m. Polished slab. Field of view = 6 mm. The sample is composed predominantly of clast-supported olivines which have been replaced by mainly light-coloured serpentine and much less common black material. The interclast material is composed of dark green serpentine and less common magnetite. The olivines display a range in size but very fine grains are not present.

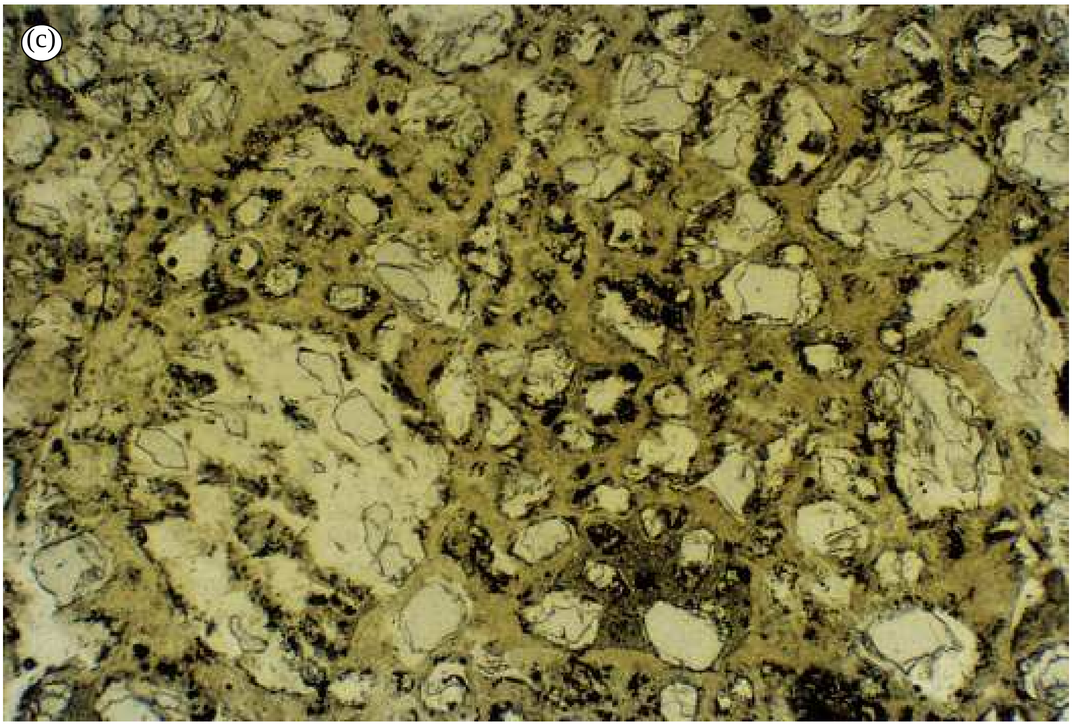

Fig.8c. Discrete olivine grains forming olivine PK. Note the clast-supported textures and the lack of fine grains. Sample 121-3-2. 130.8 m. Thin section. Plane polarised light. Field of view = 4 mm. Discrete sometimes partly-fresh olivine grains have a range of sizes. Fine olivines are not present. The white serpentine replacing the olivines is clearly different from the brown interclast material serpentine. Olivine grains protrude from the margin of the juvenile lapillus (bottom centre).

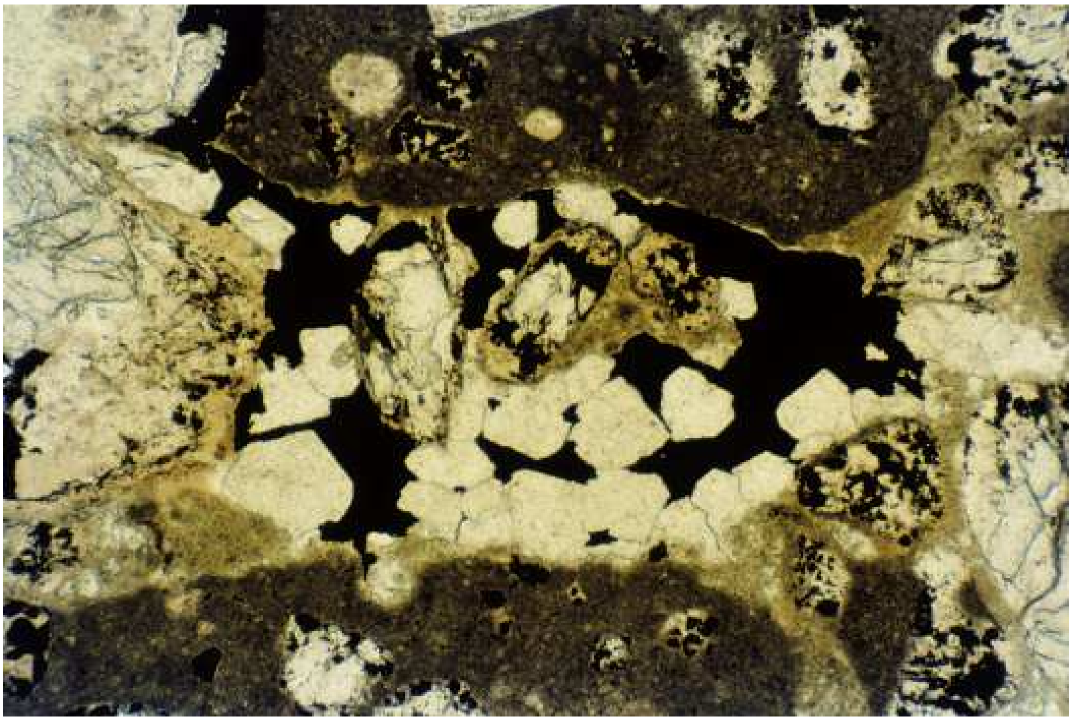

Fig.9. Interclast material. Sample 101-2-11. 197.8 m. Thin section. Plane polarised light. Field of view = 1.6 mm. The interclast material between two juvenile lapilli (top and bottom) and discrete olivines (left and right) is composed of prismatic grains of carbonate intergrown with magnetite. A few vesicles are present in the bottom lapilli.

features probably reflect a different mode of deposition, and possibly also eruption.

Main Rock Types

Most the FALC kimberlites are composed mainly of juvenile lapilli (olivine plus former melt) and discrete olivine grains (no former melt) interpreted above to have been formed and deposited by pyroclastic processes. The rocks, therefore, are termed *pyroclastic kimberlite* (PK). The rocks range from examples dominated by juvenile lapilli (Figs. 3a, 6c-d, 12a) to those dominated by olivine grains (Fig. 8). The end member rock types are termed *juvenile lapilli PK* or *olivine PK*, respectively. End member rock types are seldom pure. A full spectrum of mixtures of these constituents occur (terms such as olivine>juvenile lapilli PK or juvenile lapilli-bearing PK can be applied depending on the relative proportions of the two components). Individual bodies are commonly characterised by relatively constant proportions of the two constituents. Generalising, it appears that eight of the bodies investigated are dominated by juvenile lapilli (118 as shown in Tables 2a, b and Figs. 3a and 7c, 120, 162, 167, 175, 226, 602, 604) and seven bodies by discrete olivine grains (121 as shown in Fig. 8c, 140-141 as shown in Table 2d and Berryman et al. 2004, 148, 174, 180, 181, 606). The other bodies are composed of a mixture of juvenile lapilli and discrete olivine grains (Figs. 6a, c-d), either mixed throughout the body (Tables 2c, e) or in contrasting drillcore intersections within a single body (Figs. 12a and b which are comparable to the two main kimberlite intersections of 169-8 shown in Fig. 4 of Leckie et al. 1997a). Olivine PK is volumetrically important in the FALC province and they are the first recognised extensive deposits of olivine-dominated pyroclastics. Such deposits are unusual, not only for kimberlites but also in the geological record. Kimberlites, with extremely high crystal contents and extremely low viscosities relative to most rock types, have the greatest potential to form such deposits.

Other Constituents

Phlogopite: Phlogopite occurs as lath-like grains which are less than 2-3 mm in size. Some of these grains occur within the juvenile lapilli where textures suggest that they are probably phenocrysts. Similar phlogopite also occurs as discrete grains. Some larger grains of mica are termed macrocrysts, being of unknown origin. The abundance of phlogopite varies, from common to absent.

Mantle-derived xenocrysts other than olivine: Other mantle-derived xenocrysts are less common than olivine and include garnet, ilmenite and chrome diopside which vary in abundance from absent (e.g. 101) to relatively abundant (e.g. 120). Chrome diopside was only observed in some minor areas. No orthopyroxene was observed. These minerals occur both within juvenile lapilli and as discrete grains and are generally similar in size to the olivine macrocrysts. As with olivine, these high pressure mineral grains are typically internally fragmented. The garnet grains commonly have complete and sometimes thick kelyphitic rims. Only a small proportion of the discrete grains appear to have been broken. The overall lack of breakage and abrasion of these fragile grains suggests little reworking. Rare megacrysts (up to 30-40 mm) of olivine, ilmenite, red garnet and chrome diopside were found in some kimberlites (Fig. 4). These grains are sometimes angular again indicating a lack of reworking (Fig. 4). Many bodies appear to be devoid of megacrysts.

Mantle-derived Xenoliths: Mantle-derived xenoliths are rare to absent in most of the kimberlites, but are more frequent in a few drillcore intersections (Fig. 4). Kimberlite selvages are present on some examples. Based on macroscopic identifications, eclogites and peridotites occur. Peridotites (mainly <7 cm) are composed of olivine, altered orthopyroxene, some garnet and rare chrome diopside but can be altered. The garnets display varied colours and may have kelyphitic rims. In some peridotites a purple coloured pseudomorph may be after chrome diopside. Coarse and porphyroclastic textured examples (Fig. 4) as well as metasomatised xenoliths containing ilmenite and mica were observed. The eclogites are usually smaller (<2 cm).

Autoliths: Some angular autoliths (<15 cm) with varied appearances are present but not common (e.g. drillcore 219-3 in Table 2e). The autoliths include well to poorly-sorted, very fine to coarse grained rocks which can contain juvenile lapilli (Fig. 10). The interclast material within the autoliths is usually different to that in the host kimberlite. Thus, the autoliths are fragments of earlier cemented volcaniclastic kimberlite which indicates crater infill resulted from multiple phases of eruption in which the earlier deposits were lithified prior to inclusion in later eruptions. The possibility of magmatic kimberlite autoliths cannot be excluded because some autoliths do not contain macroscopically discernible features.

Crustal Xenoliths and Xenocrysts: Crustal xenoliths (Fig. 8 of Jellicoe et al. 1998) are not common but they can be locally abundant (up to 80%). The most notable feature of the FALC kimberlites is the overall lack of xenoliths,

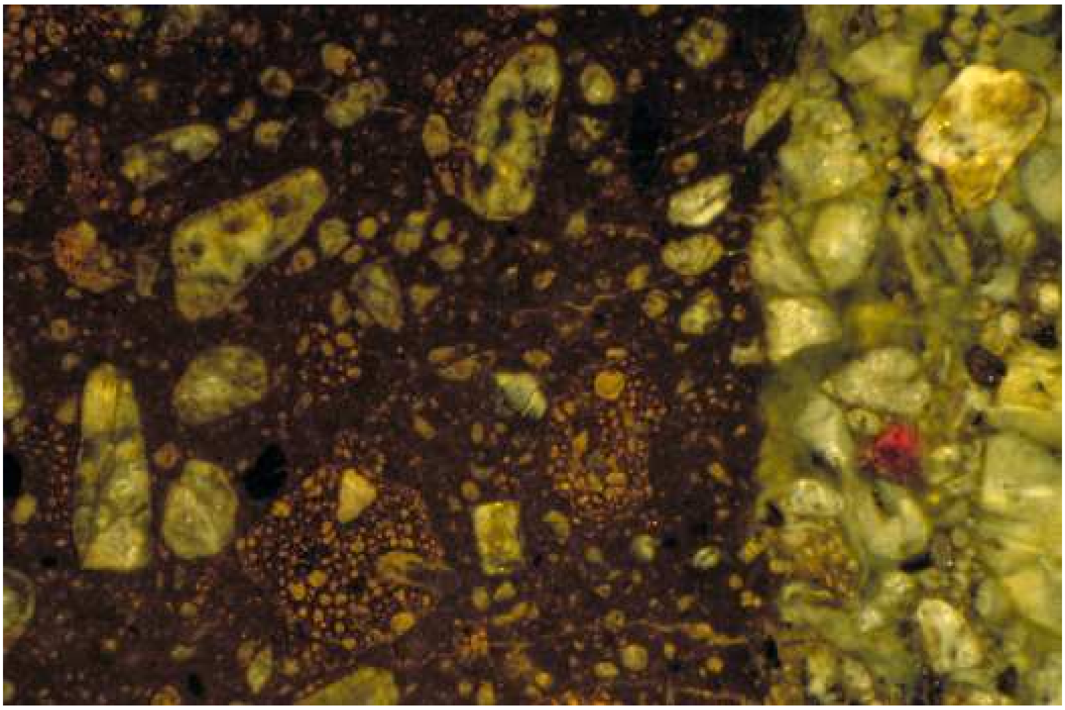

Fig.10. Autolith. Sample 145-3-101. Polished slab. Field of view = 13 mm. Part of an autolith which is composed of poorly-sorted juvenile lapilli and discrete olivines set in a dark interclast material which shows that it is lithified volcaniclastic or crater-facies kimberlite. The host kimberlite (right) is composed mainly of discrete grains of olivine set in a pale green serpentine interclast material which is very different from the interclast material within the autolith.

especially of the country rocks that originally formed the large volumes where the main kimberlites now occur. This shows that the main FALC kimberlites were completely excavated volcanic craters prior to subsequent infilling by overall xenolith-poor kimberlite. The excavated country rock material was not deposited back into the crater by primary or resedimentation processes. The xenoliths include basement, Paleozoic carbonates and Cretaceous Lower Colorado and Mannville sediments representing most of the units in the local stratigraphy (Geological Setting and Fig. 2; xenoliths described in more detail below). Not all the xenolith types are present in all the kimberlites. Paleozoic carbonates are most consistently present. Basement xenoliths are in overall low abundance. In a few drillcores shale is common in some local areas. The presence of partial or complete kimberlite selvages on many of the basement and Paleozoic carbonate xenoliths shows that they were resident in the kimberlite magma prior to eruption. Most of these kimberlite-transported xenoliths appear unbroken with sizes dependent on pre-eruption processes. Evidence of ballistic impact during pyroclastic deposition is indicated by a few examples of jig-saw fit groups of angular fragments of each of the different types of kimberlite-transported xenoliths separated by minor amounts of volcaniclastic kimberlite. In contrast Cretaceous sediments, which do not have kimberlite selvages, were not resident in the kimberlite magma and derived from the crater wall (or rim). Importantly, all Cretaceous sediments found within the main kimberlites are of xenolithic origin. Rare intersections of kimberlite predominantly located in the deeper parts of the crater contain abundant single grains of quartz presumably derived from the Mannville (e.g. 160.9-161.2 m in drillcore 119-2 presented in Table 2b). In one case, 22.5 m quartz-rich kimberlite occurs immediately above the Mannville basal poorly-consolidated sandstone.

Basement Xenoliths: The basement xenoliths (up to 7+ cm) are angular to sub-rounded and include common biotite gneisses which may contain pink garnet (Fig. 7f of Berryman et al. 2004). Davis et al. (1998) show that some of these xenoliths derive from reworked Archaean crust (crystallisation ages of 3.2-2.07 Ga. and dominant reworking at 1.76-1.77 Ga.).

Paleozoic Xenoliths: The Paleozoic xenoliths (up to 15 cm) comprise carbonates which display varied textures and colours (pink, white, green, grey, black, brown; Figs. 8a, 14) derived from different stratigraphic levels.

The xenoliths commonly display a concentric zonation resulting from reaction with the host magma (Fig. 8a), another feature indicating residence in the kimberlite magma. These clasts have partly rounded to angular shapes (Figs. 14b-c) with some more extreme irregular shapes. The latter feature suggests that some carbonate xenoliths were partly digested or even remobilised by the hot kimberlite magma. Some of these xenoliths have delicate apophyses that would readily break off during any reworking process. The lack of rounding is also consistent with no reworking.

Mannville Xenoliths: Xenoliths similar to the brown-coloured Mannville sediments are rare within the main kimberlites (probably <20 examples observed in total). Possible examples of xenoliths up to 5 m in size occur near the bottom of a few craters but it is difficult to determine if they are in situ or not (e.g. 300.5-305.3 m in drillcore 140-5 in Table 2c).

Lower Colorado Xenoliths: Black shale xenoliths are not common but can be locally abundant (mainly <30 cm in size, Fig. 11). Although not examined in detail, variations in the nature of the shale xenoliths (colour, abundance of glauconitic spots and silt, nature of laminations) correspond with variations at different stratigraphic levels observed in the *in situ* country rock. The shale xenoliths display two types of shapes. Angular shapes suggest derivation from reasonably-consolidated sediments. The more common ductile shapes with re-entrant embayments, delicate apophyses as well as distorted internal bedding indicate derivation from poorly-consolidated shales (Fig. 11) and a lack of reworking. Constituents from the host kimberlite are partly or totally enclosed in poorly-consolidated shale xenoliths. The shale xenoliths can occur at depths presumed to be below their original position in the country rock, >190 m, based on local stratigraphy (Fig. 2; e.g. >213.4 m in drillcore 118-4 in Table 2a; 299.4-300.5 m in drillcore 140-5 in Table 2c; 203-205, 260, 293.2 and probably 489-498 m in 181-2). Leckie et al. (1997a) show that shale clasts within the kimberlite from 169 contain diverse dinoflagellate assemblages presumably from different stratigraphic strata. Those from 188.15-191.68 m and 201.15-201.8 m in hole 169-8 are late Albian marine shale and thus probably below their original stratigraphic level. The occurrence of Lower Colorado xenoliths below their original stratigraphic level confirms the existence of craters. The occasional thicker intersections of black shale occur within seven of the main kimberlite bodies and they range from 30 cm up to 13 m. The shale to kimberlite contacts, when preserved, are sharp with variable and commonly steep angles (25-75° with rare examples <10°). The upper and lower contacts of a single shale intersection are typically not parallel. Smaller shale xenoliths frequently occur within the kimberlite adjacent to these contacts, most notably below the major intersections. Also, these shale intersections cannot be correlated between different holes in the same body suggesting that they have limited lateral extent. Some, but not all, of the larger shale intersections occur near the crater margins and below their stratigraphic level in the adjacent country rock. These

Fig.11. Lower Colorado shale xenoliths in bedded kimberlite. Sample 118-3-22. 150.6 m. Polished slab. See Table 2a for summary log. The upper 10 cm comprises thinly bedded FK which contains small (<3-4 mm) shale xenoliths concentrated along certain bedding planes. A thicker bed below that contains deformed poorly-consolidated shale xenoliths (<9 cm) which was partly mixed with the host FK (FKshaleB). The shale xenoliths have not been sorted and thus must have a separate mode of deposition to the main kimberlite constituents. Below this sample is well bedded VFK.

features, together, show that the >30 cm shale intersections are large crater wall, or less likely crater rim, xenoliths.

Clast Shape and Size

The size and shape of the main constituents forming the FALC kimberlites, juvenile lapilli and discrete olivines, are significantly controlled by the solid constituents present in the magma prior to eruption. The discrete olivine macrocrysts and phenocrysts, as well as other mineral grains, liberated from the magma during eruption retain their original shapes and are seldom broken (<10 mm round macrocrysts and <0.5 mm euhedral olivine phenocrysts). A juvenile lapillus composed of an olivine macrocryst or xenolith rimmed by minor adhered former melt adopts the shape of the kernel (cf. Fig. 5 of Scott Smith, 1995b). The variable sub-round (Figs. 6a, 7b-c, 12a) to amoeboid (Figs. 3, 6b-d) shapes of other juvenile lapilli composed of a number of olivine grains and abundant former melt (Figs. 3, 6) are less affected by the grains within them.

The size classification developed for this investigation (Table 1) focuses on the main constituent, olivine: VC grains are megacrysts (>10 mm, Fig. 4), the F, M and C grains are different sizes of macrocrysts (0.5-10 mm, Figs. 3 and 8) and VF and VVF grains are phenocrysts (<0.5 mm, Fig. 3b). Kimberlites (K) composed of a range of grain sizes are termed VF+F+M+CK suggesting a typical kimberlite olivine population or M+CK which implies that VF+F grains are lacking and therefore that sorting has occurred. Gradational rocks between M and C can be described as M-CK. If there are sufficient xenoliths (>15%, >10 mm) the term breccia can be added to any of the sub-divisions leading to terms such as M+CKB and VFKB (Fig. 11). The terms can be further expanded to include an interpretation of the nature of the kimberlite such as M+ColPK or M+CjlPKB for medium+coarse grained olivine-dominated pyroclastic kimberlite or juvenile lapilli-dominated pyroclastic kimberlite (Figs. 8a and 3a, respectively) or VFRVK for a very fine grained resedimented volcaniclastic kimberlite (Fig. 17a). Many rocks can be described by one term but, importantly, if the sizes of the juvenile lapilli and the olivines are different (Figs. 7a, 12a) then two terms need to be applied, e.g. F ol in a C jlK. This terminology has been applied to the summary logs presented in Table 2.

One advantage of the FALC classification is that it does not require any knowledge of the mode of formation or deposition of the clasts. Other classifications were taken into consideration (the volcanological size classes, F to VC and VVF to VF correspond to lapilli and ash, the terms M-C, VF-F and VVF-F correspond with the igneous petrological sub-divisions coarse (>5 mm), medium (1-5 mm) and fine (<1 mm) and with respect to sedimentary terminology VC-C are pebbles, M are granules, F is coarse and very coarse sand, VF is medium sand and VVF is very fine sand to silt).

Clast Sorting

Most of the FALC kimberlites can be described as poorly-sorted given that each sample or intersection contains a range of clast sizes (Figs. 6, 8c). Sorting, however, was an important process during the deposition of most, but not all, of the FALC kimberlites. A general, and significant, overall feature of the FALC rocks is that ash and coarse ash sized clasts, VVF, VF and some F, are commonly in low abundance (Figs. 3a, 6, 8a-b, Table 2e). This feature is most evident where the size distribution of the discrete olivine grains is different to the olivine grains that are present within the associated juvenile lapilli (Fig. 6a). The juvenile lapilli are representative of the erupting magma, most commonly typical kimberlite (Fig. 3) which hosted the full spectrum of olivine sizes prior to eruption. The finer grains, most notably the olivine phenocrysts which are <0.5 mm in size, are frequently missing and must have been lost through sorting. In addition, the former melt that originally hosted all the discrete mineral grains is poorly represented. There is *no* textural evidence to suggest that the finer particles have been preferentially replaced. Minor deposits are composed of fine clasts of former melt, or VVF-VFK (Figs. 11, 12a, Table 2a and top of the mega-graded bed in Table 2d or Figs. 7a-b in Berryman et al. 2004) confirming that such constituents were produced during eruption and preserved. The former melt probably formed ash-sized clasts similar to the bottom of Fig. 12a which were again lost through sorting along with the similar sized olivine phenocrysts. Thus, in many instances, it is clearly evident that the total package of juvenile clasts forming substantial parts of the drillcores (e.g. Table 2d) does not equal that of the erupting kimberlite magma. In extreme cases such as a M+ColPK, the rock is composed of only the olivine macrocrysts (Fig. 8a). The latter formed ~25% of the pre-eruption kimberlite magma. The other approximately 75% of the erupting magma, all the olivine phenocrysts and all of the former melt that hosted them, have been lost by large scale syn-eruption sorting processes. The most likely process to explain such widespread removal of fines across the FALC province is wind winnowing from subaerial pyroclastic eruption fountains or columns. In turn, this is another feature which supports the suggestion that these kimberlites were erupted in subaerial conditions.

In rocks dominated by juvenile lapilli (olivine plus former melt), it can be difficult to determine if significant

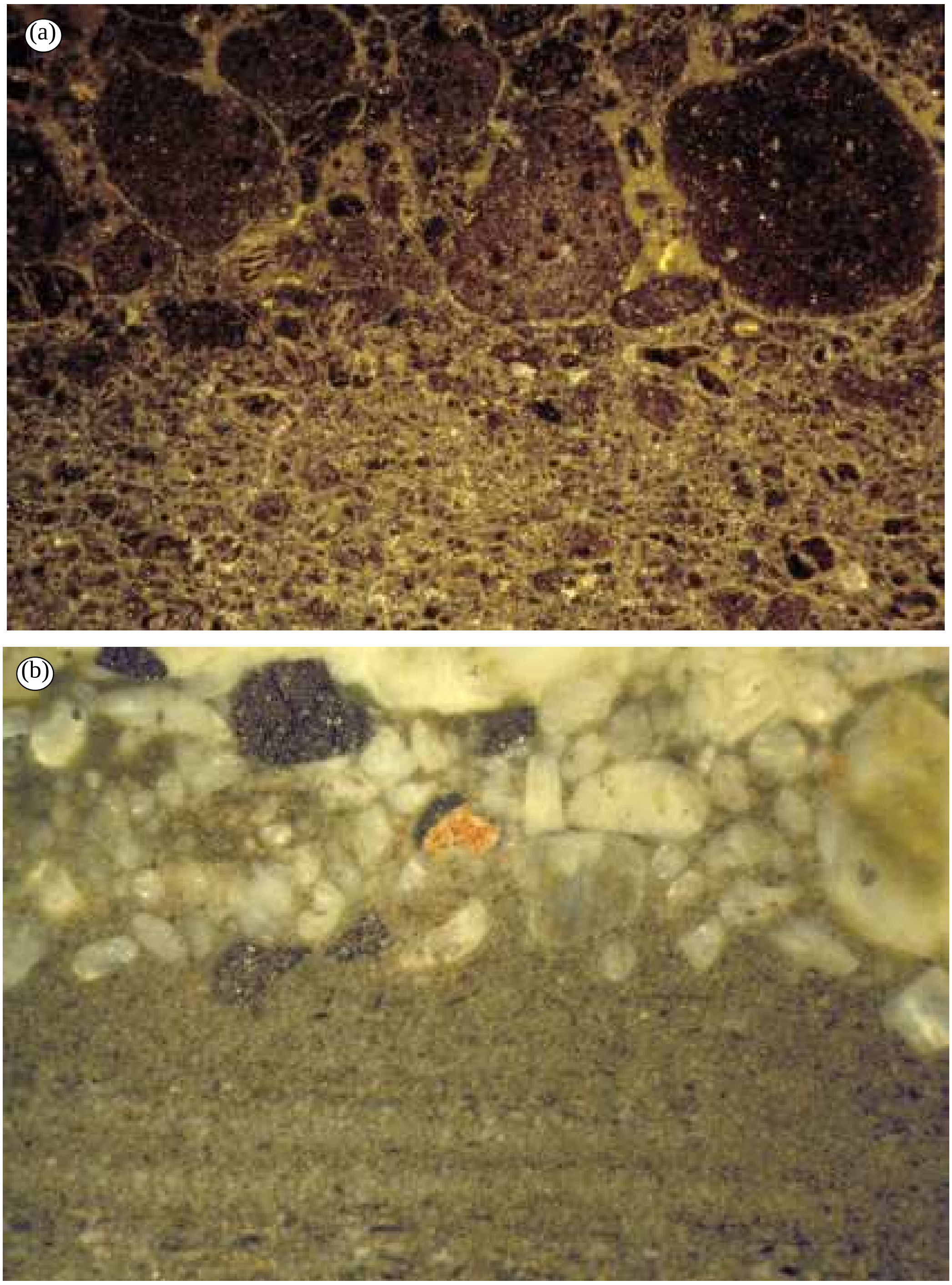

Fig.12. Well-sorted kimberlite. A wide range of clast sizes include common ash. The good sorting and retention of fines indicates deposition into water. The two samples from the same body illustrates two main phases of kimberlite, each dominated by either juvenile lapilli (a) or discrete olivines (b). These phases are separated by a sharp contact as shown in Fig. 15b. Each plate includes the contact between two horizontal normally graded beds, M+CK overlies VVF-VFK. The latter ash-sized clasts are not common in the FALC kimberlites. (**a**) Sample 169-7-25. 190.5 m. Polished slab. Field of view = 13 mm. The juvenile lapilli in the CK are composed of a number of F olivines set in a dark fine grained groundmass. Some clasts have a horizontal orientation (**b**) Sample 169-6-76. 172.5 m. Polished slab. Field of view = 13 mm. The CK is composed of olivine macrocrysts together with other macrocryst phases of ilmenite and garnet. The laminated VVF-VFK is composed mainly of olivine phenocrysts (<0.5 mm). Horizontally oriented, discrete phlogopite laths are common and are associated with olivine phenocrysts at least twice the size. Also, the former melt that originally hosted the discrete olivines is not represented in the rock.

sorting occurred because not all eruptions would have produced VVF-VF-F pyroclasts. The size of the pyroclasts resulted from not only the size of the entrained crystals and xenoliths but also the magma disruption process. For example, in areas where molding is present, it is likely that the deposits were formed by lava spatter type processes in which fine pyroclastic particles may not have formed. However, in other cases it is known that fine pyroclasts were formed on eruption (e.g. Fig. 12a).

Additional pyroclastic sorting is indicated by other constituents such as discrete mica grains and certain xenoliths. The phlogopite grains that were present in some, but not all, erupting kimberlites are typically 2-3 mm in size. When such phlogopite occurs as discrete grains in a graded bed, they are associated with smaller olivines, ~1 mm or less in size (Fig. 12b), presumably representing different hydraulic equivalents. The dominant VC constituents at FALC are xenoliths (Fig. 14) which can be sub-divided into two main types based on whether they were resident in the kimberlite magma prior to eruption. Firstly, the kimberlite-transported xenoliths (basement + Paleozoics) behaved as pyroclasts during eruption and were sorted and deposited with the coarsest olivine and juvenile lapilli (Figs. 8a, 13a, 14). Secondly, the Lower Colorado sediment xenoliths which were never incorporated into the kimberlite magma, are associated with any grain size, most notably the finer rocks, e.g. VF+FPKshaleB as shown in Fig. 11. These features support the suggestion above that the shale xenoliths were derived from the crater walls.

It is important to note that the clast type can vary with the clast size. As discussed in Clast Size and Shape above, the clast size of discrete grains and xenoliths reflects the size of that constituent in the magma prior to eruption: 1-15 cm for kimberlite transported xenoliths (basement and carbonates; Figs. 8a, 13a, 14), 1-4 cm for megacrysts (Fig. 4), 0.5-10 mm for macrocrysts of olivine, garnet and

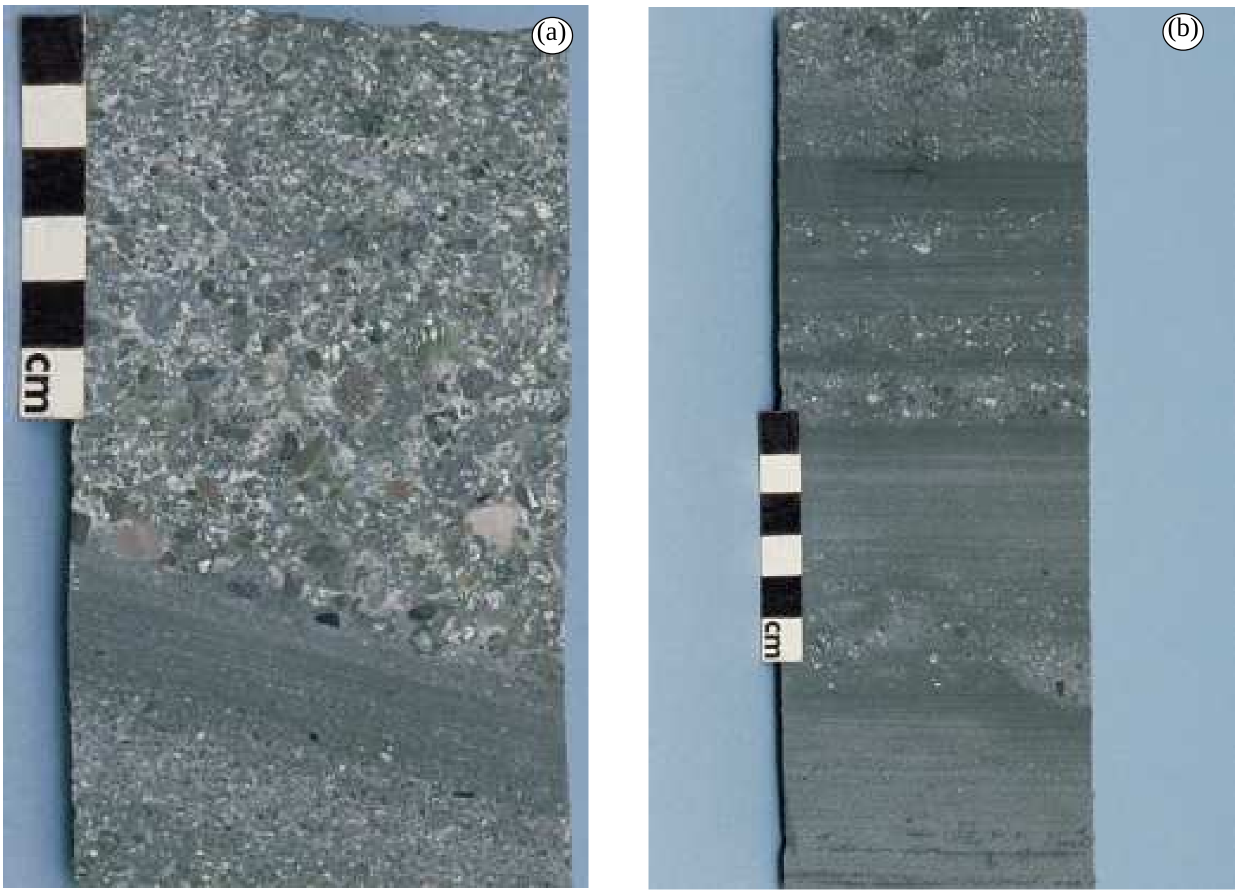

Fig.13. Well defined, plane parallel bedded finer grained samples. Fine grained kimberlites form a minor part of the FALC bodies but provide superior illustrations of bedding. The good sorting and retention of fines indicate deposition into water. See Table 2a for summary log. (**a**) Sample 118-3-7. 121.3 m. Polished slab. The boundary between the two beds is shallow dipping. (**b**) Sample 118-3-78. 123.8 m. Polished slab. Horizontally laminated to very thinly bedded VVF-VFK and FK, respectively. The thickness of the bedding varies with clast size. One possible scour is present (bottom right).

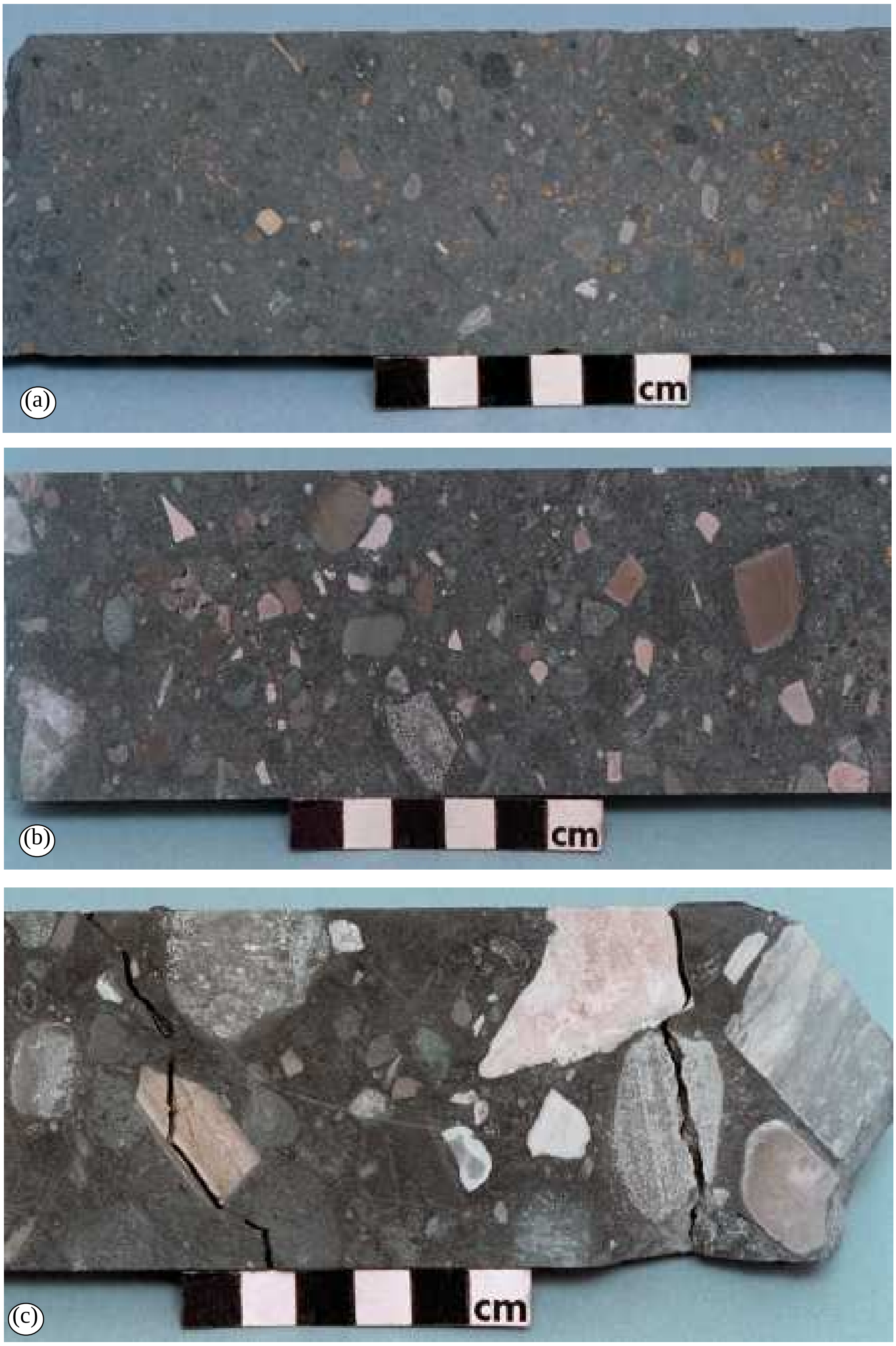

Fig. 14. Samples from a single 12 m normally graded bed where conspicuous pale coloured Paleozoic carbonate xenoliths indicate the clast size variation. Note the angular shapes of most xenoliths and the rare more rounded basement. This bed derives from the deepest drillcore well below the Cretaceous sediments in the country rock thus the carbonate xenoliths may not be kimberlite transported (cf. Fig. 2). This bed of pyroclastic kimberlite occurs within the likely feeder vent. The dark host kimberlite is composed of a few F-M olivines and juvenile lapilli (not discernible). The latter become more common and larger with depth within the bed. Polished slabs. (**a**) Sample 181-1-46. 413.1 m. (**b**) Sample 181-1-47. 418.9 m. (**c**) Sample 181-1-48. 424.3 m.

ilmenite (Fig. 12b), <2-3 mm for phlogopite (Fig. 12b), <0.5 mm for olivine phenocrysts (Fig. 12b) and <0.2 mm for groundmass grains. Thus, different drillcore intersections or samples resulting from the sorting of the ***same*** phase of kimberlite can be composed of varied constituents. For example, (i) VVF-VFK olivine phenocrysts and (ii) CKB composed of olivine, garnet and ilmenite macrocrysts together with kimberlite-transported xenoliths. Rock types (i) and (ii) can occur in the top and bottom of small graded beds (e.g. 118-3, 119-2, Tables 2a and c respectively) or in the top and bottom of the mega-graded bed as in 140-5 (Table 2d). Thus, the differences often used to differentiate phases of kimberlite must be used with caution (Multiple Phases of Kimberlite, below).

Structure

Most of the FALC rocks have loosely-packed and clast-supported textures (Figs. 3a, 6). As noted in the section above, most rocks have undergone some, and usually significant, sorting. Some drillcores are not bedded (e.g. 175; 219 in Table 2e; 226). The clast sizes of massive kimberlite vary from VF+FK to M+CK. Other drillcores display well developed bedding reflecting sorting (Figs. 12-14). Most beds are <2 m thick (cf. Fig. 5 in Scott Smith et al. 1996), but range up to 12 m (Fig. 14). Most of the bedding is plane parallel (Figs. 11, 13; Fig. 10 of Jellicoe et al. 1998). Sedimentary structures such as cross bedding and scouring are virtually absent (rare example in Fig. 13b). Probable impact and bomb sag structures were observed suggesting deposition through gravity. Single beds can be sharply bounded (Figs. 12, 13). Normal grading is common, frequently from CK to FK (Figs. 12, 13a, 14). Similar sorting and bedding occurs in both the juvenile lapilli PK as well as the olivine PK (Fig. 12). Reverse graded bedding is rare or absent. Using terminology of Fisher and Schmincke (1984), thinly laminated (<0.3 cm) to thickly bedded (<1 m) intersections are present, and sometimes dominate (e.g. Tables 2a and c). Very thick beds (>1 m) up to 12 m are more common (Fig. 14), for example in bodies 101, 118, 145, 152 and 181. Bedding dips vary from horizontal (Figs. 12a, 13b) to 80°. Most bedding has dips of less than 45º, commonly <30º (Fig. 13b). Steep bedding may reflect post-depositional movement. Some disturbed bedding including minor faulting is present (cf. Fig. 6 of Scott Smith, 1995b) and tends to occur in the deeper earlier crater infill (Table 2c).

Beds thicker than ~12 m were also identified. In body 140-141 the ultra-thick normally mega-graded bed (CKB to VFK) was identified in five different drillholes in body 140-141 (140-1, -2, -3, -4 and -5 and 141-1; summary log for 140-5 in Table 2c; and in Berryman et al. 2004 see Fig. 4 for hole locations and Figs. 7 and 8 for polished slabs and thin sections of 140-5). Such a mega-graded bed must represent continuous, massive, large-volume deposition with little or no hiatuses from a single eruption event, a suggestion supported by the determined ages of 99.5 and 99.8 Ma (*see* Age; the sample from 140 derives from the top of mega-graded bed and 141 from just below the mega-graded bed). The bed is variable in thickness in the five holes, ranging up to at least 100 m in thickness towards the centre of the body (Table 2d, 140-5). The upper finer (<2 mm) material is much better sorted than the deeper coarser kimberlite. The distinctive basal CKB, which is dominated by partly-digested kimberlite-transported basement and less Paleozoic carbonates xenoliths, can be mapped across much of the large body. The location of the CKB roughly mirrors the shape of the crater indicating that it must be an intra-crater pyroclastic deposit. The identification of this bed was an important line of evidence to suggest that the two distinct geophysical anomalies 140 and 141 represented a single body (Main Kimberlite Body Shape and Size, above).

The mega-graded bed appears to be unique in the geological record. Elsewhere in the world pyroclastic beds greater than 10 m in thickness are unusual although examples up to 30 m are known (R.A.F. Cas and J.V. Wright, *pers. comm*.). Subsequent drilling confirms that the bed is a widespread feature in the body and has shown that it ranges in thicknesses up to at least 130 m (Berryman et al. 2004). Both the initial and subsequent drillholes show that the thickness and overall clast size of the mega-graded bed increases with proximity to the proposed vent area. There is also a strong correlation in macrodiamond content in terms of stones per tonne with depth and proximity to the vent within the mega-graded bed (Berryman et al. 2004). The diamond data thus provide strong support for the occurrence of the geologically exceptional mega-graded bed. A second mega-graded bed (>40 m) is probably present in body 148. In addition, lateral fining away from postulated vents within single phases of kimberlite is apparent in other bodies in addition to 140-141, three holes in 120 and two holes in 118 (Tables 2a, b).

The widespread and sometimes thick normal grading as well as overall plane parallel bedding indicate deposition by primary pyroclastic processes. The lack of sedimentary structures supports the suggestion of mainly subaerial eruption and deposition with no subsequent reworking. VVF-VF-sized constituents are overall in low abundance at FALC and apparently lost through wind winnowing type processes. In a few instances fine clasts are concentrated in beds associated with more typical F+M+CK. These VVF-VF beds are commonly thinly bedded reflecting good sorting and retention of fines (Figs. 12, 13). The absence of sedimentary structures such as cross bedding suggests that deposition into small volumes of standing water which must be short-lived crater lakes (e.g. 118, Figs. 12, 13). Very rare examples of cross bedding (e.g. 117 m in 226-1) may represent minor ephemeral flow down a crater wall (Walker, 1993).

As noted above, the kimberlite-transported basement and Paleozoic xenoliths are pyroclastically sorted and occur within the coarser kimberlites. In contrast, the Cretaceous shales were clearly not part of this sorting process as they occur in kimberlites of all grain sizes. For example, the shale xenoliths occur in the sorted and bedded intersections where 10 cm shale xenoliths can occur within 10 cm thick beds of FK (Fig. 11). Also, shale xenoliths can be abundant in one bed and absent in the adjacent beds. The shale xenoliths, therefore, were incorporated into the kimberlite by a separate process such as crater wall failure.

Multiple Phases of Eruption

Each of the twenty-four bodies investigated is composed of different kimberlite with respect to proportions of the main and minor constituents described above, as well as in the degree of sorting and bedding (Table 2). For example, different bodies appear to be composed of (i) massive M-CK (e.g. 219, Table 2e), (ii) very thickly bedded F-CK (e.g. part of 169, Table 1 of Scott Smith and Berryman, 2007), (iii) thickly bedded VVF-CK (e.g. 118, Tables 2a-b), (iv) thinly bedded and laminated FK (e.g. 119, Table 2c) and (v) mega-graded beds (e.g. 140-141, Table 2d). Different bodies also have different juvenile lapilli, xenolith, autolith or ilmenite/garnet contents (e.g. garnet and ilmenite are abundant, common or rare in 219, 118 and 119 respectively, Tables 2e, a+b, c).

As in most kimberlite pipes, distinct separate pulses of magma or phases of kimberlite have been identified within single bodies. The emplacement of discrete pulses of magma with different mantle-derived characteristics is consistent with the lack of involvement of a magma chamber during ascent. Features used to characterise each pulse of magma include the nature of the macrocrysts and phenocrysts of olivine and phlogopite, the juvenile lapilli, the kimberlite-transported xenoliths and the mantle-derived xenocrysts other than olivine (e.g. Table 2c). Additional features reflect differences in the style of eruption and final deposition of each pulse of kimberlite, such as the ratio of juvenile lapilli to discrete olivines (Figs. 12 and 15a), clast sizes, proportion and nature of autoliths, changes in nature of the bedding (Table 2c, Fig. 15a), as well as the occurrence of some sharp internal contacts (Fig. 15). The interclast material is not usually useful as it is a post-depositional cement which can vary within one phase of kimberlite or be similar in adjacent phases. Based on these criteria, contrasting phases of kimberlite were identified in many of the FALC bodies (e.g. Figs. 1c-d and Fig. 4 of Leckie et al. 1997a). The sub-division of a similar drillcore from Sturgeon Lake 02 is presented in a graphic log in Fig. 3 of Scott Smith (1995b). The abundance of many constituents must be used with caution as they can also vary substantially as a result of sorting within a single phase of kimberlite (see end of Clast Sorting, above).

The compositions of the mantle-derived minerals were used to confirm proposed phases of kimberlite identified during logging. For example, the one drillcore from body 119 is composed of two logged phases of kimberlite: an upper plane parallel bedded F-MK and a deeper F-MK with disturbed bedding (Table 2c). Samples of the upper phase yielded abundant garnet, chromite and high MgO (>8 wt%) ilmenites including some grains with high Cr_2O_3 contents up to 4.5 wt%. In contrast, the deeper kimberlite contains only rare garnet, chromite and low MgO (<6 wt%) ilmenites with rare grains containing high Cr_2O_3 (>1.5 wt%). Conversely, the similarity in composition of ilmenites derived from 3 samples collected through the mega-graded bed intersection in one drillcore in body 140-141 (140-4) confirmed the suggestion that the bed derives from a single eruption and represents a single phase of kimberlite (Structure, above; Berryman et al. 2004). Other lines of evidence support proposed phases such as micro- and macrodiamond sampling (Economic Implications, below) and geophysics (e.g. Mwenifumbo and Kjarsgaard, 1999).

The identification of different phases of kimberlite in many bodies shows that the FALC craters were infilled by (i) major eruptions forming massive or unstratified deposits (e.g. Table 2e), (ii) major eruptions resulting in deposits that display some internal variation (e.g. graded bedding on different scales; e.g. Tables 2a-b, <243.6 m in d), or (iii) numerous commonly smaller diverse eruptions (Tables 2c, >243.6 m in Table 2d). The occurrence of distinct phases of kimberlite, sharp internal contacts (Fig. 15) and autoliths (Fig. 10) show that little or no reworking occurred and that most phases of kimberlite were deposited and cemented prior to the next eruption. The absence of reworked kimberlite, soil or sediments at the internal contacts shows each phase of kimberlite was deposited shortly after the excavation of a nested crater within previously-consolidated kimberlite. A few examples of mixed types of juvenile lapilli and rare

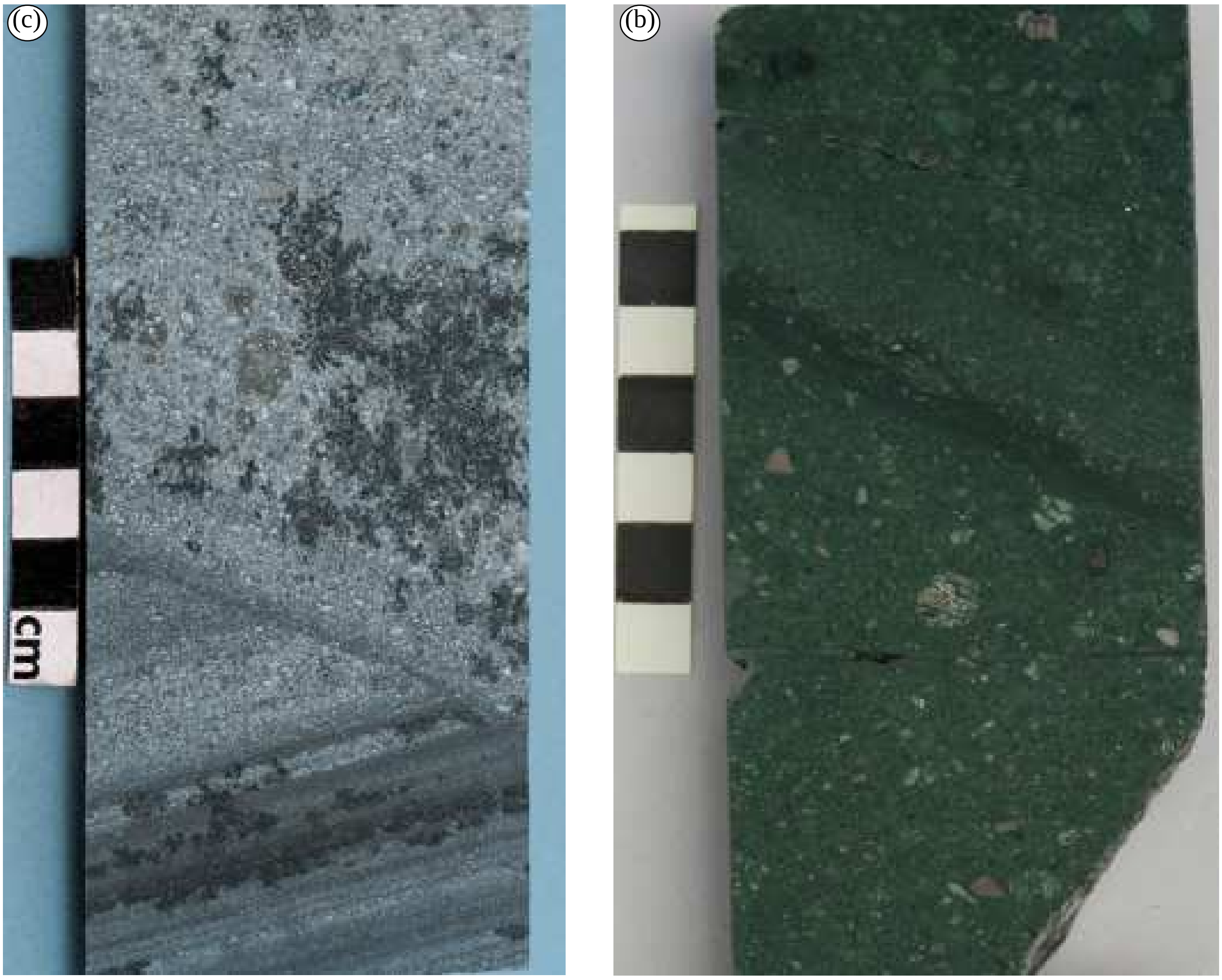

Fig.15. Sharp internal contacts. (**a**) Sample 604-1-8. 110.3 m. Polished slab. This cross-cutting contact dips at 20º. There is an obvious change in grain size and bedding. The upper kimberlite is uniform and composed of three types of juvenile lapilli. Mica is present (see Fig. 7a for composite lapilli from nearby). The deeper kimberlite is laminated VVF-VF-FK with bedding that dips at ~15º. The constituents include no mica and one of the three types of juvenile lapilli observed in the overlying kimberlite. Irregular patches of secondary magnetite are present. Below the contact they are smaller and concentrated along bedding planes. (**b**) Sample 169-12-133. 217.6 m. Polished slab. Less obvious 20º sharp contact between an upper loosely-packed juvenile lapilli PK (as Fig. 12a) and a deeper olivine PK (as Fig. 12b). The deeper kimberlite contains more common xenoliths of basement and carbonates as well as mantle-derived xenocrysts compared to the overlying phase.

composite lapilli (Fig. 7a) show that mixed or gradational contacts are possible (as described by Webb et al. 2004) but none have been identified during this investigation.

The generally low number of drillholes per body examined during this investigation limits the determination of the distribution of the identified phases of kimberlite within each body. Among the bodies examined there appear to be examples with both simple and complex histories. The main central areas of any body are composed of one or a few dominant phases of kimberlite (e.g. 174, 219 in Table 2e, 140-141 in Table 2c or Berryman et al. 2004). The results of this investigation provided a preliminary indication that the different phases of kimberlite could occur as nested craters (Fig. 18e). Near the margins of the craters, however, there can be many small intersections of contrasting phases (e.g. >243.6 m in Table 2d). These appear to be volumetrically limited remnants of early crater infill. Another example occurs below one main phase of F-M-CK which dominated three drillcores from body 120 where the deepest <25 m of kimberlite in each hole is composed of a different much coarser grained phase of kimberlite, CK, which contains abundant chrome diopside, an unusual feature at FALC. This unit occurs just above the country rock contact and thus has a similar shape consistent with the suggestion that this phase of kimberlite was deposited into a previously excavated crater.

NEAR SURFACE EMPLACEMENT PROCESSES

The FALC bodies, as with most kimberlites, are intra-continental small-volume, point-source volcanoes formed from mantle-derived magmas that have not stagnated in magma chambers. Most bodies have formed from a number of discrete eruptions.

Crater Formation

Most of the main craters occur immediately below the glacial overburden showing that they must be younger than the uppermost sediments in the adjacent country rock. Thus, the FALC craters formed during, or after, the Joli Fou (Fig. 2) which is consistent with the radiometric ages of 94-101 Ma of the infill (Age, above). Kimberlite 169, one of the oldest bodies, is overlain by Westgate Formation (Fig. 2; Kjarsgaard et al. 1995). The main bodies represent subaerial, explosively excavated, shallow volcanic craters (Main Kimberlite Body Shape and Size, above). The high diameter/depth ratios of the bodies probably reflects the poorly-consolidated nature of the host Cretaceous sediments. The overall absence of country rock xenoliths shows that little of the resulting material was deposited back into the craters. The products of the crater excavation process were deposited outside the crater. The nature of the extra-crater deposits provide direct evidence for the formation processes but none have been encountered because of the location of the drilling and the lack of preservation.

Many of the main FALC bodies flare from the base of the Mannville where a porous sandstone forms a well known aquifer. The coincidence of the flaring with an aquifer as well as the crater size and shapes, is comparable to phreatomagmatic maar craters. These empirical observations provide the only evidence for the crater excavation processes. Kimberlite magmas, however, are rich in both water and carbon dioxide. Juvenile gases could have had an equally major affect on the crater formation. The development of deeper pipes appears to be rare. The one deeper pipe contains bedded pyroclastic material to the maximum depth of the drilling (375 m). Feeders are presumed to be narrow.

Crater Infill

Although each FALC body is distinct (Table 2), many common features must reflect similar overall processes. The craters were rapidly infilled predominantly with partly-bedded, xenolith-poor pyroclastic kimberlite (PK) composed of juvenile lapilli and discrete olivines which formed during subaerial magmatic eruptions and were deposited mainly by primary pyroclastic processes. The crater infill was not formed by phreatomagmatic eruptions as indicated by the lack of fines, xenolithic material, accretionary lapilli, blocky-shaped juvenile lapilli, dominant thin bedding with low angle cross beds and erosive bases. There is no evidence for any passive effusive eruptions to form magmatic rocks such as lava lakes or flows. Such eruptions may have been prevented by high crystal contents, degassing causing freezing and magma disruption induced by narrow vents and high exit velocities of very low viscosity magmas. Crystal contents of >40% in basalts are generally thought to retard eruption. There is no evidence for submarine eruption or deposition.

Features which support the pyroclastic activity being subaerial include: the occurrence of fluidal lapilli shapes, molding, vesicular lapilli, poor sorting of a wide range of clast sizes and a general lack of fines comprising kimberlite ash and/or shale. Degraded plant fragments and other non-marine material were among found sparse organic remains in similar rocks from Sturgeon Lake 01 (Scott Smith et al. 1996). The notable feature of the palynology and micropaleontology studies of the main kimberlite in 169-8 was the lack of organic material (Kjarsgaard et al. 1995; Leckie et al. 1997).

Many features show that resedimentation of the pyroclastic material was not important. These features include: the low particle density (Fig. 6b); consistent nature of the juvenile lapilli within rocks or intersections (Figs. 6c-d, Tables 2a-b, e); the presence of occasional molding of plastic lapilli; the occurrence of composite lapilli (Fig. 7a) showing that mixed lapilli populations result from recycling not resedimentation; the presence of different phases of eruption (Tables 2c-d) with marker horizons and sharp internal contacts (Fig. 15); the significant lack of abrasion or breakage of most and commonly fragile juvenile (Figs. 4, 6b-d), xenolithic (Figs. 11, 14) and rare but even more fragile organic clasts; evidence of large scale sorting resulting in the overall paucity of ash (Fig. 6a) and the presence of mega-graded beds (Table 2d; Berryman et al. 2004); the nature and distribution of the xenoliths (Fig. 11); the lack of cross bedding and other sedimentary features (Fig. 13); *in situ* impact-fragmented xenolithic bombs and the overall lack of incorporation of crater wall material. Some of these features also show that the pyroclastic deposition processes other than by gravity from an eruption column (fall) were not important in forming the observed kimberlites. Flow and surge deposits would be limited by the negative relief of the craters which are less than 1-2 km in diameter. Extra-crater deposits would have formed and could have been different from the crater infill. Such deposits, however, have a low probability of preservation especially in this regressive-transgressive environment. The surface relief of the intra-crater deposits is not known but they could have formed positive features such as scoria cone-like deposits but again are likely to have been eroded. There is also a possibility of eruptive products from one volcanic centre depositing within a crater or over the crater infill of a separate volcanic centre.

Variations in the nature of the pyroclastic deposits indicates a range in style of eruption. The relatively non-explosive eruptions are most comparable with lower viscosity basalts rather than viscous siliceous magmas. The least explosive eruptions appear to have varied from fines-poor Hawaiian-style lava spatter with minor molding to higher lava fountains resulting in poorly stratified near vent deposits. Higher eruption plumes most comparable to Strombolian-type eruptions which formed volumetrically more extensive and better stratified deposits with thicker bedding (up to 12 m thick) and the removal of fines by wind action. Lateral fining within the crater also occurred. The thicker beds may be a result of even higher eruption plumes perhaps relating to the faster ascent of low viscosity volatile-rich magmas derived directly from the mantle and high exit velocities from narrow feeders. The high specific gravity of the discrete grains and vesicle-poor Mg-rich juvenile lapilli (~3 gm/cc) may have restricted lateral dispersion and resulted in greater deposition into the crater. Well defined bedding also resulted from a series of closely related discrete eruptions separated by distinct breaks. Bedding was enhanced in some instances by the retention of fines and better sorting resulting from deposition into crater lakes (e.g. 118, Tables 2a-b). There is no evidence for extensive or long-lived crater lakes infilled with lacustrine sediments as found at Orapa in Botswana (Field et al. 1997) which supports the proposed rapid infilling of the craters.

The occurrence of repeated large volumes of olivine PK are unusual. It appears that the physical separation of the high specific gravity crystals from very low viscosity magmas during eruption was responsible for their formation. Other processes could have enhanced the separation. Kimberlites, being some of the most crystal-rich and fluidal erupting magmas, are good candidates for the formation of such olivine PK. The host former melt was removed as wind blown ash. Some olivine PK formed exceptional mega-graded beds. Presumably, higher eruption columns were involved but with limited lateral transport and greater deposition back into the crater. This suggests that there was no wind action, a process otherwise considered to be common across FALC. Fisher and Schmincke (1984) note that the presence of carbon dioxide may limit the height of an eruption column and cause it to collapse, which together with the high specific gravity of the pyroclasts could have inhibited movement of the pyroclastic material from the vent so resulting in formation of the geologically exceptional mega-graded beds within the craters. Such eruption styles may be unique to kimberlites reflecting their unusual magma properties. Water, such as a crater lake, could also limit dispersion of the pyroclasts but better sorting and laminations in the VVF-VF material would be expected.

Significant carbon dioxide and water contents would have had a major affect on eruption processes. Juvenile water is probably present in the common groundmass serpentine. Primary carbonate occurs as laths and cryptocrystalline bases within the juvenile lapilli (Figs. 5b, 7b) in some, but not all, bodies (e.g. contrast 118 in Tables 2a-b with 119 in Table 2c). Cryptocrystalline carbonate located near juvenile lapilli margins (Fig. 7c) possibly indicates degassing at the time of solidification. In other cases the magmas either contained little or no carbon dioxide or had degassed prior to, or during, formation of the pyroclasts given the high diffusivity of carbon dioxide in such magmas (Juvenile Lapilli in Dominant Constituents, above).

The size of juvenile pyroclasts is largely controlled by the mineral grains and xenoliths resident in the magma with sizes defined by pre-eruption processes. Kimberlite-transported xenoliths (<15 cm) behaved as pyroclasts during eruption, sorting and deposition and occasionally formed pyroclastic marker horizons such as the base to the mega-graded bed. The Cretaceous sediment xenoliths which were not resident in the kimberlite magma can be much larger (up to 13 m) and must have formed by failure of crater wall material or perhaps vent erosion.

The interclast cement formed through the crystallisation of minerals from upward percolating kimberlitic fluids derived from subsequent eruptions. Multiple and sequential phases of cementation show that lithification occurred during the infilling of the craters and thus occurred shortly after deposition preventing extensive pyroclastic mixing, resedimentation, erosion and/or weathering.

The main crater infilling events appear to have occurred over at least 7 Ma. (Age, above). The formation of each body was probably a very short-lived event, possibly in the order of days, months up to several years and unlikely >1 Ma. Composite bodies may have been longer-lived volcanic centres. The subaerial crater excavation and infilling process must have occurred during periods of regression of the Western Interior seaway. Given that magma generation processes in the mantle were unrelated to the Interior Seaway, kimberlite volcanism probably occurred throughout this period. Transgressions and submarine eruptions are likely to have occurred. If so, they probably did not form craters of any size and any submarine volcaniclastic deposits are unlikely to be preserved.

Comparison to Other Localities

The FALC bodies are clearly different from the southern African kimberlite pipes and thus do not conform to the 'classic' kimberlite pipe model (Hawthorne, 1975; Clement, 1982; Clement and Reid, 1989; Field et al. 1997). Carrot-shaped pipes contain common tuffisitic kimberlite breccia composed of unsorted completely-serpentinised olivines and abundant locally-derived xenoliths which are coated with very thin selvages of magmatic material set in a serpentine-like matrix which contains microlitic grains. There is a remarkable similarity, however, in both the geological setting and the nature of the kimberlite pipes at FALC and Mbuji-Maya in Democratic Republic of the Congo (Meyer de Stadelhofen, 1963; Demaiffe et al. 1991). The Mbuji Maya bodies have plan view diameters up to 1700 m in diameter and depths up to 100-200 m (excluding the feeder). The country rocks comprise Proterozoic carbonates overlain by 50-200 m of poorly-consolidated Upper Cretaceous sandstones. The kimberlites are similar in age to the sediments (<95 Ma, Bardet, 1977; 71.3 Ma, Davis, 1977). The crater-like bodies appear to be infilled with bedded crater-facies material. The similarities suggest that near surface geology, e.g. competent versus incompetent, has an important affect on pipe formation (Field and Scott Smith, 1999). Somewhat similar pyroclastic deposits occur in diamondiferous lamproites such as Prairie Creek, Arkansas and Majhgawan, India (Scott Smith, 1992; Scott Smith and Skinner, 1984; Scott Smith, 2007). Effusive eruption products such as found in lamproites (Scott Smith, 1992), interestingly, have not been found at FALC.

Certain maars also seem to be comparable. For example, the <20,000 year old Tower Hill maar within the Newer Volcanics Province in Victoria, Australia (Figs. 13.13-13.16 in Cas and Wright, 1987; Nicholls and Joyce, 1989) which is a 3.2 km diameter crater with scalloped plan view shape possibly representing three cross-cutting craters. Tower Hill is unusual compared to many maars in that the crater was partly infilled with a nested scoria cone complex, up to 80 m high, that form islands towards the centre of the crater lake. The scoria cones are dark grey Hawaiian and diffusely bedded Strombolian deposits composed of loosely-packed, clast-supported juvenile lapilli (<1-2 cm; fragments of former melt). Ash and xenoliths are not common. These deposits show many similarities to the FALC pyroclastic crater-infill. The material resulting from crater excavation formed crater rim deposits of typical phreatomagmatic base surge material: light coloured, thinly and cross bedded, ash-rich fine grained material containing accretionary lapilli (Figs. 7.4, 13.23 in Cas and Wright, 1987). Such deposits have not been observed at FALC. If the FALC craters were formed by similar phreatomagmatic processes similar deposits may have formed in now-eroded crater rims.

ECONOMIC IMPLICATIONS

The early identification of the large FALC bodies as macrocrystic kimberlites with the potential to contain economic quantities of diamonds showed that further exploration work was warranted. This investigation formed part of that work. Shortly after discovery, this study showed the FALC bodies were different from previously documented kimberlites both in shape and the nature of the infill. The kimberlite geology, therefore, was very important because applying predictive geology based on knowledge obtained from other types of kimberlite bodies would have been misleading. Given the ~100 m of overburden (Fig. 2), investigation of these bodies is limited to drillholes. The overall fresh nature of the drillcores provided high degrees of confidence in the observations and, in turn, the interpretations. The lack of secondary alteration of the drillcore reflects (i) the young age (Age, above), (ii) the paucity of fines (Clast Sorting, above) and rapid cementation (Interclast Material, above), (iii) the presence of common carbonate in both the pyroclasts (Juvenile Lapilli, above) and the interclast material (Interclast Material, above), (iv) the impermeable nature of the adjacent country rocks (Geological Setting, above), and (v) the rapid burial by shale and subsequent glacial material limiting their exposure to surface processes (Geological Setting, above).

The proposed shallow bowl-like body shapes based on very limited drilling were supported by the absence of tuffisitic- or hypabyssal-kimberlites (Textural Classification, above) and the apparent control by the country rock geology. The kimberlite drillcore geology was used to further delineate single bodies within large, or between adjacent, geophysical anomalies (Main Kimberlite Body and Shape, above). The limits of the pipe, and thus ore reserves, were reduced based on the interpretation that some kimberlite intersections form part of the country rock sediments and not the crater (Minor Kimberlites Overlying the Main Kimberlite, below). Resulting reasonable degrees of confidence in the pipe shapes allowed initial ore reserve estimates and early considerations of mining methods, very important given the substantial amounts of overburden.

The interpretation as crater-facies kimberlites indicated the potential for complex internal geology resulting from a spectrum of possible processes: submarine and/or subaerial primary pyroclastic and/or secondary reworking. The conclusion that the FALC kimberlites were subaerial primary pyroclastic deposits showed that a single overall emplacement model with a restricted number of processes and deposits was applicable to the whole FALC province. Higher confidence could then be placed on the geological models based on limited evaluation drilling. The low xenolith contents means dilution is not important. Most bodies are composed of significant volumes of a relatively small number of major phases that could be extrapolated between drillholes. Most of the identified phases of kimberlites appeared to be separated by sharp internal contacts allowing for more straightforward interpretation. This resulted in the definition of large volume units with more predictable continuity in diamond grades. Systematic changes that could affect macrodiamond grades were recognised within the single phase geologically exceptional mega-graded bed (Structure, above; Berryman et al. 2004). Subsequent evaluation of this body (62 core holes) resulted in the sub-division of the bed into an upper finer VF+FK (<2 mm) and a deeper coarser M+CK±B that were shown to have contrasting macrodiamond sample grades of 2.7 and 8.4 carats per hundred tonnes, respectively (29 RC holes; >1.5 mm). Contrasting sample grades of 4-9 and 18.6 carats per hundred tonnes supported two other proposed phases of kimberlite in this body.

Although the range of processes is limited as discussed above, variations in eruption style modify the grade of the erupting magma. The widespread loss of fines (<0.5 mm) requires caution in the determination of predicted macrodiamond grades based on microdiamond (<0.5 mm) recoveries. Juvenile lapilli-rich rocks are loosely-packed, effectively reducing the grade of the erupting kimberlite by the proportion of the rock that is now represented by interclast material. The latter can form up to half of rocks composed of elongate amoeboid lapilli (Figs. 6b-d). Presuming that diamond behaved as the discrete olivine grains with similar specific gravity, the macrodiamond grade of olivine PK should have been doubled by removal of 50% former melt. Most olivine PK is composed mainly of macrocrysts with the 25% olivine phenocrysts also having been removed by sorting. These rocks have lower proportions of interclast material because these grains are generally round in shape. The effective grades could be nearly four times that of the original magma. These types of interpretations are used, with caution, to prioritise evaluation work in this large province of bodies. Petrological-based interest ratings can also be applied. A small number of bodies, or parts of bodies, were formed from magmas that do not resemble typical kimberlites (Petrological Classification, above). Commonly with a lower mantle-derived component, they are less likely to be of economic interest.

MINOR KIMBERLITES WITHIN THE ADJACENT SEDIMENTS

As noted in General Nature of the Drillcores above, the drillcores are dominated by one main intersection of kimberlite that represents the main crater infill and is the subject of preceding sections. In addition, much smaller intersections of kimberlite (<10 m thick) occur within the sediments adjacent to the main kimberlites. These kimberlites are of limited economic interest and, although intriguing, were not examined in detail.

Minor Kimberlites Underlying the Main Bodies

Undisturbed Cretaceous country rock sediments were recovered from below the main crater-infill kimberlites (General Nature of the Drillcores, above; Table 2). In at least ten drillcores from seven bodies one to five small intersections of kimberlite 0.3 to 4.8 m, possibly up to 10 m, thick occur within the sediments up to 40 m below the main kimberlite (e.g. 180-180.6 m, 181.4-184.7 m and 214-214.55 m in 118-3 and 305.3-315.6 m in 140-5, Tables 2a and d; >249 m in 169-7 in Table 1b of Scott Smith and Berryman, 2007). As much as 31 m of the sediments can occur between the main crater and the uppermost intra-sediment kimberlite. In some cases sediments near the contact could be xenoliths within the main kimberlite rather than being in situ (e.g. 159.9-160.9 m in 119-2 and 300.5-305.3 m in 140-5, Table 2). These examples have not been included in this discussion.

The intra-sediment kimberlites were found mainly in the central cluster of kimberlites (between 169 and 140-141) with one example to the northeast of the province (604). Mainly Cantuar Formation sediments were recovered from below the main kimberlites and most of the intra-sediment kimberlites occur within this formation. The occasional kimberlite occurs within the limited amounts of black shales recovered. One bed was identified to occur in the Pense Formation of the upper Mannville (Christopher, 1993; hole 900-1 from 140 at ~170 m; hole location given in Fig. 4 of Berryman et al. 2004). Importantly, this bed appears to have replaced the McLaren Member of the Pense Formation (Fig. 2) showing that the kimberlite forms part of the sedimentary sequence (Christopher, 1993). Other

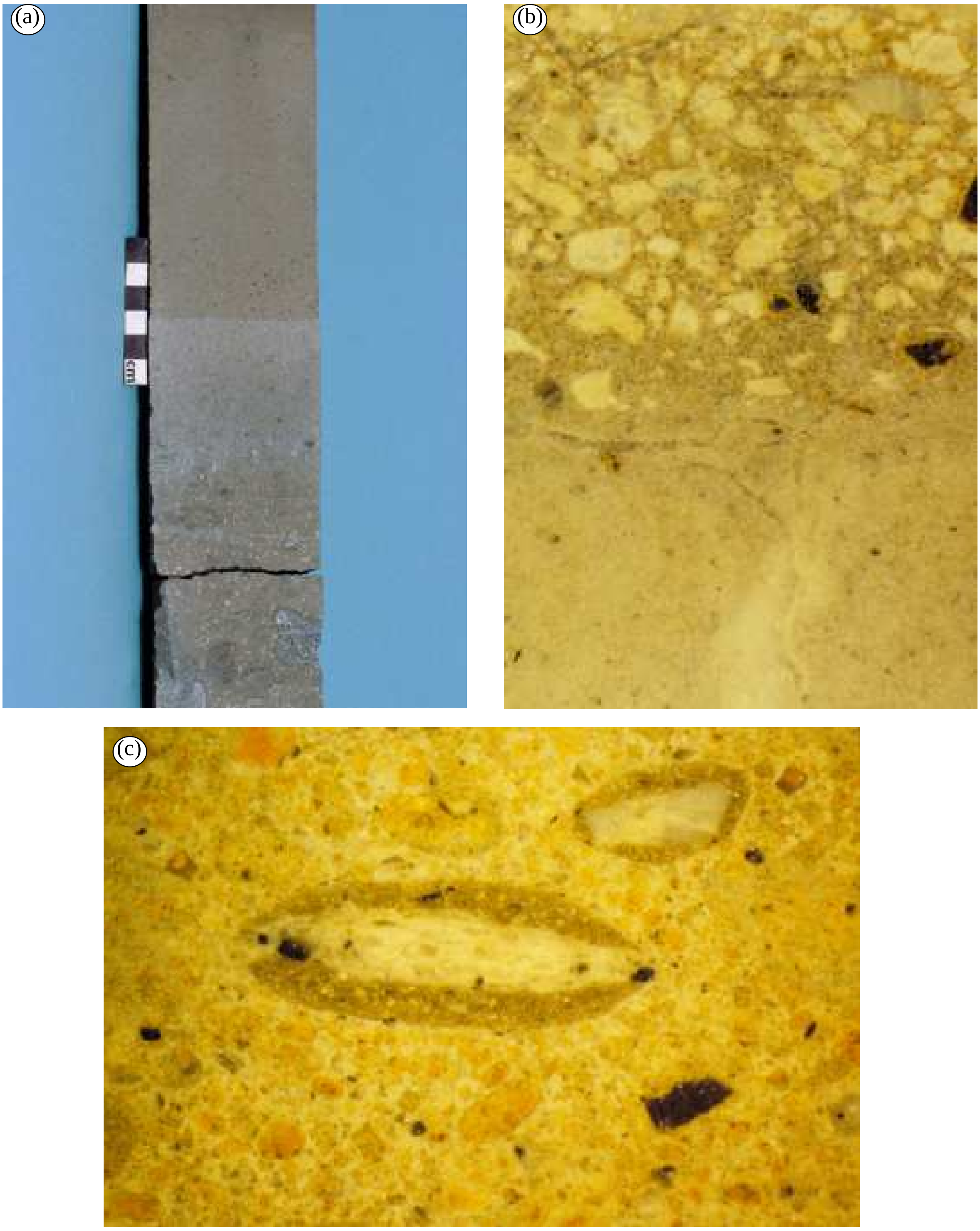

Fig.16. Intra-sediment kimberlites. (**a**) Sample 141-1-22. 185.8 m. Polished slab. A single graded bed forms the 0.6 m buff coloured carbonatised kimberlite. A few xenoliths occur in the bottom 10 cm. (**b**) Sample 169-7-40. 245.1 m. See Table 1 of Scott Smith and Berryman (2007) for summary log. Polished slab. Field of view = 13 mm. A horizontal sharp basal contact of an intra-sediment kimberlite and underlying Mannville sediments. Limited mixing, over <5 mm, has occurred between the single olivines and fine sand grains. This suggests quiet deposition, likely airfall, of the extrusive kimberlitic material onto unconsolidated sediments. (**c**) Sample 118-3-43. 214.5 m. See Table 2a for summary log. Polished slab. Field of view = 13 mm. Poorly-sorted kimberlite composed of discrete grains of pseudomorphed olivine. The presence of ovoid-shaped juvenile lapilli confirms an extrusive origin.

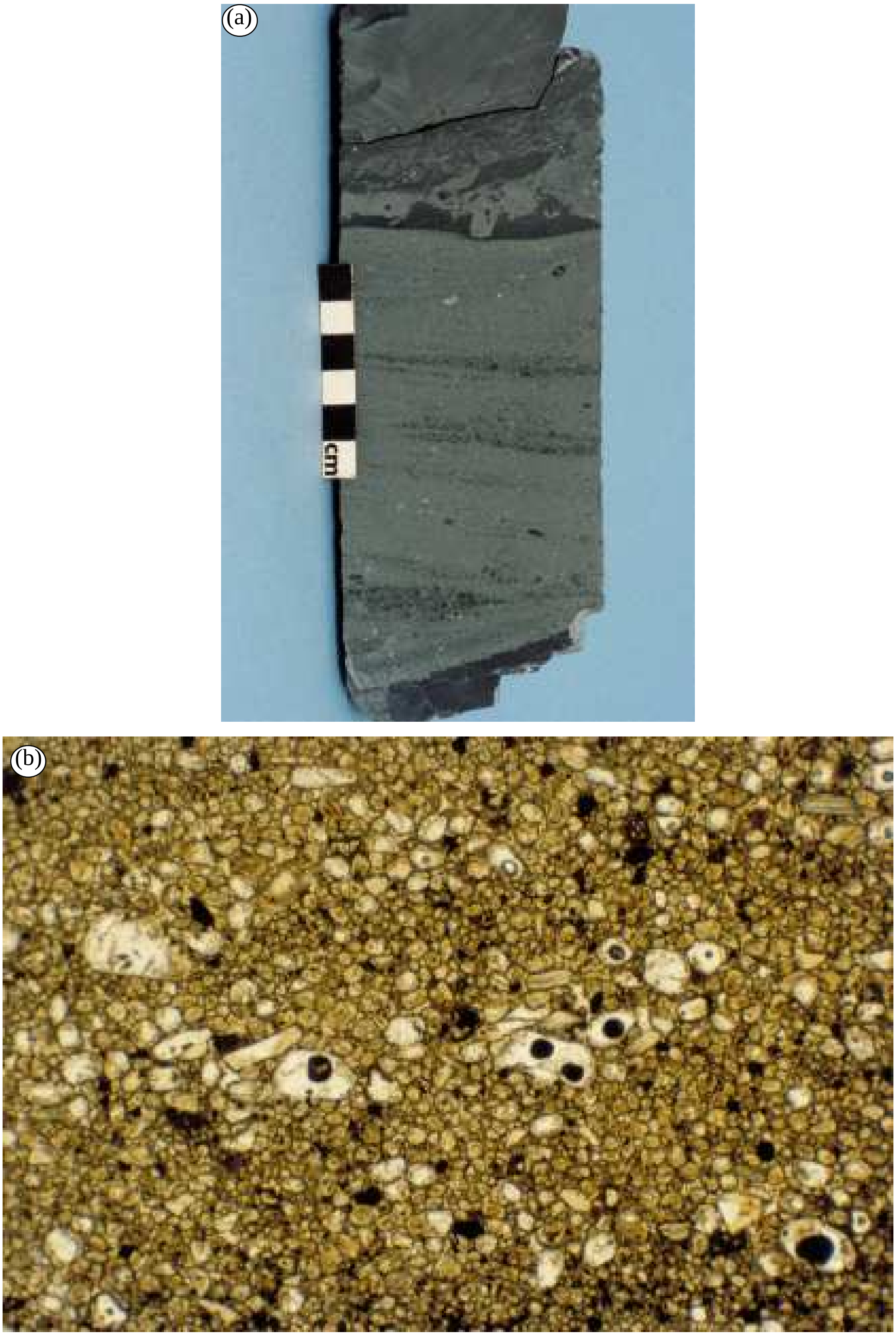

Fig.17. Resedimented kimberlites probably interbedded with shale overlie the main kimberlites in body 169; see Fig. 3 of Berryman et al. (2004) and Table 1 of Scott Smith and Berryman (2007) for summary log. These rocks are very different to the pyroclastic kimberlites forming the main kimberlites and must have formed by different processes. (**a**) Sample 169-7-8. 123.2 m. Polished slab. The well-sorted and cross bedded VFK contains shale both as discontinuous thin layers and as small blebs. (**b**) Sample 169-8-97. 152.75 m. Thin section. Plane polarised light. Field of view = 4 mm. Laminated VFK composed of closely-packed discrete olivines.

possibilities of intra-shale kimberlites include 180.0-180.6 m in 118-3 and 160.9-161.2 m in 119-2 (Tables 2a and c) which occur below shale that could not be confirmed as truly *in situ*.

These minor kimberlite intersections comprise single normally-graded beds of juvenile lapilli-bearing volcaniclastic kimberlites (Figs. 16a-b) which are different from the main kimberlites. They contain abundant fines and no interclast carbonate or serpentine, are commonly altered, and have frequent horizontal conformable contacts with the adjacent sediments. Rare steep upper and lower contacts (40-60°) can be separated by sediments containing vertical roots suggesting that the enclosing sediments are in situ. The presence of non-erosional concordant bases, the limited mixing between the kimberlite and the adjacent sediment (Fig. 16c), the lack of internal stratification and the absence of other sedimentary features (Fig. 16a) shows that these kimberlites have not been subjected to significant reworking. Walker (1993) determined that specific kimberlites within the Cantuar accumulated on subaerial dry vegetated floodplains or in swampy lakes. The sharp bases of each kimberlite suggests sudden emplacement which is consistent with pyroclastic deposition during ongoing sedimentation. The single intra-marine shale kimberlite (in 900-1) is a normally graded unit likely formed by primary pyroclastic processes and deposited below the storm wave base (Walker, 1993).

The time of deposition of each of the kimberlites in the Mannville could be determined using stratigraphy but this aspect was not examined in detail. The intra-sediment kimberlites, however, do occur at different depths from surface: 171, 175, 180, 183, 181-185, 182, 186, 187-192, 192, 214, 216, 239, 240, 250, 253, 259, 275 and possibly from 300 m (without adjusting for topographic differences between drillcore collars) which can be compared with the local stratigraphy presented in Fig. 2. The kimberlite from 187-192 m was identified as being within Pense Formation (Christopher, 1993). Palynology reported by Kjarsgaard et al. (1995) suggests that the sediments hosting some of these kimberlites include Middle Albian sediments (103-108 Ma; Fig. 2). Zonneveld et al. (2004) also show kimberlites as deep as the Lloydminster Member (Fig. 2). Thus, the intra-sediment kimberlites appear to have formed throughout most of the Cantuar and Pense Formations of the Mannville Group (~112-103 Ma), somewhere in the FALC province. Some examples could be both older (118-112 Ma) and younger.

The intra-sediment kimberlites are clearly not related to the main craters, and in essence, form part of the Mannville wall rock to the main craters. There is no evidence that these precursor kimberlite eruptions were associated with crater excavation. It seems most likely that they formed small, possibly cone-like, layers on the substrate at the time of eruption. The lateral extent of these kimberlites is not known but they may be limited. Large bodies would produce geophysical anomalies. It is not clear if the location of the precursors is related to the main kimberlites below which they occur or whether they may occur throughout FALC irrespective of where the later main craters formed.

Minor Kimberlites Overlying the Main Bodies

Relatively thin kimberlites were found to overlie the main crater in a few instances. Comparable deposits may occur over other bodies but were not recovered within the drillcore (Methods, above). These kimberlites are different from those described in Minor Kimberlite Underlying the Main Bodies above. Some of the overlying minor kimberlites are fine grained and display similar features to the main kimberlites and thus have the potential to be distal deposits from adjacent bodies. Other very different kimberlite is interbedded with shale (e.g. 169 as shown in Fig. 3 of Berryman et al. 2004 and <141.3 m in 169-6 in Table 2a of Scott Smith and Berryman, 2007; and upper ~10 m over 181). The thinly and cross bedded kimberlite is very fine grained (VFK) and composed of relatively well-sorted, closely-packed, discrete pseudomorphed olivine grains (Fig. 17; also Figs. 8d and 9 of Leckie et al. 1997a). Juvenile lapilli (olivine plus former melt) were not observed. Minor constituents include bivalve shells (one example identified as Mytilus typically shallow marine to intertidal from Jurassic to Recent, Kjarsgaard et al. 1995) and very small mudballs. The observed features are consistent with reworking during, or after, a transgression. In one hole, Kjarsgaard et al. (1995) show that palynology of the youngest sediments indicate that they are marine shales of the Westgate Formation. The contrasting nature of the reworked kimberlite associated with the shale was important to the investigation because it provided further confidence to the interpretation of the economically important main crater infill as primary pyroclastic deposits.

CONCLUSIONS

The Cretaceous Fort à la Corne province is one of the largest in the world, with at least seventy well preserved bodies ranging up to 200 hectares in size. Most bodies comprise typical archetypal kimberlites composed of olivine macrocrysts and phenocrysts set in a fine grained groundmass, but some marginal varieties occur. Except for Sturgeon Lake, the FALC kimberlites are texturally different

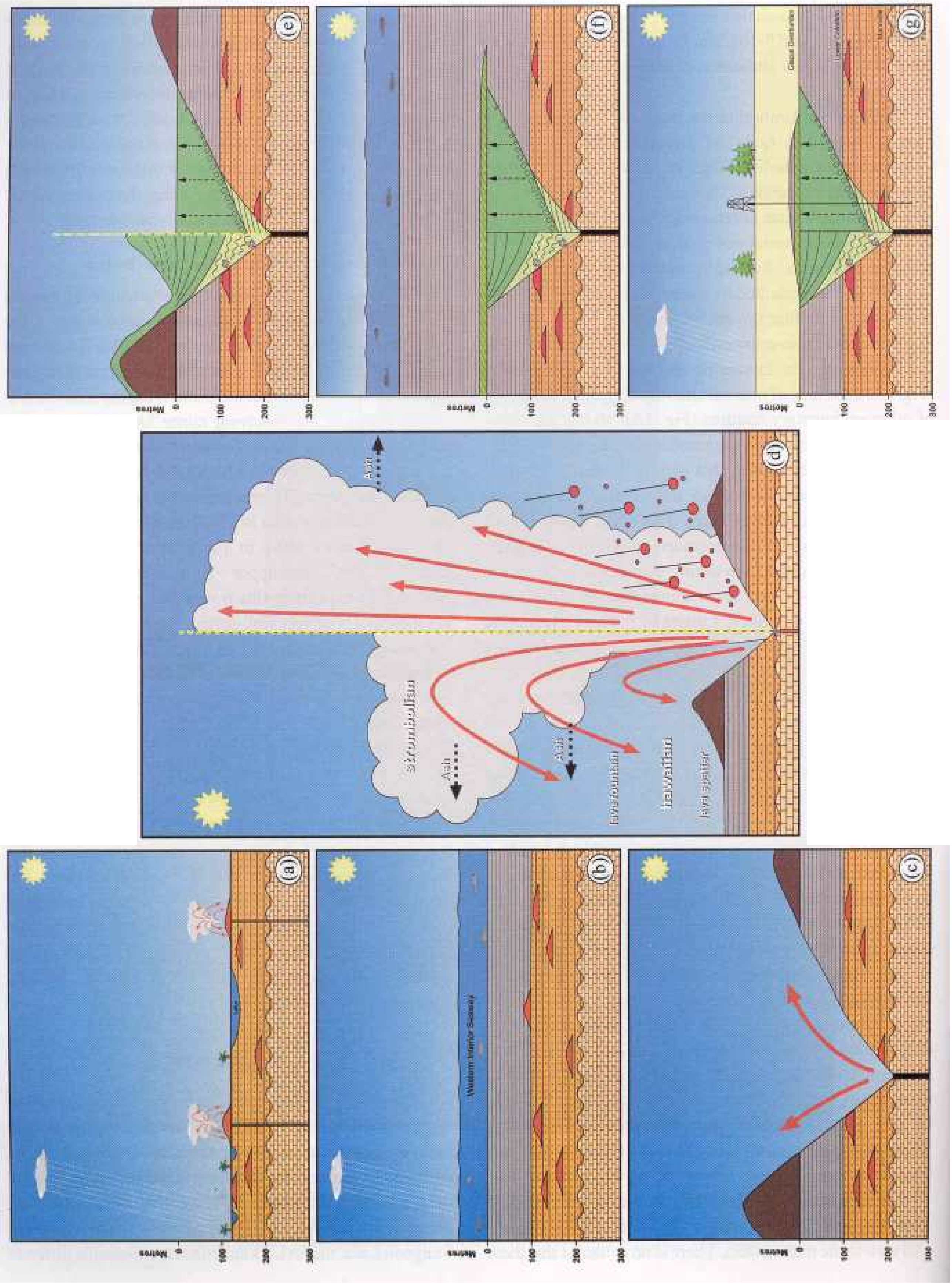
(a)
(b)
(c)
(d)
(e)
(f)
(g)
Strombolian
Hawaiian
lava fountain
lava spatter
Ash
Metres
0
100
200
300

Fig. 18. Emplacement Model for the Fort à la Corne Kimberlites (slightly modified from oral/poster figures of Scott Smith et al. 1994, 1998, respectively). The FALC kimberlites formed by the eruption of many discrete pulses of mantle-derived (>150 km) kimberlite magmas over at least 20 Ma. The magmas mostly underwent rapid ascent to surface without the involvement of magma chambers and erupted from narrow feeder vents. Most preserved kimberlites erupted in subaerial conditions during periods of low sea level. The formation of each main body was probably a short-lived overall event, probably less than a few years and unlikely >1 Ma.. Depths on left hand side: 0 meters is the present day sub-glacial bedrock surface, ~100 m below the present day surface. Country rock: brick symbol = indurated Paleozoic carbonates, fine dots = basal poorly-consolidated sandstone of the Cretaceous Mannville sediments, alternating solid and dashed lines = main Mannville variably-consolidated clay-rich mudstones and siltstones, solid lines = Lower Colorado variably-consolidated marine shale. Stratigraphy from Fig. 2. Sea levels and approximate ages from Fig. 3 of Kauffman and Caldwell (1993). (**a**) During the Cantuar Formation of the Mannville (~112 to >103 Ma) varied sediments were deposited in subaerial flood plain and/or lacustrine environments over the eroded surface of the indurated Paleozoic carbonates. Throughout this time kimberlites erupted in variable environments across the FALC province and formed thin (<10 m) deposits as conformable beds. Single short-lived pyroclastic eruptions probably formed low relief pyroclastic cones. The narrow feeders likely did not survive. (**b**) Transgressions of the Western Interior Seaway deposited ~100 m of black marine shales during the Pense (Upper Mannville) and the Joli Fou (± Viking) of the Lower Colorado (approximately >103 to <98.5 Ma). Small cone-like deposits comparable to (a) continued to form, presumably in marine conditions, during at least the Pense, and possibly into the Lower Colorado. (**c**) Explosive eruptions resulted in complete crater excavation during subaerial conditions after a marine regression, apparently starting at >101 Ma, or 103 Ma if the more recently discovered Star pipe is included. Craters formed at different locations across the province for at least ~9 Ma. Most craters (except Star) are post Joli Fou and cut into Joli Fou sediments. The material that originally formed the area of the crater was deposited in extra-crater deposits. The crater rim deposits were not preserved, limiting the evidence for crater excavation processes. Phreatomagmatic processes could have been involved given that the craters typically flare from the base of the Cretaceous sediments where there is a known sandstone aquifer. The crater shape shown here is for a small steeper sided body (selected only to facilitate compact figures). Other bodies are larger with overall shallower dipping contacts. The craters can be asymmetric and include changes of crater wall slope, perhaps with changes in country rock type. The precursor kimberlites within the Mannville effectively form a volumetrically minor part of the country rock at the time of the crater formation. (**d**) Varied styles of magmatic eruptions rapidly infilled the crater by mainly passive primary pyroclastic processes. Common eruption styles, as depicted on the left hand side, ranged from Hawaiian-style lava spatter and lava fountains that formed poorly bedded juvenile lapilli-rich deposits to Strombolian-style eruptions that formed better bedded deposits. In many eruptions the olivine grains separated from the magma to form olivine PK. Any ash was commonly removed by wind winnowing processes and deposited outside the crater. In rare instances, deposition into short-lived crater lakes resulted in better retention of fines and well defined bedding (not shown). Unusual eruptions, possibly more explosive and associated with massive degassing, formed mega-graded beds of olivine PK as shown on the right hand side of the figure. The presence of abundant carbon dioxide and high specific gravity of the pyroclasts may have limited development of the eruption column and resulted in significant deposition back into the crater. Variations in styles of eruption would have reflected differences in factors such as volatile content, rate of supply of magma, discharge rates, exit velocities, viscosity and vent size. Figure not to scale. (**e**) The craters rapidly infilled with the products of a number of eruptions. Different types of crater infills resulted from the contrasting eruption styles shown in (d). Continuous eruption from one phase of kimberlite formed uniform deposits as 219 in Table 2e (not shown here). A series of discrete eruptions from a single phase of kimberlite produced bedded sequences of similar material (as 118-4 in Table 2b). Eruptions from different phases of kimberlite resulted in a sequence of contrasting deposits (pale pink then dark pink). For example, as shown on the left hand side, early bedded deposits were deformed prior to the deposition of later overlying undisturbed bedded material from a subsequent phase of kimberlite (cf. 119-2 in Table 2c). Variable amounts of Lower Colorado shale xenoliths were incorporated by crater wall and/or rim collapse. In rare instances the shale xenoliths are large, especially where there were steeper crater walls, as shown here within the deeper deformed deposits on the left hand side. The crater infill may have had positive relief. In contrast as shown on the right hand side of the figure, a single large eruption resulted in the deposition, over previous crater infill, of a mega-graded bed (arrows indicate upward fining; cf. 140-5 in Table 2d). The basal breccia formed a widespread pyroclastic marker horizon. Fining away from the vent as shown in the basal breccia could occur in other types of deposits (cf. 118-3 and 04 in Tables 2a-b). Cementation by crystallisation from the upward percolation of kimberlitic fluids resulted in consolidation shortly after deposition. Sequential eruptions excavated nested craters into previous consolidated infill to produce sharp internal contacts and sometimes extensions to the crater. Other eruptions formed cross-cutting or coalesced craters not shown here. Pyroclastic material was also deposited outside the crater. (**f**) Westgate (just prior to ~98.5 Ma.) and Upper Cretaceous (>98.5 Ma. possibly to ~70 Ma.) marine transgressions reworked (green) and eroded any positive relief kimberlite deposits and then buried the body under marine shales. (**g**) Subaerial and glacial erosion re-exposed the craters, probably close to the surface at the time of emplacement. Sub-glacial positive relief is limited (cf. Fig. 3 in Berryman et al. 2004). The kimberlites were overlain by ~100 m of glacial material (pale yellow).

from previously documented bodies requiring the development of new models. Applying predictive geology during evaluation based on knowledge obtained from other kimberlites would have been misleading.

The main FALC bodies are formed by a two stage process: (i) excavation of wide shallow craters into poorly-consolidated Cretaceous sediments, and (ii) crater infilling by subaerial magmatic pyroclastic processes during regressions of the Western Interior Seaway. Pre-crater small conformable intra-Mannville kimberlites appear to have formed over at least ~10 Ma (minimum ~112-103 Ma). The main craters formed over at least the subsequent ~10 Ma (~103-94 Ma). This shows that kimberlite volcanism at FALC spanned at least 20 Ma. An emplacement model for the FALC kimberlite province is proposed in Fig. 18. The model has been an important foundation of the ongoing evaluation and includes the first recognition in kimberlites of eruption styles varying from Hawaiian and Strombolian-styles to a kimberlite-specific eruption which formed geologically exceptional mega-graded beds. These, and other unusual features, reflect the different properties of kimberlite magmas. Confidence in the shape and nature of the bodies allowed early consideration of ore reserve estimates and mining methods. Although the craters were relatively shallow, the potential ore reserves are large. It was also shown that well constrained external and internal models could be developed on limited drillcore, especially important given that kimberlites under 100 m of overburden, while maintaining a high degree of confidence.

The crater infill is partly bedded, xenolith-poor, poorly-sorted, clast-supported pyroclastic kimberlite composed of variable mixtures of juvenile lapilli (olivine plus former melt) and discrete olivine grains (no former melt). The contrasting nature and fluidal shapes of the juvenile lapilli compared to other magma types such as basalts indicate that the FALC magmas had very low viscosities. The effective and widespread separation of crystals from the very low viscosity melts resulted in discrete olivine grains forming approximately half of the pyroclasts across the province. Rock types range from juvenile lapilli PK through intermediate mixtures to unusually extensive olivine PK. The size of the pyroclasts is largely defined by the mineral grains and xenoliths resident in the magma prior to eruption. Ash and coarse ash is not common and, in many instances, was removed by a province-wide sorting process, probably wind winnowing from eruption columns. This, and other eruption and deposition processes, modified the macro-diamond content of the erupting magma from half to nearly four times the original grade. These variations, together with petrological interest ratings, were used to prioritize evaluation work within this large province. Each of the twenty-four bodies investigated is different. Each body, however, is dominated by a few volumetrically significant phases of kimberlite separated by sharp internal contacts. Each new eruptive phase forms a nested crater within previously cemented kimberlite. Continuity of diamond grade can be predicted within most phases of kimberlite while large scale systematic changes within single phases that affect diamond grade were identified.

The FALC province lacks diatremes, root zones, dykes and significant volumes of resedimented material. The contrast in geology supports, rather than negates, the ‘classic’ kimberlite pipe and emplacement models (Hawthorne, 1975; Clement, 1982; Clement and Reid, 1989). The Fort à la Corne mode of emplacement (Fig. 18), therefore, comprises a second style of eruption or model which is applicable to kimberlites. Field and Scott Smith (1999) suggested that near surface country rock geology may have an important effect on kimberlite emplacement processes, the Prairies kimberlite all being emplaced into poorly-consolidated sediments that lack any igneous rocks. As suggested by Scott Smith (1995b), all kimberlites subsequently discovered in the Prairies are broadly similar to the FALC bodies investigated here. The FALC kimberlite emplacement is comparable to localities such as Tower Hill in the Newer Volcanics of southern Australia.

OTHER WORK

In the area of FALC and Sturgeon Lake, the similarity in age of the kimberlites to sub-glacial Cretaceous sediments which formed in generally overall marine conditions, led to a number of suggestions that the kimberlites were submarine (e.g. Gent, 1992; Nixon et al. 1993; Strnad, 1993; Aaron Oil Corp. Annual Report, 1993; Mining Journal, 1993; and more recently Lefebvre and Kurszlaukis, 2006). Many features show that the kimberlites are subaerial magmatic eruptions including the fact that each volcanic centre is unique which shows that the FALC kimberlites cannot represent a very large beach or blanket deposit. Nixon et al. (1993) proposed that the Sturgeon Lake kimberlites are widespread, horizontal, thin sheet-like extra-crater volcanic surge deposits of phreatomagmatic origin. The Sturgeon Lake kimberlites are glacial mega-blocks (Scott Smith, 1995b; Scott Smith et al. 1996).

Kjarsgaard (1996a, b), Leckie et al. (1997a) and Kjarsgaard et al. (2007) proposed a positive-relief volcanic-tephra-cone model for FALC body 169. As stated by Scott Smith et al. (1998) and Scott Smith and Berryman (2007), the evidence presented for the geometry of the FALC bodies, including 169 (Fig. 3 of Berryman et al. 2004), contradicts tephra cone-like models. Scott Smith (in press) presents a compilation of the ten available FALC kimberlite shapes, all of which are shallow-bowl crater-like shapes (schematically summarised in Fig. 18e). The FALC crater infill, however, may have originally included positive relief deposits (schematically shown in left hand side of Fig. 18e). The main kimberlite crater-infill was peneplaned before, or during, the deposition of the overlying shale in one or more marine transgressions (schematically shown in Figs. 18e, f). The peneplaning resulted in some reworking of the uppermost crater infill of pyroclastic kimberlite into one or more relatively thin layers of contrasting kimberlite (Fig. 17) interbedded with Lower Colorado Group shale (shown to be Westgate Member in FALC body 169, Fig. 2; see Minor Kimberlites Overlying the Main Bodies, above). This is consistent with the fact that positive relief volcanic material, whether associated with an underlying crater or not, has little chance of preservation, especially given the cyclic transgressive-regressive environment. Also, exposed volcaniclastic deposits are very susceptible to weathering for which there is little evidence at FALC. The observed sub-glacial positive relief of some of the kimberlite bodies is an erosional remnant formed during the ~100 Ma unconformity between the bedrock and the overlying Quaternary overburden (schematically shown in Fig. 18g). The volcanic-tephra-cones are proposed to have formed contemporaneously with the adjacent country rock that comprise diverse sediments deposited in variable environments (Geological Setting, above). Additional contradictory evidence includes the lack of inter-layered or mixed kimberlite and sediment within the *main* kimberlites (Table 2), the deposition of subaerial pyroclastic kimberlite at stratigraphic levels/times with marine conditions, the occurrence of vertically extensive (>100 m; Tables 2d, e) single phases of rapidly deposited pyroclastic kimberlite. The mega-graded bed (Table 2d) occurs at depths equivalent to both the Joli Fou and Mannville and the 99-100 Ma age of the mega-graded bed and adjacent underlying kimberlite (Structure, above) correlates with the age of the youngest country rock sediments (Fig. 2).

The presence of craters is also clearly indicated by the presence of xenoliths of the uppermost country rock, the Lower Colorado marine shale, in the kimberlite well below their stratigraphic levels (see Lower Colorado Xenoliths; more detailed discussion in Scott Smith and Berryman, 2007; schematically shown on left hand side in Fig. 18e). The proposed tephra cones would have formed before the deposition of the shales from which the xenoliths were derived. Another key feature in the interpretation of the FALC geology is that the minor kimberlites within the country rock sediments are separate volumetrically-minor units that either precede (Figs. 18a, b) or post-date the main crater infill (Minor Kimberlite within the Adjacent Sediments, above). Further evidence which supports the rapid infilling and consolidation of craters, rather than the development of volcanic cones contemporaneous with sedimentation, includes the occurrence of phases of kimberlite with geometries mirroring the crater-shape best shown by the distinctive basal breccia of the mega-graded bed (schematically shown on right hand side in Fig. 18e), the occurrence of nested craters (Multiple Phases of Eruption, above; schematically shown on left hand side in Fig. 18e) and the lack of sediment at internal contacts between different phases of kimberlite (Table 2, Fig. 15).

Crater excavation and subsequent infill are also the conclusions of recent work on particular FALC kimberlites (Berryman et al. 2004 for body 140/141; Fig. 10 of Zonneveld et al. 2004 for the more recently discovered Star; Lefebvre and Kurszlaukis, 2006 for body 147; Pittari et al. 2006 for body 219; Hetman, 2007 for Candle Lake C28, north of FALC as shown in Fig. 1). A number of other aspects of some of these studies are noteworthy. Additional evidence for vertically extensive single phases of kimberlite within the main bodies at depths equivalent to both the Joli Fou and Mannville show that they must have formed after the Joli Fou (e.g. Tables 2d, e; Table 1 of Scott Smith and Berryman, 2007). The presence of mega-graded beds is supported by the recognition of a comparable >40 m bed Diavik, Lac de Gras, NWT (Graham et al. 1999; Moss and Russell, 2006). Another example of a vertically extensive single phase of kimberlite is shown in Fig. 4 of Pittari et al. (2006) in body 219. Hetman (2007) not only shows two vertically extensive single phases of kimberlite in Candle Lake C28, but also shows that these two phases are nested craters comparable with those reported by Webb et al. (2004) for Victor in Ontario. Nested craters cannot form in tephra cones. In addition, Lefebvre and Kurszlaukis (2006) identified large blocks of Mannville sediments at high levels within the main kimberlite of body 147 (confirmed by this author). These Mannville blocks occur well above (~60 m) their stratigraphic level in the adjacent country rock and must have been explosively ejected from deeper parts of a crater as suggested by Lefebvre and Kurszlaukis (2006).

Most of the other Canadian occurrences of pyroclastic kimberlites similar to FALC occur within pipes which are clearly excavated into basement as well as overlying but commonly-now-eroded sediments. The occurrences include

Victor (Webb et al. 2004), some other bodies in the Attawapiskat Province, Ontario (Kong et al. 1999), many Lac de Gras bodies, NWT in the central Slave (Moss and Russell, 2006; Scott Smith, 2006) and at a number of localities in Nunavut in the northern Slave (e.g. Jericho and Knife Lake; Scott Smith, 2006).

Similar arguments to those discussed above negate the proposal that the FALC main kimberlites represent stacked, temporally distinct, horizontal pancake-shaped, layers of pyroclastic kimberlite (Jellicoe et al. 1998 - Fig. 11; Kaiser, 2004). Zonneveld et al. (2002), Kjarsgaard (2002) and Harvey et al. (2003) then propose a stack of kimberlites of different stratigraphic ages in combined crater and low relief tephra cones.

Not coincidently, all kimberlites subsequently discovered in the Prairies are broadly similar to FALC. These include Candle Lake north of FALC (Mitchell, 1997; Field and Scott Smith, 1999; Hetman, 2007), and in Alberta, Mountain Lake (Wood et al. 1998; Leckie et al. 1997b), Buffalo Hills (Carlson et al. 1999; Boyer et al. 2003) and Birch Mountains (Eccles et al. 2004). Leckie et al. (1997b) proposed a tephra cone model for the Mountain Lake pipes, which was negated by Wood et al. (1998) using similar evidence to that discussed above. This supports the suggestion of Scott Smith (1995b) that any kimberlite erupting in this type of country rock under similar near surface conditions would form texturally similar kimberlites and that different modes of formation are most likely to be reflection of contrasting country rocks (Field and Scott Smith, 1999).

The Star kimberlite was discovered by Shore Gold Inc. in 1996 at the southwestern extremity of the FALC province. Leroux (2005) reports that this body is >225 hectares or >2 km in diameter. The main features for Star are similar to other FALC bodies. Substantial amounts of drilling have shown that the Star kimberlites have a similar shallow bowl-shape (Fig. 5 in Leroux, 2005; Shore Gold Inc. website; Zonneveld et al. 2004). A wide peripheral zone comprises thicknesses of <50 m of kimberlite (central zone is <1 km diameter). Zonneveld et al. (2004) document similar minor intra-Mannville kimberlites to those described above and a similar emplacement model of nested craters for two late Joli Fou phases of pyroclastic kimberlites. Interestingly, Star differs from many FALC bodies in that it is buried deeper in the Lower Colorado sediments which shows that it is one of the oldest kimberlites, confirmed by the ages of ~103 Ma reported by Zonneveld et al. (2004). Two samples, 200 m and 566.3 m from surface, from one deep drillcore gave model ages of 103.0±1 Ma and 102.8± 0.8 Ma, respectively (U-Pb perovskite, Zonneveld et al. 2004) confirming that this narrow feeder vent is composed of a single phase of kimberlite. It is vertically extensive single phases of kimberlites such as this, that negate any stacked crater/ pancake model as discussed above but rather shows the presence of nested craters.

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