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and Associated Processes

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Volcanology of the Aries micaceous kimberlite, central Kimberley Basin, Western Australia

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Abstract

The Neoproterozoic (815.4 ± 4.3 Ma) Aries kimberlite intrudes the King Leopold Sandstone and the Carson Volcanics in the central Kimberley Basin, northern Western Australia. Aries is comprised of a N–NNE-trending series of three diatremes and associated hypabyssal kimberlite dykes and plugs. The diatremes are volumetrically dominated by massive, clast-supported, accidental lithic-rich kimberlite breccias that were intruded by hypabyssal macrocrystic phlogopite kimberlite dykes and plugs with variably uniform- to globular segregationary-textured groundmasses. Lower-diatreme facies, accidental lithic-rich breccias probably formed through fall-back of debris into the vent with a major contribution from the collapse of the vent walls. These massive breccias are overlain by a sequence of bedded volcanoclastic breccias in the upper part of the north lobe diatreme. Abundant, poorly vesicular to nonvesicular, juvenile kimberlite ash and lapilli, with morphologies that are indicative of phreatomagmatic fragmentation processes, occur in a reversely graded volcanoclastic kimberlite breccia unit at the base of this sequence. This unit and overlying bedded accidental lithic-rich breccias are interpreted to be sediment gravity-flow deposits (including possible debris flows) derived from the collapse of the crater walls and/or tephra ring deposits that surrounded the crater. Diatreme-forming eruptions may have been initiated by magma–water interactions along fracture and joint-controlled aquifers within the King Leopold Sandstone. The current level of exposure of the diatremes probably extends from the lower-diatreme facies up into the base of a bedded upper-diatreme sequence.

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Keywords: kimberlite; diatreme; pipe; phreatomagmatism; debris flow; erosion

1. Introduction

The Aries kimberlite was emplaced in the central Kimberley Basin, northern Western Australia, at approximately 815.4 ± 4.3 Ma (Figs. 1 and 2; Ar–Ar on phlogopite, weighted mean, 95% confidence, $n=15$; P. Downes, unpubl. data), and comprises a N–NNE-

trending series of three steep-sided diatremes and associated hypabyssal kimberlite dykes and plugs. Aries is a micaceous kimberlite that has close mineralogical affinities to group 2 kimberlites (orangeites) and olivine lamproites (Edwards et al., 1992). However, trace element and isotope geochemistry—notably a Nd–Sr isotopic signature that suggests an asthenospheric source similar to that of group 1 kimberlites—indicates that it is petrogenetically distinct from these two groups of rocks (Edwards et al., 1992; Taylor et al., 1994). On the basis of

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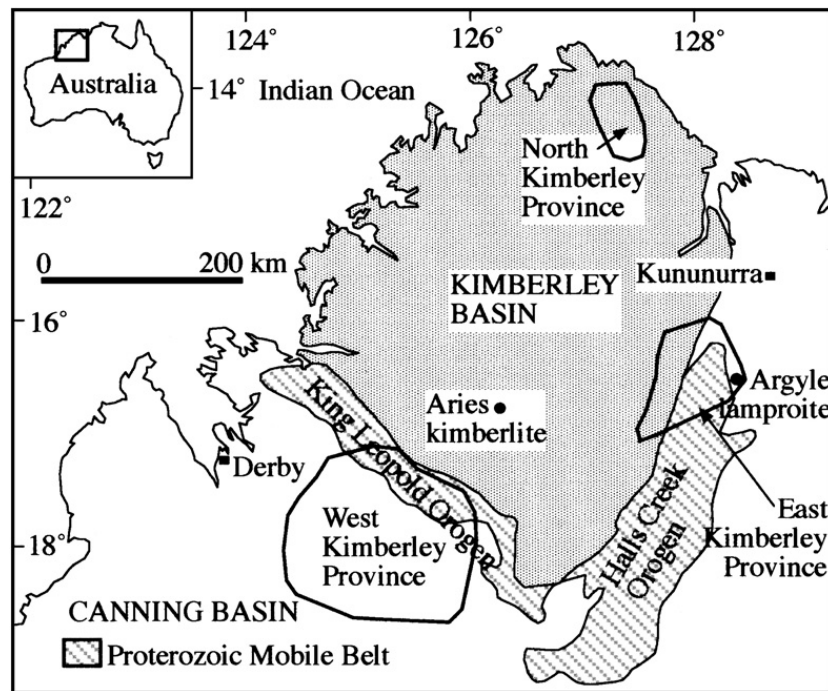


Fig. 1. Map showing the location of the Aries kimberlite and the north, east and west Kimberley kimberlite-lamproite provinces in the Kimberley region of Western Australia.

limited diamond drillcore information, [Edwards et al. \(1992\)](#) and [Towie et al. \(1994\)](#) interpreted the exposed volcanoclastic and hypabyssal rocks to have formed within the root zones of the diatremes. Exploration drilling has now produced over 7000 m of diamond drillcore, sampling each of the kimberlite lobes and penetrating to a maximum depth of over 300 m below the present surface. This new data makes Aries one of the best-exposed kimberlite occurrences in Australia and enables the first detailed reconstruction of the volcanology of the diatremes. Detailed facies analysis of diatreme deposits assists in determining the level within the volcanic system that is exposed at the current land surface for a given kimberlite pipe. This is of interest to diamond explorers in evaluating the economic potential of a pipe. Such studies also have had broad implications for understanding the landscape evolution, neotectonics and three-dimensional stratigraphy of an area in basaltic diatreme fields, e.g. the Waipata Volcanic Field, New Zealand ([Nemeth, 2003](#); [Nemeth and White, 2003](#)).

The Aries kimberlite is an example where the deeper levels of a maar-diatreme volcano have been revealed by extensive exploration drilling, as is often the case for diamondiferous kimberlites and lamproites. Studies of such diatreme facies rocks allow the evaluation of processes that may have been involved in diatreme development at these levels, and the documentation of relationships between lithofacies in both fragmental and

non-fragmental rocks. Diatreme fill in the Aries kimberlite is dominated by very coarse, massive, chaotic, clast-supported, accidental lithic-rich kimberlite breccias, that may represent an end-member style of diatreme fill for kimberlites and lamproites. A number of studies have illustrated the contrasting influences of fracture-controlled (e.g. [Aranda-Gomez and Luhr, 1996](#); [Nemeth et al., 2001](#)) versus porous media aquifers (e.g. [Boxer et al., 1989](#); [Smith and Lorenz, 1989](#)) on the morphology of maar-diatreme volcanoes and the facies characteristics of related volcanoclastic deposits. In the case of phreatomagmatism involving fracture-controlled aquifers (e.g. [Aranda-Gomez and Luhr, 1996](#); [Nemeth et al., 2001](#)), these studies were generally limited to tephra aprons surrounding the maar craters. However, studies focusing on diatreme facies rocks produced by eruptions involving fracture-controlled aquifers are less common. In this paper, we will evaluate the extent to which the morphology of the Aries kimberlite diatremes, and the facies characteristics of the diatreme fill, were influenced by the type of groundwater aquifers encountered by the kimberlite magma.

A bedded, upper-diatreme sequence, consisting of sediment gravity-flow deposits, was also recognised in the north lobe diatreme. Upper-diatreme or crater facies volcanic sequences of this kind occur in a number of kimberlite diatremes, such as Orapa, Botswana ([Field et al., 1997](#)); Mwadui, Tanzania ([Stiefenhofer and](#)

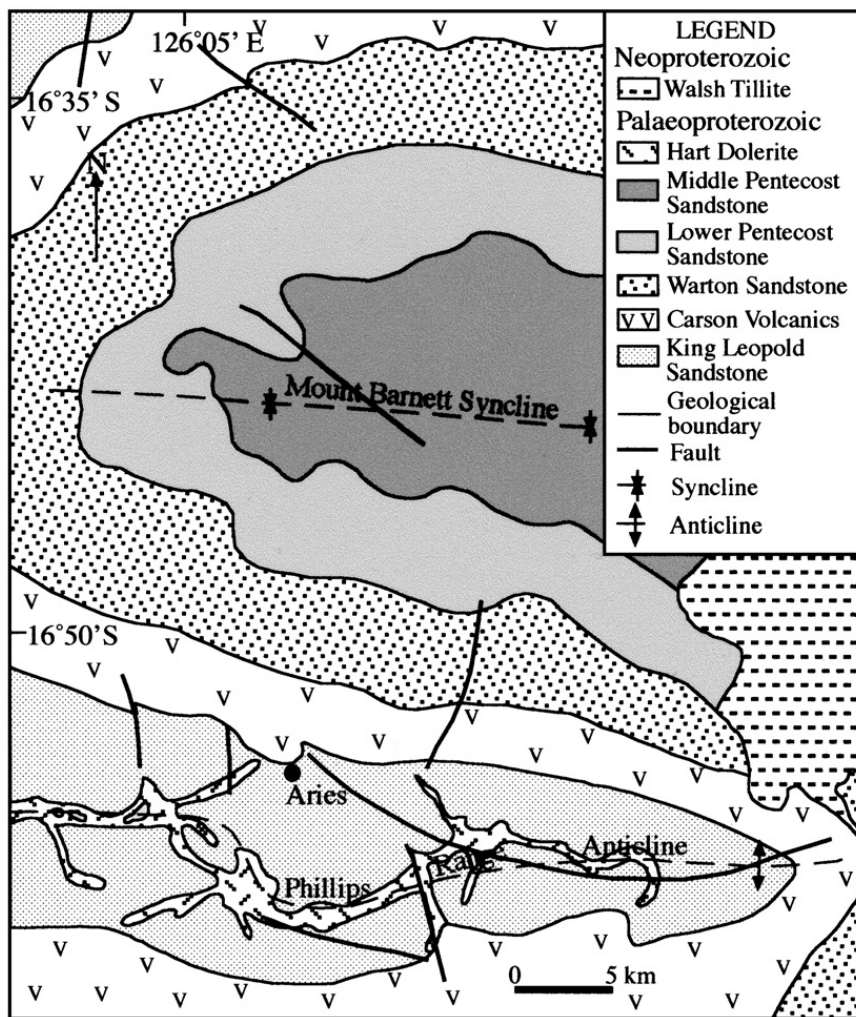


Fig. 2. A simplified geological map of the Phillips Range area showing basement geology and the location of the Aries kimberlite.

Farrow, 2004); Diavik and Ekati, Lac de Gras, Canada (Graham et al., 1999a; Nowicki et al., 2004); Star, Canada (Zonneveld et al., 2004); Venetia, South Africa (Kurszlaukis and Barnett, 2003); and Tokapal, India (Mainkar et al., 2004), but are particularly rare in Proterozoic kimberlites like Aries. The detailed analysis of this upper-diatreme sequence, presented here, certainly improves our understanding of later phases in the development of the Aries kimberlite diatremes, including the relationship between lower- and upper-diatreme deposits.

2. Geological setting

The Kimberley and Speewah Basins contain gently folded to flat-lying Palaeoproterozoic sequences that are bounded to the south by the King Leopold Orogen, and to the east by the Halls Creek Orogen, and overlie the granitic basement rocks of the Kimberley Craton, that are poorly constrained to Archaean to Palaeoproterozoic in

age (Fig. 1; Gunn and Meixner, 1998; Graham et al., 1999b; Tyler et al., 1999). The Aries kimberlite intrudes the Kimberley Group within the Kimberley Basin succession, the stratigraphy of which is illustrated in Fig. 3. The Kimberley Group unconformably and disconformably overlies the fluvial to marine Speewah Group, that was deposited in the Speewah Basin, and is comprised of quartz and feldspathic sandstone interbedded with mudstone and minor amounts of felsic volcanic rocks (Griffin and Grey, 1990; Griffin et al., 1993). The basal unit of the Kimberley Group is the King Leopold Sandstone, which is dominated by white to pink quartz sandstone, but contains minor intervals of conglomerate and siltstone (Griffin and Grey, 1990; Griffin et al., 1993). In the vicinity of the Aries kimberlite, the King Leopold Sandstone is a hard, silica-cemented variety. Tholeiitic basaltic lavas comprising the Carson Volcanics conformably overlie the King Leopold Sandstone, and are predominantly massive and fine- to medium-grained, but locally amygdaloidal. Minor interbeds of pyroclastic

STRATIGRAPHIC UNITS (Approximate maximum formation thickness)		AGE CONSTRAINTS (Ma)			LITHOLOGICAL DESCRIPTION
		Available age data	Youngest detrital zircon grains	Diagenetic xenotime	
KUNIANDI GROUP		≈ 750			Tillite, siltstone, shale, fine sandstone.
COLOMBO SANDSTONE					Quartz sandstone
CROWHURST GROUP					Dolomite, siltstone, shale, quartz sandstone.
BASTION GROUP					Quartz sandstone, shale, siltstone, micaceous sandstone.
KIMBERLEY GROUP	Pentecost Sandstone		1800?	1704±14	Quartz and feldspathic sandstone, ferruginous siltstone and sandstone, glauconitic sandstone.
	Elgee Siltstone				Massive red siltstone, sandstone and green shale.
	Warton Sandstone		1786±14	1704±7	Quartz and feldspathic sandstone and minor shale.
	Carson Volcanics	1790±4			Tholeiitic basalt, feldspathic sandstone, siltstone, chert.
	Aries Kimberlite	815.4±4.3			
	King Leopold Sandstone				Quartz sandstone, conglomerate, micaceous siltstone.
	Hart Dolerite				
SPEEWAH GROUP	Luman Siltstone				Micaceous siltstone, shale, minor sandstone.
	Lansdowne Arkose				Feldspathic and quartz sandstone, arkose, minor siltstone.
	Valentine Siltstone	1834±3			Chloritic siltstone
	Tunganary Formation				Feldspathic and quartz sandst, arkose, siltst
	O'Donnell Formation				Quartz sandstone, shale and siltstone.
HOOPER & LAMBOO COMPLEXES					

Fig. 3. The stratigraphy of the Kimberley and Speewah Basins (sandst, sandstone; siltst, siltstone). Modified after Griffin and Grey (1990) and McNaughton et al. (1999).

rocks, feldspathic sandstone and micaceous siltstone are interleaved with the basalts (Roberts and Perry, 1969). Some authors (Derrick, 1966; Gellatly and Soufoulis,

1966) have reported a thin unit of stromatolitic chert near the top of the Carson Volcanics, that Ruddock (2003) suggested could record hydrothermal hot-spring activity

within the basin near the end of the volcanic period. Quartz and feldspathic sandstones also dominate the sequence overlying the Carson Volcanics to the top of the Kimberley Group (Griffin and Grey, 1990). Plumb et al. (1981) interpreted the rocks of the Kimberley Group to have been ‘deposited within a broad, semi-enclosed, shallow marine basin’ in which sediments were derived from the north and northwest (Gellatly et al., 1970). The Speewah and Kimberley Groups are intruded by the ~ 1790 Ma Hart Dolerite (Thorne et al., 1999), a massive composite sill of tholeiitic dolerite and less extensive granophyre, which reaches a total thickness of up to 3 km and covers an extensive surface region of approximately 160,000 km² (Plumb and Gemuts, 1976; Griffin et al., 1993).

The Aries kimberlite forms a composite pipe consisting of four lobes, at its current level of exposure (south, central, north and north extension), orientated along a N–NNE trend (Fig. 4). It has a total surface area of approximately 18 ha and is covered by about 5 m of sand, clay and scree (Ramsay et al., 1994).

The depth to which the Aries kimberlite has been eroded since emplacement is poorly constrained. Edwards et al. (1992) estimated that approximately several hundred metres had been removed during the 750 Ma Sturtian glaciation (Kuniandi Group) and subsequent fluvial activity; an estimate apparently based on an interpretation of the level of exposure of the pipe to be within the root zone. The country rock stratigraphy does not place any tight control on the level to which the kimberlite originally penetrated, as no xenoliths from distinctive horizons within the Carson Volcanics have been recovered from the diatremes (although the stratigraphy in the region is poorly known), and the diatremes contain xenoliths of both King Leopold Sandstone and Carson Volcanics. The current level of exposure of the Aries kimberlite is right on the boundary between the Carson Volcanics and the underlying King Leopold Sandstone.

The geomorphological evolution of the Kimberley block, with possible implications for the preservation of ancient landscapes (including Proterozoic maar-diatreme volcanoes), has been the subject of some discussion (e.g. Ollier et al., 1988; Gale, 1992; Twidale, 1994, 1998; Kohn et al., 2002 and references therein). The King Leopold Sandstone exposed in the Phillips Range, partly hosts the Aries kimberlite and forms part of the Prince Regent Plateau, a subprovince of the Kimberley Plateau (Roberts and Perry, 1969). Ancient Proterozoic erosion surfaces (the High Kimberley Surface) have been identified in the Kimberley Plateau, and were interpreted by Ollier et al. (1988) as pre-dating the ~ 700 Ma glaciation that scoured the surface contemporaneously with the deposition of the

Walsh Tillite. Ollier et al. (1988) suggested that the High Kimberley Surface might have been subaerially exposed since its inception and never covered by younger deposits, by pointing to the lack of bedded terrigenous sediments in the Kimberley Plateau from the period ~ 750 Ma to the Quaternary. However, Kohn et al. (2002), from Phanerozoic denudation rates derived from apatite fission track data, proposed that such ancient surfaces must have been buried and later exhumed, to be preserved. Twidale (1994) also suggested that exhumation exposed the glaciated platforms from beneath the Walsh Tillite or other beds of the Mt House Group. The Phanerozoic denudation recorded in the Kimberley block by fission track data is consistent with the thick successions (≥ 5 km) of Permian to Jurassic sedimentary rocks that occur in the main basins, the Canning, Bonaparte and Browse, adjacent to the region (Kohn et al., 2002). A mechanism that could contribute to the preservation of ancient landscapes, in light of such a sedimentary record, is unequal erosive activity across the land surface combined with uplift, where denudation is confined to major drainage lines and intervening divides may remain dry and untouched by weathering and erosion (Gale, 1992; Twidale, 1998). Although it should also be noted that bedded volcanoclastic kimberlite deposits, including both sediment gravity-flow deposits and primary pyroclastic rock units, may occur to considerable depths ($> \sim 500$ m, below the syn-volcanic palaeosurface) within kimberlite maar craters or diatremes (e.g. Graham et al., 1999a; Nowicki et al., 2004; Stiefenhofer and Farrow, 2004), potentially allowing for both the preservation of bedded deposits within a pipe, and the removal of substantial volumes of rock from the crater to upper-diatreme levels of a volcano.

3. Terminology

Herein, the term *diatreme* is used as defined by Cas and Wright (1987) to describe a “pipe-like volcanic conduit filled with volcanoclastic debris”. White (1991) provided a similar definition, stating that diatremes are “tephra-filled volcanic necks exposed below the eruptive surface, and are believed to be the subsurface roots of maars and related volcanoes.”

Segregationary texture and *globular segregationary texture* are used in the sense of Clement (1982), Clement and Skinner (1985), Clement and Reid (1989), Mitchell (1986, 1995) and Field and Scott Smith (1999). Where Mitchell (1995) indicates that the groundmass of hypabyssal facies kimberlite is described as “uniform or segregationary, depending on whether the primary groundmass phases and mesostasis have crystallised

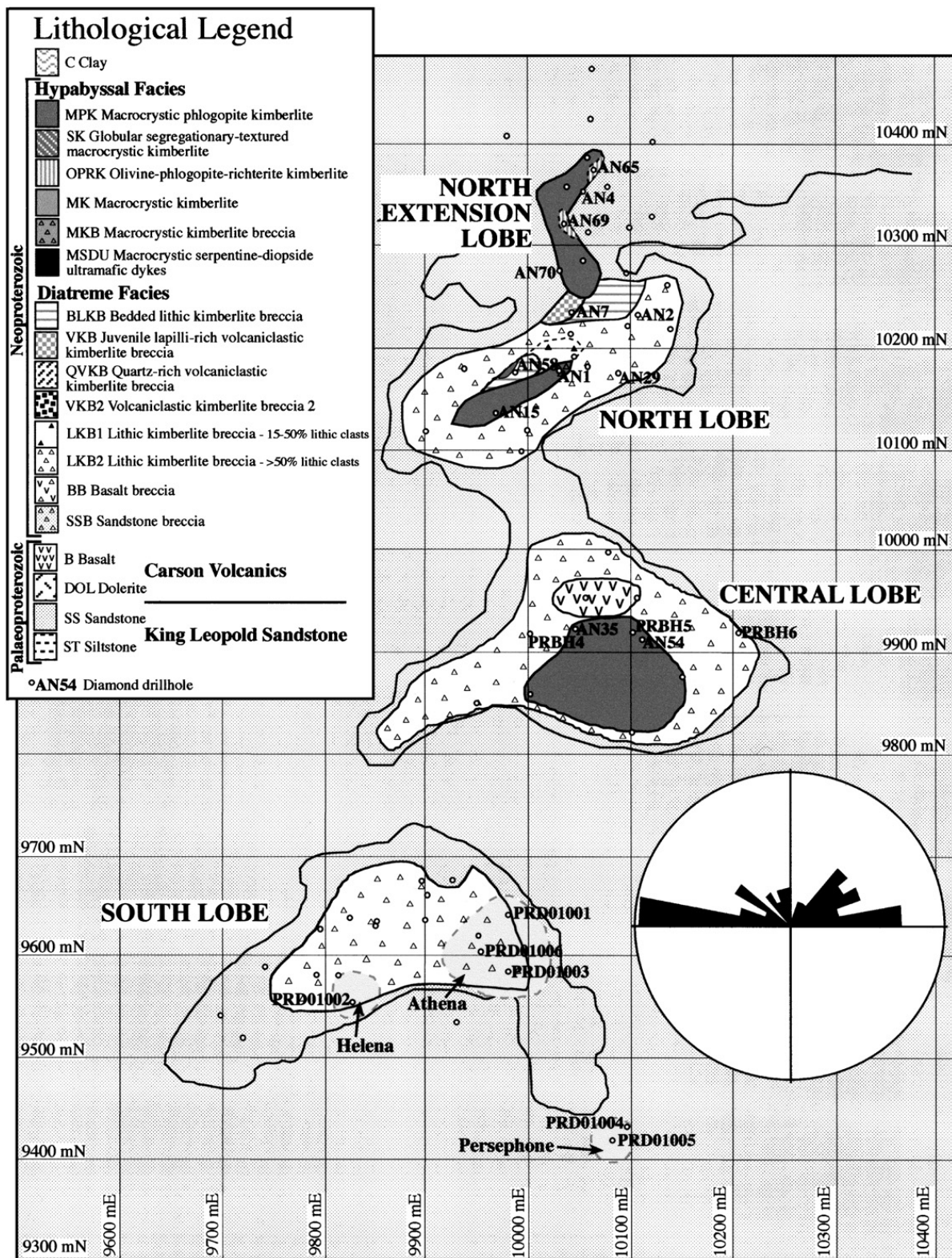


Fig. 4. Geological plan of the Aries kimberlite at the 350 m relative level (RL), 50 m below the current surface. The boundary of the diatremes at the surface, as defined by the edge of outcrop of the King Leopold Sandstone, is shown. An equal area rose diagram illustrates the orientation of joint surfaces in the King Leopold Sandstone immediately adjacent to the Aries kimberlite ($n=136$, circle radius=18%). Dashed grey lines and light grey shaded areas show the approximate positions of the Persephone, Athena and Helena gravity anomalies beneath the south lobe.

together or separately.... Segregationary-textured kimberlites have a non-uniform distribution of groundmass minerals and mesostasis. The groundmass is commonly identical in texture and character to that of uniformly textured hypabyssal kimberlite. The segregations are amoeboid-to-spherical discrete regions consisting of relatively coarse-grained phlogopite-kinoshitalite solid solutions, apatite, calcite and primary serpentine. Segregations consisting of calcite and serpentine are particularly common.... Segregations may be described as being bounded or gradational, depending upon whether their contact with the uniformly textured groundmass is sharp ($<50\ \mu\text{m}$) or gradational ($20\text{--}500\ \mu\text{m}$)."

In some instances, hypabyssal kimberlites may develop a globular segregationary texture, where spherical to elliptical globular masses of hypabyssal material ($\leq 100\ \text{mm}$ diameter) have formed and are separated by inter-globular calcite and/or serpentine-rich groundmass segregations (Clement, 1982; Clement and Skinner, 1985; Clement and Reid, 1989). These globules may have a nucleus of either a macrocryst or a small xenolith (Field and Scott Smith, 1999). Mitchell (1995) notes that globular segregationary textures are not restricted to group 1 kimberlites, but have been documented from lamproite dykes (Pilot Butte, Wyoming) and group 2 kimberlites (orangeites; Finsch, Clement, 1982).

Macrocryst and *phenocryst* respectively apply to crystals of uncertain and cognate origin to their host.

4. Lithofacies in the Aries kimberlite

A detailed analysis of volcanic lithologies and their distribution within the Aries diatremes and dykes is presented below, based on descriptive logging of diamond drillcore and the petrographic examination of polished thin sections.

4.1. Hypabyssal lithofacies

4.1.1. Macrocrystic phlogopite kimberlite (MPK), macrocrystic kimberlite (MK) and macrocrystic kimberlite breccia (MKB) dykes

Hypabyssal kimberlite dykes and plugs intrude each of the lobes of the Aries kimberlite and range from several centimetres up to approximately 70 m wide (Figs. 4 and 5). Bodies of macrocrystic phlogopite kimberlite generally have sharp intrusive contacts and cross-cutting relationships with surrounding volcanoclastic breccias and country rocks. Smaller dykes and stringers or pods ($<1\ \text{m}$ wide) of macrocrystic phlogopite kimberlite (MPK) may be highly irregular and discontinuous in form. Hypabyssal kimberlite dykes sometimes intruded

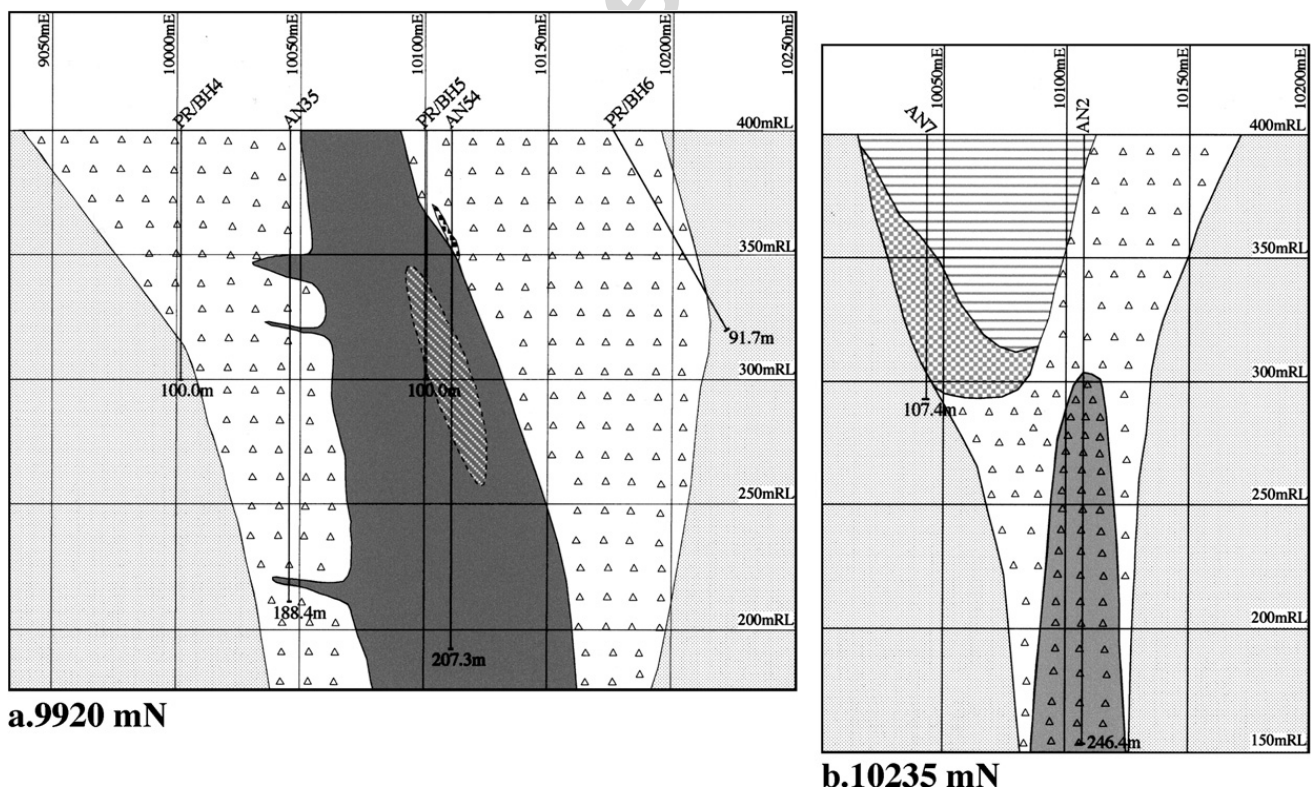


Fig. 5. Geological cross-sections of the Aries kimberlite: (a) central lobe—9920 mN and (b) north lobe—10235 mN (local grid). See Fig. 4 for lithological legend.

along the boundaries of the diatreme or along the boundaries between volcaniclastic units (Fig. 6). Hypabyssal macrocrystic phlogopite kimberlite occurring at Aries is defined by an inequigranular or macrocrystic texture, where olivine macrocrysts and phenocrysts

(≤ 20 mm long) comprise up to 50% of the rock (mostly $< 10\%$ macrocrysts and $< 20\%$ phenocrysts) and are set in a variably fine to coarse-grained phlogopite-rich ground-mass containing variable proportions of spinels, serpentine, talc, calcite, diopside and/or apatite (Fig. 7). The

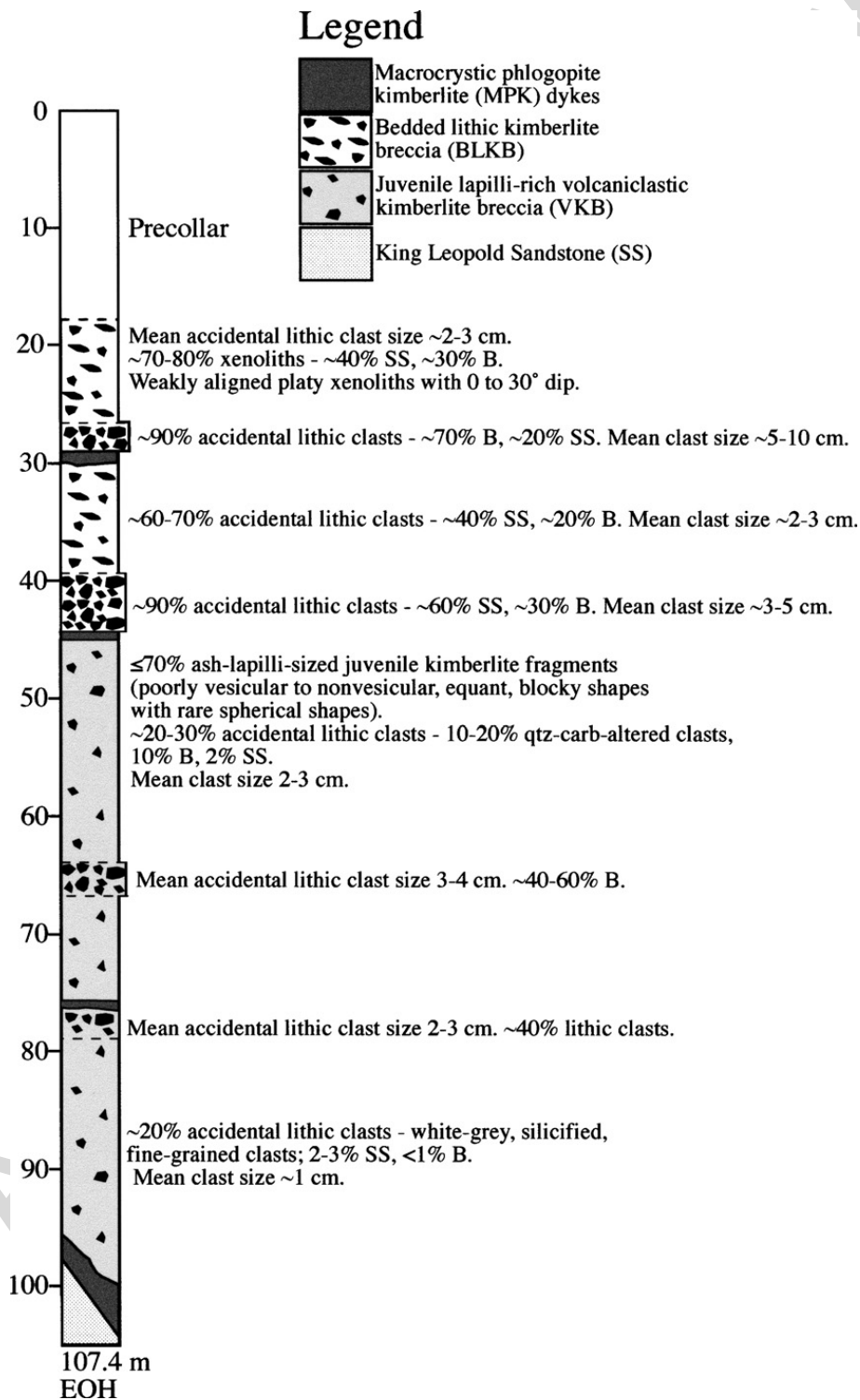


Fig. 6. Graphic log of DDH AN7, from the north lobe of the Aries kimberlite (B, basalt; SS, sandstone; qtz, quartz; carb, carbonate).

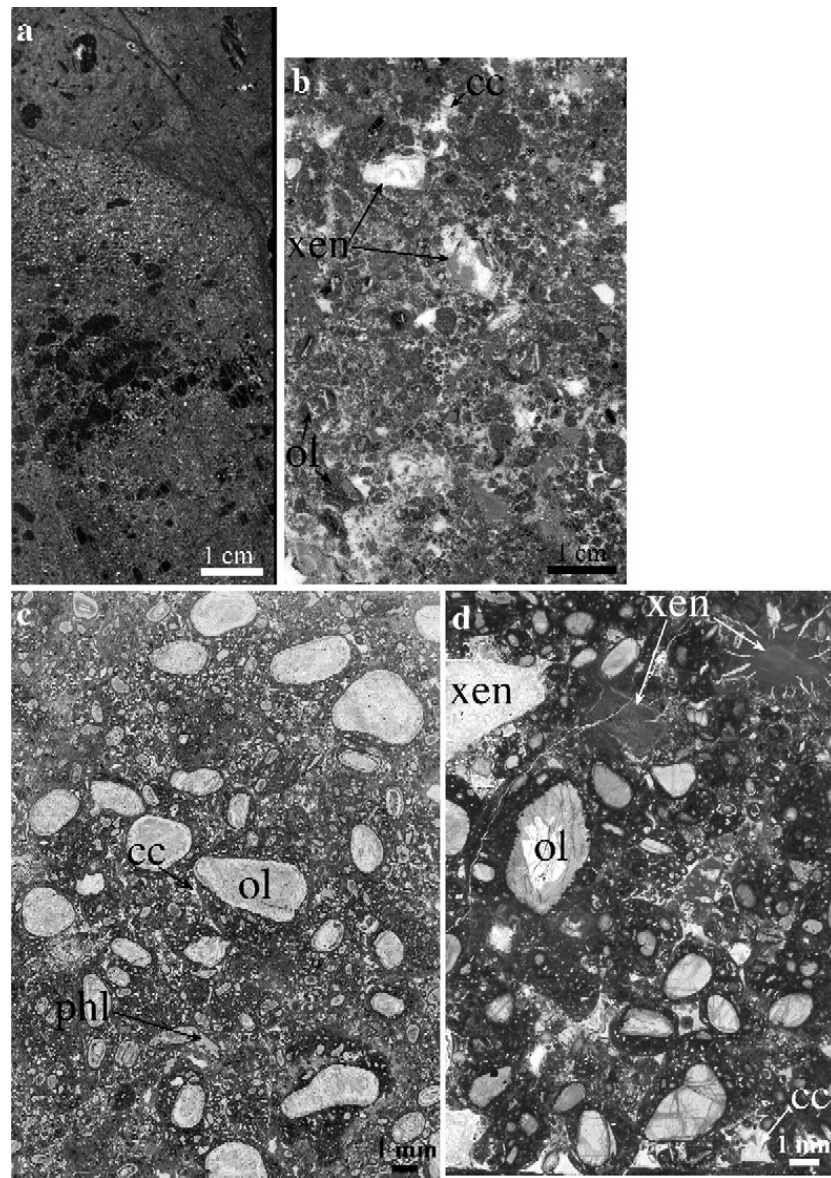


Fig. 7. (a) Photograph of macrocrystic phlogopite kimberlite with olivine macrocrysts in a grey fine- to medium-grained groundmass. (b) Photograph of globular segregationary-textured macrocrystic kimberlite (DDH AN1-57.28 m) with groundmass segregations of white calcite (cc; ol, olivine) and highly altered country rock xenoliths (xen). (c–d) Photomicrographs of globular segregationary-textured macrocrystic kimberlite (DDH AN15-95.77 m; phl, phlogopite; DDH AN15-99.55 m).

margins of hypabyssal kimberlite dykes may contain rafted xenoliths sourced from surrounding volcanoclastic kimberlite or country rocks and may grade into macrocrystic kimberlite breccia. The margins of macrocrystic phlogopite kimberlite dykes are commonly aphanitic, containing $\leq 5\%$ olivine macrocrysts in bands generally ≤ 8 cm wide, but ranging up to 28 cm wide. Olivine-rich bands and aphanitic zones, up to 40 cm wide, also occur within dykes away from their margins. Macrocrystic phlogopite kimberlite exhibits high magnetic susceptibilities, reflecting abundant groundmass magnetite to titanomagnetite, in contrast to the weakly to non-magnetic

volcanoclastic kimberlite lithologies and altered macrocrystic kimberlite.

Where the primary mineral assemblage of macrocrystic phlogopite kimberlite has been extensively altered and replaced by quartz, talc-serpentine, chlorite, clay and/or carbonate assemblages, but a macrocrystic rock texture is retained, hypabyssal kimberlite is designated as macrocrystic kimberlite (MK). Altered hypabyssal macrocrystic kimberlites are non-magnetic and contain $\leq 1\%$ spinels. Macrocrystic kimberlite has the same geometry and contact relationships as MPK described above.

Hypabyssal macrocrystic kimberlites that contain $\geq 15\%$ country rock xenoliths are classified as macrocrystic kimberlite breccia (MKB). Distinctive dykes of massive, groundmass-supported macrocrystic kimberlite breccia that contain 30–40% angular-subrounded sandstone xenoliths (≤ 20 cm wide) set in a nonmagnetic, green, fine-grained, secondary talc-quartz groundmass (including minor titanite ($\leq 5\%$) and primary phlogopite-biotite laths ($\leq 3\%$)) are common, especially in the north lobe (Fig. 5). These dykes may range up to approximately 50 m wide (Fig. 5). Macrocrystic kimberlite breccias may have gradational boundaries with macrocrystic phlogopite kimberlite or macrocrystic kimberlite and generally sharp, or rarely gradational, boundaries with lithic kimberlite breccia. Macrocrystic kimberlite breccia also may be intruded by cross-cutting macrocrystic phlogopite kimberlite dykes. Secondary talc veining is common in the groundmass of the macrocrystic kimberlite and macrocrystic kimberlite breccia and also along the boundaries of, or replacing, sandstone xenoliths within macrocrystic kimberlite breccia. Sprays of acicular, secondary magnesio-arfvedsonite to ferrowinchite crystals (≤ 0.25 mm long) also occur distributed along the margins of sandstone xenoliths in macrocrystic kimberlite breccia, in zones ~ 0.5 mm wide.

Interpretation: The accidental lithic-rich kimberlite breccias that infill the Aries kimberlite diatremes were intruded by bodies of hypabyssal macrocrystic kimberlite (MPK, MK, MKB) that are often centrally located in each lobe. Macrocrystic phlogopite kimberlite dykes and stringers become thinner away from the central plugs or dykes and some are interpreted as sills dispersing away from the core of an intrusion. Cross-cutting dyke relationships suggest that multiple phases of hypabyssal kimberlite intruded the diatremes. The assimilation of unconsolidated accidental lithic-rich kimberlite breccias and other volcanically fragmented country rock debris may have been an important process in the formation of macrocrystic kimberlite breccias and non-micaceous macrocrystic kimberlite. Evidence for the flow segregation of olivine crystals within these dykes during emplacement includes the development of aphanitic zones along dyke margins and the internal variation from olivine-rich bands to aphanitic zones.

4.1.2. Globular segregationary-textured macrocrystic kimberlite (SK)

Globular segregationary-textured kimberlites are a sub-facies of MPK and MK, and contain abundant, oval to spherical or more irregularly shaped, rounded globules (< 1 –50 mm wide) of macrocrystic phlogopite kimberlite (Fig. 7). These globules contain olivine macrocrysts and

phenocrysts, phlogopite phenocrysts and spinels, commonly set in a fine-grained, phlogopite-rich groundmass. Individual globules may be separated from each other by interglobular groundmass segregations of calcite and/or serpentine (Fig. 7), and can be either nucleated around single olivine grains or have macrocrystic textures. Generally, olivine and phlogopite macrocrysts and phenocrysts are randomly orientated and only rarely display a weak alignment parallel to globule boundaries. Globular segregationary-textured zones are widely developed in hypabyssal macrocrystic phlogopite kimberlite dykes throughout each of the lobes, occurring over a great vertical extent, from the surface to approximately 210 m depth. This texture is perhaps most prevalent within the top 100 m of the current exposure of the kimberlite, with wide intersections occurring at these depths in diamond drillholes (DDH) AN15, 54, 23 and 70. Globular segregationary-textured zones range from 10 cm to about 15 m wide and commonly merge into hypabyssal macrocrystic kimberlite with a uniform-textured groundmass. Alteration of kimberlite dykes makes the recognition of the full extent of globular segregationary-textured kimberlite difficult in many cases.

Interpretation: The origins of globular segregationary textures in hypabyssal kimberlite are not well understood, and Mitchell (1986, 1995) observed that groundmass segregations, which constitute the inter-globular groundmass, may form through a number of processes, including the separation of immiscible carbonate-rich liquids from the kimberlite magma, the separation of low-temperature residual fluids into discrete areas of the groundmass, as gas condensates in vesicles, or as vesicles that have been breached and filled with residual carbonate-rich fluids. Similar globular segregationary textures that occur in South African kimberlites (notably the Finsch group 2 kimberlite (orangeite); Clement, 1982) have been ascribed to processes involving the exsolution of gases from hypabyssal kimberlite magma in closed, near-surface environments (e.g. Clement, 1982; Clement and Skinner, 1985; Clement and Reid, 1989; Field and Scott Smith, 1999). Globular segregationary textures are absent from any of the lamproites that occur in the Kimberley region of W.A., but have been observed in micaceous kimberlite (Seppelt 2) from the North Kimberley field (P. Downes, unpubl. data). In the Aries kimberlite, the fine-grained nature of the phlogopite-rich groundmass within globular segregationary-textured zones suggests that they were rapidly cooled during formation, effectively freezing the magma in the state of phenocryst crystallisation that existed immediately prior to a possible degassing event. The adiabatic expansion of CO_2 upon exsolution from the kimberlite magma may have had a strong cooling effect on the rock

(cf. Williams and McBirney, 1979), and this textural feature perhaps represents evidence in favour of volatile exsolution. The spherical-oval shapes of some globules possibly were formed by surface tension effects and a contrast in viscosity between globules and interglobular calcite-serpentine groundmass segregations (Mitchell, 1986).

It is interesting that the distribution of globular segregationary-textured zones within hypabyssal kimberlite dykes at Aries is not restricted to the root zone of the diatremes, but extends from at least 210 m depth to the current surface. The extensive vertical distribution of this lithofacies at Aries provides a contrast with its distribution in South African kimberlites, where it appears to be restricted to root-zone hypabyssal kimberlite dykes (Clement, 1982; Mitchell, 1986; Clement and Reid, 1989; Field and Scott Smith, 1999). There is no evidence preserved at Aries to suggest an important role for globular segregationary-textured kimberlite in the development of fragmental rocks within the diatremes, such as gradations from globular segregationary-textured kimberlite into ‘tuffisitic kimberlite breccia’ (cf. Clement, 1982; Clement and Reid, 1989; Field and Scott Smith, 1999; Hetman et al., 2004; Skinner and Marsh, 2004).

4.1.3. Olivine-phlogopite-richterite kimberlite dykes (OPRK)

The massive, hypabyssal macrocrystic phlogopite kimberlite exposed in the north-extension lobe varies in composition to an olivine-phlogopite-richterite kimberlite (OPRK) that contains potassian richterite to magnesio-arfvedsonite, diopside and/or sanidine as fine-grained granular groundmass phases or euhedral–subhedral poikilitic laths (≤ 1 mm long) in the case of the potassian richterite (Fig. 4). Similar to MPK, OPRK contains up to $\sim 10\%$ phlogopite phenocrysts, generally <0.5 mm long. The groundmass of OPRK commonly is fine-grained and varies from phlogopite-rich to diopside-amphibole-rich on a millimetre scale. OPRK is also distinguished by the morphology of contained olivine macrocrysts and phenocrysts, commonly containing $<5\%$ olivine macrocrysts (≤ 5 mm wide), that may exhibit resorption features such as heavily embayed margins, but abundant ($<30\%$) smaller, euhedral olivine phenocrysts (≤ 1 mm long) that may form twins and complex saw-tooth crystal groups. As there is a lack of sharp, well-defined contacts between OPRK and MPK, the relative timing of intrusion could not be defined, and the precise relationship between the two units remains uncertain, but may be gradational.

Interpretation: The occurrence of OPRK adjacent to the walls of the north-extension lobe and its significant content of country rock sandstone xenoliths suggests that it formed from MPK through the assimilation of

sandstone. Essentially, OPRK is a sub-facies of MPK and is limited in extent.

4.1.4. Macrocrystic serpentine-diopside ultramafic dykes (MSDU)

Several narrow (≤ 1 m wide) macrocrystic serpentine-diopside ultramafic (MSDU) dykes intrude macrocrystic phlogopite kimberlite in the north-extension lobe (DDH AN4). These kimberlite dykes contain $<40\%$ rounded olivine macrocrysts (to ~ 10 mm long) separated by interstitial diopside (including continuous crystals of poikilitic diopside enclosing olivine macrocrysts), serpentine and spinels (chromite to magnetite), and minor apatite, calcite, phlogopite, allanite-(Ce) and aeschynite-(Ce). These dykes are confined to DDH AN4 and thus appear to be of very limited extent. They have sharp, intrusive contacts with surrounding macrocrystic phlogopite kimberlite.

Interpretation: MSDU dykes are interpreted as mafic cumulates from macrocrystic phlogopite kimberlite, which is suggested by the occurrence of poikilitic crystals of diopside enclosing olivine macrocrysts, and cross-cut macrocrystic phlogopite kimberlite as late stage intrusives.

4.2. Diatreme lithofacies

4.2.1. Lithic kimberlite breccia (LKB1 15–50 vol.% accidental lithic clasts, LKB2 >50 vol.% accidental lithic clasts)

The largest volumes of the diatremes are infilled with massive, poorly-sorted, clast-supported, accidental lithic-rich kimberlite breccias. These rocks contain angular to subrounded country rock xenoliths that generally range in abundance from approximately 60% to almost 100%, and vary in size from lapilli to blocks several metres in diameter (Fig. 8). The original nature of the matrix in these breccias is generally obscured by fine-grained silica-talc alteration, but may include olivine macrocrysts (generally <5 – 10%), abundant angular quartz grains (<2 mm wide), and less common kimberlite lapilli. We have divided the lithic kimberlite breccias according to the volume of contained accidental lithic clasts, into LKB1, 15–50% lithics, and LKB2, 50–100% lithics, where 50% is an arbitrary division but provides an indication of where breccias vary to matrix-supported types.

Lithic clasts are mostly derived from local country rocks. Fragments of the Carson Volcanics constitute a large volume of the lithic kimberlite breccias and exhibit a range of textures including fine-grained, massive, green-grey basalt; fine-grained, amygdaloidal basalt; and medium-grained dolerite. Basalt fragments range in size



Fig. 8. (a) Lithic kimberlite breccia (LKB2) from the north lobe (DDH AN58 ~ 65 m; b, basalt; ss, sandstone; g, granite; nl, nucleated lapilli). Note the shattered siltstone clast indicated by the white arrow in the top right corner of the photograph, possibly caused by compaction or impact. (b) Clast-supported LKB2 from the north lobe (DDH AN29 ~ 244 m). (c) Accidental lithic-rich breccia composed of sandstone (ss) and basalt (b) boulders (north lobe; DDH AN58 ~ 196–203 m).

from lapilli to megaclasts (termed ‘floating reefs’ in the literature) up to 57.5 m in diameter (Fig. 4). The other major component of the lithic kimberlite breccias is fragments of the King Leopold Sandstone, which is generally a pink, white or grey, massive to laminated quartz sandstone, but also contains intervals of laminated, brown to red siltstone.

Serpentinised mantle xenoliths are rare, but occur in both hypabyssal kimberlite dykes and lithic kimberlite breccias. These are ultramafic lithologies in which the silicate mineralogy generally has been altered to serpentine-talc, quartz and/or calcite (Ludemann, 1999), but the primary coarse-grained, granoblastic texture is retained. Rare phlogopite-biotite and diopside grains remain

unaltered in these xenoliths. Granite xenoliths occur in north, and north-extension lobes (in DDH AN1, 2, 29, 58 and 69). U–Pb SHRIMP analysis of contained zircon (1851 ± 10 Ma; P. Downes, unpubl. data) indicates that a granite xenolith from north-extension lobe was derived from Palaeoproterozoic basement rocks that are contemporaneous with the Whitewater Volcanics and the Bow River Batholith in the Halls Creek and King Leopold Orogens (cf. Gunn and Meixner, 1998).

Lithic kimberlite breccias can contain up to ~ 60% kimberlite lapilli, but lapilli are generally sparse. Kimberlite lapilli are typically spherical to ovoid and 2–50 mm in diameter (Fig. 9). They can be either shelled, with rinds of brown or grey fine-grained macrocrystic kimberlite material on a nucleus of a lithic fragment—generally King Leopold Sandstone—or an olivine macrocryst, or have a macrocrystic texture. Olivine macrocrysts and phenocrysts within the lapilli generally are randomly orientated, but rarely exhibit weak alignment tangential to lapilli boundaries (Fig. 9a). Nuclei may be centrally or eccentrically situated within nucleated kimberlite lapilli. The shapes of kimberlite lapilli also can be more irregular. Intervals of lithic kimberlite breccia containing >15% kimberlite lapilli have gradational boundaries with surrounding lithic kimberlite breccias.

Interpretation: The accidental lithic-rich kimberlite breccias are the major diatreme-filling lithology in the Aries kimberlite. They are interpreted as products of

volcanic explosions within the King Leopold Sandstone, causing massive disruption of country rock sandstone and basalt. The chaotic, massive and well-mixed nature of these breccias may have been produced through constant disruption of deposits and recycling of clasts by tephra jets during repeated volcanic explosions in the root zone of the diatreme (cf. Lorenz, 1985, 1986; White, 1991). The extremely accidental lithic-rich nature of the breccias is similar to other kimberlite, carbonatite and basaltic diatreme-filling breccias related to phreatomagmatic eruptions and maar-diatreme development (cf. White, 1991; Kurszlaukis and Lorenz, 1997; Kurszlaukis et al., 1998; Nemeth and White, 2003). A contribution to these breccias by collapse of the vent wall is indicated by the presence of megaclasts of Carson Volcanics from higher stratigraphic levels, and very coarse, basalt-rich lithic breccias adjacent to the walls of the diatreme on the northern side of central lobe. Much of this country rock debris possibly was deposited by fall-back into the vent.

4.2.2. Basalt breccia (BB) and sandstone breccia (SSB)

Basalt and sandstone breccias (BB, SSB), with jigsaw-fit textures, composed of angular *in situ* or clast-rotated fragments (centimetre to decimetre size) and minimal fine-grained matrix, represent a volumetrically small component of the diatremes. They are commonly located at the margins of the diatremes within country rocks, lithic blocks or megaclasts. Zones

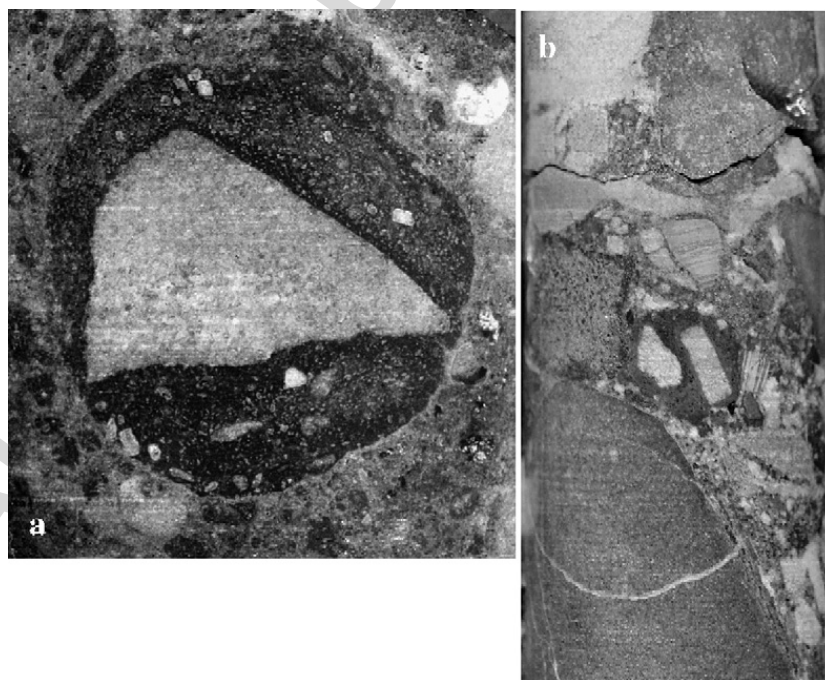


Fig. 9. (a) Spherical nucleated lapillus with sandstone xenolith core, in lithic kimberlite breccia. Note the aligned olivine macrocrysts along the lower edge (DDH AN2-74.03 m, north lobe; lapillus is 2.6 cm wide). (b) Spherical nucleated lapillus containing two sandstone fragments (DDH AN55-103.2 m; core is 4.7 cm wide).

of basalt or sandstone breccia range from tens of cm up to ~ 25 m wide. Basalt and sandstone breccias are not gradational into lithic kimberlite breccia.

Interpretation: Textures which characterise this facies suggest a brittle, *in situ* mode of fragmentation. The facies is comparable to the contact breccias characteristic of the root zones of diatremes and produced by the shattering of country rocks by shock waves from volcanic explosions (Clement, 1982; Clement and Reid, 1989; Lorenz et al., 1999, 2002). In the Aries kimberlite, the breccias do not occur in large volumes, which is consistent with the interpretation that the level of exposure does not extend to the root zone of the diatremes. The distribution of the breccia zones within country rocks adjacent to the margins of diatremes and within larger country rock boulders and megaclasts suggests that the locus of explosive brecciation of country rocks may have deepened with time, or that some brecciated country rock xenoliths were ejected to higher levels of the diatreme during development. Similar features have been documented from basaltic diatremes of the Hopi Buttes Volcanic Field, Arizona (White, 1991). Textures of this kind may also be produced by hydraulic fracturing of basalt or sandstone in volcanic systems (Cas and Wright, 1987).

4.2.3. Bedded lithic kimberlite breccia (BLKB)

A sequence of bedded accidental lithic-rich kimberlite breccias occurs in DDH AN7 adjacent to the margin of the north lobe diatreme (Figs. 4–6). The matrix-supported, polymictic breccias generally contain ~ 70–80% accidental lithic clasts, including white-pink sandstone (≤ 23 cm long), green-grey basalt (≤ 15 cm long) and minor black shale. The accidental lithic clasts in this unit commonly are angular, thin and platy, with low sphericity (length/width aspect ratio ~ 10:1), and some of which are lens-shaped or wispy (Fig. 10). These platy clasts define weak bedding with ~ 0–30° dip. The matrix contains minor kimberlite fragments (<5%), including rare ovoid, nucleated lapilli, along with isolated pseudomorphed olivine macrocrysts. The bedded accidental lithic-rich breccia grades into two separate layers of coarser, clast-supported accidental lithic-rich breccia (~ 90% accidental lithic clasts), within and at the base of the interval, that lacks aligned platy clasts (Fig. 6). The breccia is truncated by a macrocrystic kimberlite dyke at the base of the sequence. Matrix-supported accidental lithic-rich breccias with weakly aligned platy xenoliths also occur in the upper part of DDH AN58 (Fig. 4), where the contact relationship with underlying breccias also is obscured by a hypabyssal kimberlite sill.

Interpretation: An unusual feature of the bedded lithic kimberlite breccias is the high proportion of platy accidental lithic clasts that define the bedding in this unit. The alignment of these clasts may have been produced in part by compaction during burial, thus not necessarily reflecting the original bedding orientation. This population of platy clasts is restricted to this lithofacies and suggests a distinctive process in the quarrying of country rocks to produce the clasts, possibly within the margins of the pipe. This lithofacies is interpreted as forming from high-density sediment gravity flows (possibly debris flows) down the margins of the diatreme onto the maar-crater floor, based upon the high concentration of accidental lithic clasts, the thickness and generally massive nature of the beds, and the matrix-supported texture. Within the sequence exposed in DDH AN7, there are two possible flow units of bedded lithic breccia with basal coarser, accidental lithic-rich, clast-supported layers. There is no field evidence for hot emplacement, such as hot blocks, thermal colour alteration or gas segregation structures.

4.2.4. Juvenile lapilli-rich volcanoclastic kimberlite breccia (VKB)

The bedded lithic kimberlite breccias in the upper part of DDH AN7 are underlain by an interval of polymictic, juvenile ash and lapilli-rich, volcanoclastic kimberlite breccia (Figs. 4–6), with an interpreted true thickness of up to 25 m. This unit mostly contains ~ 20–30% accidental lithic clasts; including subangular to sub-rounded, fine-grained, green basalt and grey-white altered clasts that are typically zoned, with cores of chalcedony and rims of carbonate (Figs. 6 and 10). Sandstone and siltstone are minor accidental lithic components in this unit. Two thin zones of coarser accidental lithic-rich breccia, each ~ 2 m thick, occur within the unit (Fig. 6). They contain ~ 40–60% accidental lithic clasts and have gradational contacts with the surrounding breccia. Plots of maximum lithic clast sizes, recorded at 1 m intervals, indicate that the unit is reversely graded (Fig. 11). No other bedding features are evident.

Juvenile kimberlite fragments (<1–7 mm diameter) comprise approximately 40–70% of the rock. Fragments are blocky, equant and rarely spherical-oval, ash to lapilli (Figs. 10 and 12). Lapilli boundaries are commonly obscured by alteration, but where original boundaries are preserved they are curvilinear with embayments that are former vesicle walls. Rare vesicles are preserved, but fragments are generally nonvesicular (Fig. 12). The kimberlite fragments contain $\leq 1\%$ olivine macrocrysts, 30–40% euhedral–subhedral olivine phenocrysts, including twinned crystals and crystal groups ≤ 2 mm long, and

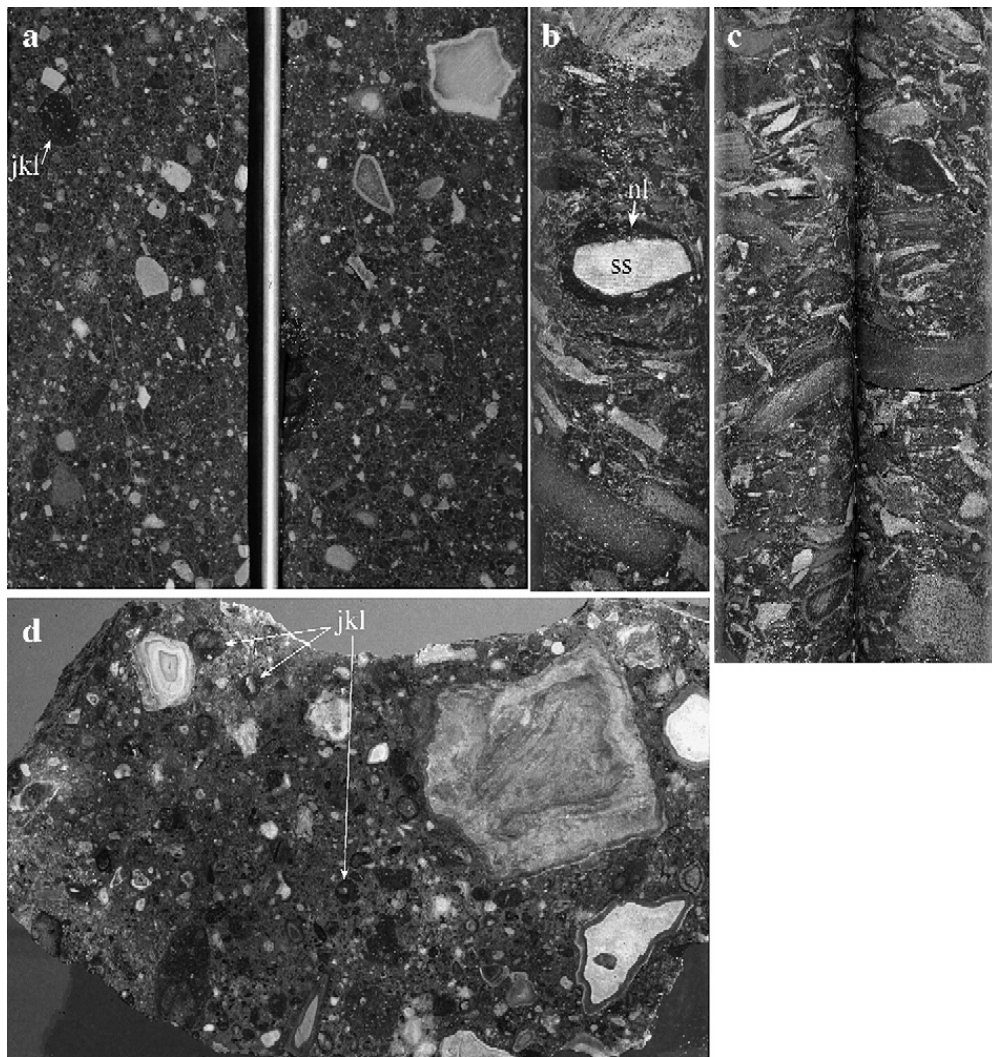


Fig. 10. (a) VKB from the north lobe. Juvenile kimberlite lapilli are dark grey in the photograph. Accidental lithic clasts are dominantly quartz-carbonate altered. Note the zoned lithic clasts in the top right of the photograph (DDH AN7 ~ 80 m; jkl, juvenile kimberlite lapilli; core is 4.7 cm wide). (b) Bedded lithic kimberlite breccia (BLKB) from the north lobe (DDH AN7-19.3 m) exhibiting aligned clasts and nucleated kimberlite lapilli. (nl; SS, sandstone). (c) Similar BLKB with bedding defined by aligned platy or elongate lithic clasts (DDH AN7 ~ 22 m). (d) Boulder of volcanoclastic kimberlite breccia (VKB2) derived from the central lobe pit (sample is 6.6 cm high; jkl, juvenile kimberlite lapilli).

1–2% phlogopite phenocrysts (≤ 0.5 mm long) in a very fine-grained groundmass. Some olivine crystals were fractured and cross-cut by grain boundaries. Accidental lithic and juvenile kimberlite clasts are set in a crystal-rich, fine-grained matrix ($< 20\%$) that has been altered to clays and carbonate. The upper contact of the unit with a macrocrystic kimberlite dyke is approximately horizontal (Fig. 6). The lower contact of the unit is also formed by a macrocrystic kimberlite dyke that has intruded along the contact between the breccia and the King Leopold Sandstone at the edge of the diatreme. The macrocrystic kimberlite dyke has a sheared, planar contact with the King Leopold Sandstone that dips at $\sim 45^\circ$.

Interpretation: This unit is distinct from the overlying bedded lithic kimberlite breccias in the high content

of juvenile ash and lapilli, and the composition of accidental lithic fragments. The zoned texture of quartz-carbonate clasts in the upper part of the unit suggests that they were altered during and/or after emplacement of the unit. This is a possible indication of elevated temperatures within the unit during emplacement, although associated altered basalt clasts are not zoned and the alteration may have taken place post-emplacement. The style of alteration that produced the zoned clasts is, however, restricted to this unit. Other breccia lithofacies do not contain clasts that have been altered in this manner, as might be expected if the alteration occurred post-emplacement. A reverse grading in the size of accidental lithic clasts is the only distinctive bedding feature present in the unit. Reverse grading of

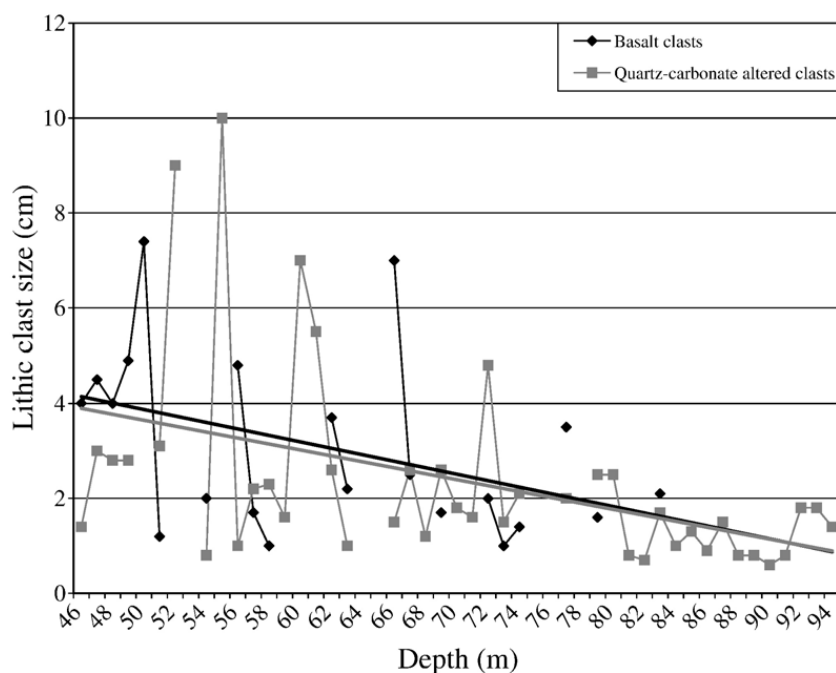


Fig. 11. Graph of maximum lithic clast size versus depth in DDH AN7 for the VKB unit. Trend lines represent average maximum lithic clast size.

lithic clasts is a feature that occurs in some dense, poorly expanded, pyroclastic-flow deposits and dense mass-flow deposits more generally (Cas and Wright, 1987).

This volcanoclastic kimberlite breccia preserves abundant, equant, blocky, poorly vesicular to nonvesicular,

juvenile kimberlite ash and lapilli with morphologies that are consistent with brittle fracture during phreatomagmatic fragmentation (cf. Wohletz, 1983; Sheridan and Wohletz, 1983; Heiken and Wohletz, 1985; Dellino and La Volpe, 2000; Dellino and Liotino, 2002). These

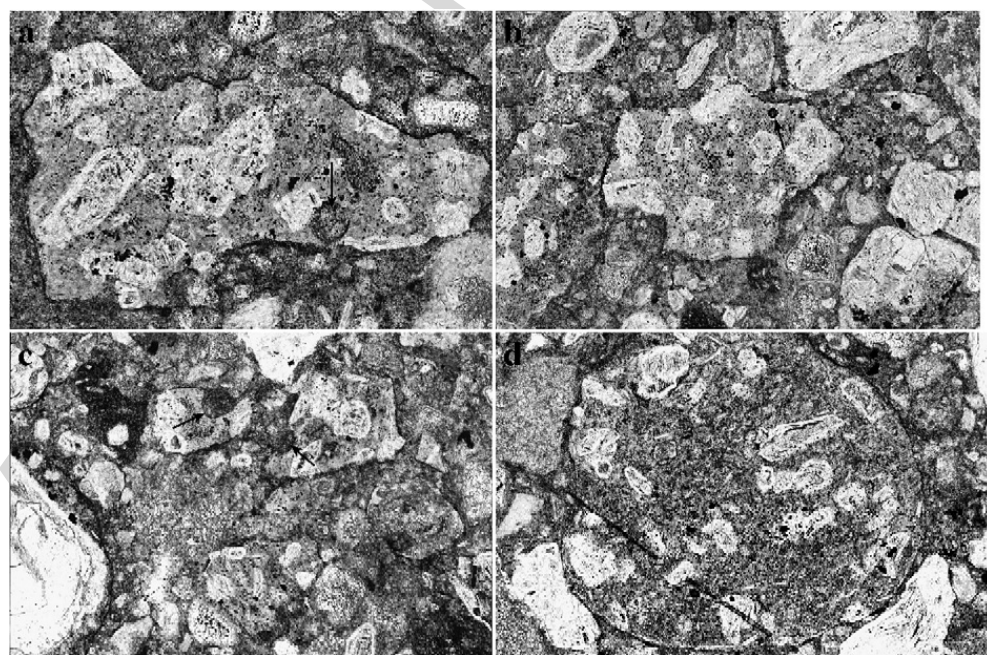


Fig. 12. (a–c) Photomicrographs showing poorly vesicular, ash-sized, juvenile kimberlite fragments in VKB. Intact and breached vesicles are indicated with arrows (field of view is 1 mm wide for (a) and 2 mm wide for (b)–(d), plane-polarised light). (d) Photomicrograph showing a roughly spherical, non-vesicular, juvenile kimberlite fragment from VKB.

textures provide the best evidence for the operation of phreatomagmatic processes during the development of the Aries kimberlite diatremes, and preserved vesicles also indicate that juvenile gases were simultaneously exsolving from the magma. Minor (<5%) spherical-oval juvenile kimberlite fragments indicate that some magma was molten after fragmentation.

Possible origins for this volcanoclastic breccia unit include deposition as a primary pyroclastic flow, or deposition from a sediment gravity flow down the walls of the diatreme, that included a significant amount of juvenile kimberlite ash and lapilli. As the evidence for hot emplacement is equivocal, we interpret this unit to have been deposited from a dense sediment gravity flow that produced a reverse grading in the size of accidental lithic clasts and a stratification in the abundance of basalt clasts within the flow. The differences in the content of juvenile kimberlite tephra and accidental lithic clasts between this unit and the overlying sediment gravity-flow breccias (possibly debris flows) indicate that they originated from different sources; possibly crater-rim deposits of quite different character. The VKB and overlying bedded lithic kimberlite breccias could represent an exposure of the lowest part of a bedded upper-diatreme sequence (cf. White, 1991; Graham et al., 1999a).

4.2.5. Quartz-rich volcanoclastic kimberlite breccia (QVKB)

DDH AN1 in north lobe contains a narrow interval (77.75–81.05 m depth) of massive volcanoclastic kimberlite breccia that contains ~ 20–30% subangular sandstone clasts (<40 mm wide), 10–20% subangular kimberlite fragments (<15 mm wide) and 40% subangular–angular quartz grains (1–4 mm wide) in a fine-grained, secondary talc-clay matrix. The primary boundaries of the kimberlite lapilli have been modified by alteration and vary from irregularly shaped to rounded lapilli. Kimberlite lapilli contain ≤1% rounded olivine macrocrysts (≤5 mm long), ~ 30% olivine phenocrysts (≤1 mm long) and 5–10% phlogopite phenocrysts (≤0.5 mm long) set in a very fine-grained groundmass. The phlogopite phenocrysts are high in Cr₂O₃ and similar in composition to early-formed phlogopite phenocrysts that occur in the macrocrystic phlogopite kimberlite (zone 2 composition of Edwards et al., 1992). The QVKB has sharp contacts with, and is completely enclosed by, surrounding hypabyssal macrocrystic kimberlite.

Interpretation: The small interval of QVKB exposed in the upper part of DDH AN1 contains juvenile kimberlite lapilli that have been modified in shape by groundmass alteration. Therefore, they provide no information on a possible fragmentation mechanism,

but their internal texture is the same as that of kimberlite lapilli from the VKB. Associated angular quartz grains distributed through the groundmass were probably produced by fragmentation of sandstone country rocks, and their angularity indicates that the sandstone was competent and lithified at the time of disaggregation. The QVKB is enclosed by hypabyssal macrocrystic kimberlite suggesting that it is a rafted block situated either *in situ* or slumped down within the pipe.

Phlogopite phenocrysts occurring within the juvenile lapilli in the QVKB are compositionally similar to zone 2 phlogopite (high Cr₂O₃; Edwards et al., 1992) from later macrocrystic phlogopite kimberlite dykes, indicating that the fragmented magma in the QVKB is similar to that represented in later intrusive phases. This suggests that the transition from initial explosive activity to later intrusive hypabyssal activity occurred over a relatively short time frame, or within the same magmatic episode, as there is a similarity in composition between magmatic components involved in both phases.

4.2.6. Volcanoclastic kimberlite breccia 2 (VKB2)

In the core of the central lobe, DDH AN54 intersects a small interval of massive, homogeneous, matrix-supported volcanoclastic kimberlite breccia (VKB2; 46.1–47.5 m depth; Fig. 10). The nature of the upper contact is obscured by broken, rubbly core and the lower boundary occurs where it is truncated by a macrocrystic phlogopite kimberlite dyke. VKB2 is also preserved as boulders that are currently distributed on mine dumps, but were originally derived from the Aries pit in central lobe. The weathered green VKB2 contains 15–20% subangular to subrounded, carbonate-silica replaced lithic clasts (<20 cm wide), and 20–30% rounded phlogopite-rich macrocrystic kimberlite lapilli (<12 mm wide and lacking central nuclei), set in a fine-grained, altered, talc-clay-carbonate matrix that also contains isolated phlogopite laths and olivine crystals. The primary morphologies of kimberlite lapilli are invariably affected by alteration. Kimberlite lapilli are phlogopite-rich, containing ~ 40–50% phlogopite laths (≤1 mm long), ~ 5% olivine macrocrysts (≤3 mm long) and 10–15% olivine phenocrysts (≤1 mm long). The phenocryst content in olivine and phlogopite is markedly different in morphology and abundance from kimberlite lapilli in the juvenile lapilli-rich volcanoclastic kimberlite breccia and lithic kimberlite breccias. This VKB2 is intruded by macrocrystic phlogopite kimberlite dykes.

Interpretation: A precise interpretation for the origin of this lithofacies is not possible given the poor exposure in drillcore and at the surface. The texture of the rock indicates that it is a volcanoclastic breccia. Notably, the

texture and composition of kimberlite lapilli and the matrix of the breccia are different from those preserved in other volcanoclastic breccias within the diatremes.

5. Distribution of volcanic lithofacies

The distribution of volcanic lithofacies within the Aries diatremes and dykes is illustrated in Figs. 4 and 5. The current surface expression of the Aries diatremes is as depressions between low hills of King Leopold Sandstone. The position of diatreme boundaries at the surface was mapped by tracing the outcrop of King Leopold Sandstone. This geomorphological feature may have been pushed back from the true diatreme boundaries by erosion subsequent to emplacement.

The high angle of diatreme walls in all lobes of the kimberlite—varying from $\sim 45^\circ$ to 80° , and locally overhanging on the eastern side of the central lobe—is probably a reflection of the high competency of the King Leopold Sandstone at the time of kimberlite emplacement. The nature of diatreme contacts as revealed in drillcore is variable: contacts may be sharp and stepped, or sometimes the adjacent kimberlite is sheared or altered/oxidised and basement sandstone is fractured. Thin macrocrystic phlogopite kimberlite dykes sometimes have intruded along the contacts of the diatreme.

The south lobe is infilled with highly oxidised and silicified, accidental lithic-rich kimberlite breccia and fractured sandstone blocks and megaclasts, such that large parts of the lobe may represent collapse zones composed of country rock sandstone within fractured areas extending out to the margins of the diatreme. Lithic kimberlite breccias in the south lobe generally contain between 50% and 90% basalt and sandstone clasts up to 1.5 m across, and are intruded by minor macrocrystic phlogopite kimberlite stringers and dykes. Minor intervals of lithic kimberlite breccia, up to 1.2 m wide, contain up to 60% kimberlite lapilli. The accidental lithic component of the diatreme fill is well mixed, with large volumes of basalt clasts present in the breccias, and basalt-dominated lithic breccias occurring up to 176 m from the current surface.

More recent exploration (2000–2001) has defined three gravity lows (Persephone, Athena, Helena) beneath, and adjacent to, the south lobe (Fig. 4; Grimley et al., 2002). Diamond drilling was carried out to test these gravity anomalies. Testing of the Helena anomaly produced lithic kimberlite breccias, similar to those in the remainder of the south lobe, intruded by minor altered, hypabyssal macrocrystic kimberlite dykes. Testing of the Athena anomaly indicated that quartz sand-rich, matrix-supported accidental lithic-rich breccias, and mudstone-

dominated accidental lithic-rich breccias and mudstone blocks to ~ 2 m wide (pyritic, with fine bedding and soft sediment deformation structures), occur at shallow levels (< 50 m depth) near the eastern edge of the diatreme. At deeper levels, and to the west of the Athena anomaly, further lithic kimberlite breccias, intruded by altered MPK/MK dykes (intersections may be up to ~ 15 m in true thickness; however, this maximum width is poorly constrained by drilling) with high former olivine macrocryst contents, were intersected. The Persephone anomaly proved to be a body of hypabyssal macrocrystic phlogopite kimberlite (MPK/MK) that is commonly altered to clay and contains up to 50% former olivine macrocrysts. The macrocrystic kimberlite includes variable proportions of sandstone and minor basalt xenoliths, ranging up to $\sim 65\%$ over restricted intervals. Fractured sandstone forms the wall-rock adjacent to the hypabyssal kimberlite.

The central and north lobe diatremes contain cores of hypabyssal macrocrystic kimberlite surrounded by lithic kimberlite breccias. Large volumes of very coarse, clast-supported, basalt-rich lithic breccias are present along the northern side of the central lobe, including a basalt megaclast at least 57.5 m in diameter. The central lobe is separated from the north lobe by a narrow bridge of King Leopold Sandstone. The shape and dimensions of the hypabyssal kimberlite core to central lobe are still poorly constrained by current drilling. The best intersection of hypabyssal kimberlite, in DDH AN54, suggests that the body may be up to 70 m wide. Due to poor exposure, the dimensions and orientation of the body of VKB2 in central lobe is unknown, but it occurs between approximately 50 m depth and the surface. Towards the edges of the north lobe diatreme, the breccias are lithic-rich, containing 70–90% accidental lithic clasts, and generally are basalt-dominated. Lithic kimberlite breccias in the north lobe contain rare kimberlite lapilli, although intervals up to 30 m wide and containing 10–40% kimberlite lapilli also occur. The sequence of bedded lithic kimberlite breccia (BLKB) overlying juvenile kimberlite ash and lapilli-rich volcanoclastic kimberlite breccia (VKB) occurring adjacent to the NW margin of the north lobe appears to be restricted in lateral distribution. Similar bedded lithic kimberlite breccias (BLKB) only occur in DDH AN58 towards the centre of the lobe, overlying massive lithic kimberlite breccia. The geometries of these units remain poorly defined because of the limited exposure in drill core.

The north-extension lobe has a dyke-like form and is composed of hypabyssal macrocrystic kimberlite, apparently lacking adjacent lithic kimberlite breccias. It varies in composition from macrocrystic phlogopite kimberlite to olivine-phlogopite-rich kimberlite, adjacent to the

walls of the lobe, and is intruded by macrocrystic serpentine-diopside ultramafic dykes.

6. Structural setting

The orientation of diatreme-country rock contacts in the Aries kimberlite indicates that the shape of individual lobes is partially controlled by regional joint patterns in the King Leopold Sandstone (Fig. 4). The joint orientation pattern suggests that the diatremes developed along a N-trending dyke or fault system and that the shape of individual lobes was controlled by the intersection of NNW-trending joints with an 060° orientated joint set. This observation is consistent with regional joint and fault orientations (e.g. Roberts and Perry, 1969; Griffin et al., 1993). In the Phillips Range area, N- and NW-trending faults are most abundant and were thought by Gellatly et al. (1975) to have formed in association with the major folding events in the basin. Ruddock (2003) noted that kimberlite dykes and pipe clusters also are aligned N–NE in the North Kimberley field, a trend that is parallel to that of the Halls Creek Orogen.

7. Discussion

7.1. Evaluation of potential eruption mechanisms and the possible influence of country-rock aquifers on diatreme development

Interpretations of the volcanological origins of the Aries kimberlite diatremes are limited by the fact that the rocks are only exposed in drillcore, thus obscuring the larger scale geometry of some important lithofacies, and the generally poor preservation of juvenile kimberlite components in the volcanoclastic deposits because of strong alteration in parts. The facies characteristics of the diatremes fill and the steep-sided morphology of the Aries diatremes contrast with those of the lamproite diatremes at Argyle and in the Ellendale field (Jaques et al., 1986; Boxer et al., 1989; Smith and Lorenz, 1989). The deep (≥ 350 m), steep-sided form of the Aries diatremes is similar to the general form of many kimberlite diatremes (e.g. Kimberley, Koffiefontein, Finsch and diatremes at Lac de Gras, Canada) and some basaltic diatremes (Aranda-Gomez and Luhr, 1996; Nemeth et al., 2001). Whereas, the champagne-glass form, and shallow extent, of the lamproite diatremes at Argyle and Ellendale reflect the role of phreatomagmatic eruptions within porous-media aquifers (Jaques et al., 1986; Boxer et al., 1989; Smith and Lorenz, 1989), and are similar to alkaline basaltic phreatomagmatic volcanoes erupted in thick,

water-saturated siliciclastic sediment-filled basins (cf. Martin and Nemeth, 2004). The resultant volcanoclastic facies produced by the Argyle and Ellendale lamproites are thus relatively fine-grained, country rock xenolith-poor lamproite tuffs that are rich in quartz sand (Boxer et al., 1989; Smith and Lorenz, 1989). These examples indicate that the nature of the country rocks and contained aquifers played an important role in determining the morphology and facies characteristics of the lamproite diatremes in each case.

In considering the potential influence of country rock aquifers, that may have been involved in eruptions, upon the facies characteristics and morphology of the Aries diatremes, it is pertinent to review the evidence for phreatomagmatism that is preserved in the diatremes. This is limited to the abundant blocky, equant, non-vesicular to poorly vesicular juvenile kimberlite ash and lapilli in volcanoclastic kimberlite breccia in the north lobe diatreme (Fig. 12), which suggest a role for magma–water interaction during this phase. From the composition of accidental lithic clasts in the kimberlite breccias, it appears that the locus of volcanic explosions during diatreme development was within the King Leopold Sandstone. The high competency and low porosity of the King Leopold Sandstone suggests that any potential aquifers involved in magma–water interactions at the time of the eruptions would have been joint and fracture-controlled. Studies of the Joya Honda Maar, Mexico (Aranda-Gomez and Luhr, 1996), and the Tihany Maar Volcanic Complex, Hungary (Nemeth et al., 2001), have shown that phreatomagmatism involving fracture-controlled aquifers is capable of producing deep, steep-sided maars with lithic-rich, tuff cone-like sequences around their rims. Aranda-Gomez and Luhr (1996) suggested that an increase in the secondary permeability of the country rocks produced by early phreatomagmatic blasts at the Joya Honda Maar, resulted in an increase in the water influx to the system. Water supply by fracture-controlled aquifers to a volcanic vent may be inconsistent, depending upon the local permeability and hydraulic conductivity of the country rocks, seasonal variations in groundwater supply, or whether or not the magma has intercepted a hydrologically important fracture (Aranda-Gomez and Luhr, 1996). Factors such as these could explain the lack of a diatreme in the north-extension lobe at Aries, and the presence of hypabyssal dykes intruding the diatremes at all levels up to the present surface. Such distribution patterns have been documented from Pliocene alkaline basaltic volcanic fields in the Pannonian Basin, Central Europe (Martin and Nemeth, 2004) as well.

Direct evidence of the volatile content of the Aries kimberlite and the role of magmatic volatiles in eruptions

is limited. No juvenile pyroclasts with morphologies that are indicative of magmatic volatile-driven fragmentation are preserved, but globular segregationary-textured kimberlite is widespread in hypabyssal dykes (Fig. 7). Hence, it is difficult to comment upon the role of magmatic volatiles in eruptions at any stage during diatreme development. Suffice it to say that complex variations between phreatomagmatic and magmatic eruption mechanisms over the course of eruptions have been shown to have occurred in recent, well-preserved deposits of explosive basaltic volcanism (e.g. Houghton and Hackett, 1984; Houghton and Schmincke, 1989; Houghton et al., 1999), but such variations are difficult to prove or define for kimberlites, without the preservation of tephra ring deposits surrounding maar craters.

7.2. Origin of nucleated lapilli

The presence of widespread spherical-ovoid nucleated lapilli in lithic breccias within the Aries kimberlite diatremes provides some insight into magma fragmentation processes during diatreme development. Spherical-ovoid nucleated lapilli, or ‘nucleated autoliths’ (in the sense of Mitchell, 1986, 1995), occur in many kimberlites. Similar lapilli also occur in carbonatite diatremes in Namibia and Italy (Kurszlaukis and Lorenz, 1997; termed ‘concentrically shelled lapilli’ by Stoppa, 1996), although the carbonatite lapilli have a finely layered, concentric structure. Stoppa (1996) suggested an origin for these carbonatitic lapilli involving the rapid quenching of magma droplets, produced by magma fragmentation during violent CO₂ release, that had been coated around nuclei of xenoliths and xenocrysts within the volcanic conduit. At Aries, the spherical-ovoid morphology of the nucleated lapilli probably was produced by surface tension effects in molten fragments of magma prior to rapid quenching. Evidence for this is provided by the alignment of olivine macrocrysts and phenocrysts tangential to the edge of some nucleated lapilli (Fig. 9a), indicating that the rounding of these lapilli did not occur due to abrasion during emplacement. A possible mechanism for the formation of these lapilli in the root zone of diatremes has been proposed by Lorenz et al. (2002). They suggest that clastic debris composed of fragmented country rocks is enclosed by hypabyssal kimberlite magma prior to fragmentation through explosions in the root zone of the diatreme, releasing magma fragments, with xenolith or xenocryst cores, that shortly after are rapidly quenched. The considerable volumes of xenolith-rich, non-fragmental, hypabyssal kimberlite dykes (MKB) that occur within the Aries diatremes probably represent those regions where fragmented

country rocks or diatreme fill were incorporated in intruding magma without subsequent fragmentation due to phreatomagmatic interactions.

7.3. Origin of bedded upper diatreme-facies volcanoclastic rocks and implications for the erosion level of Aries diatremes

Bedded volcanoclastic deposits from the crater to upper-diatreme facies, such as those preserved in the upper part of the Aries north lobe diatreme, have been described from a number of kimberlite diatremes worldwide (e.g. Orapa, Botswana (Field et al., 1997); Mwadui, Tanzania (Stiefenhofer and Farrow, 2004); Diavik and Ekati, Lac de Gras, Canada (Graham et al., 1999a; Nowicki et al., 2004); Star, Canada (Zonneveld et al., 2004); Venetia, South Africa (Kurszlaukis and Barnett, 2003); and Tokapal, India (Mainkar et al., 2004)). Although there are differences in detail between these crater to upper-diatreme deposits and those at Aries, the general pattern of talus and debris flows, derived from the collapse of the crater walls and tephra ring deposits onto a subsiding maar crater floor, is often similar. The bedded sequence exposed in DDH AN7 does not directly overlie the massive lower-diatreme rocks (Fig. 9). However, mapping suggests that this would be the case moving away from the diatreme wall (Figs. 4 and 5), although the bedded sequence is discontinuous and may have been disrupted in other parts of the diatreme by continued explosive activity in the root zone. There is no evidence from the exposed sequence that it represents a very large megaclast that has been recycled into the lower diatreme. The distinct composition of the juvenile lapilli-rich VKB suggests a different source to overlying mass flow deposits; possibly crater-rim deposits derived from an episode of magma fragmentation that may have occurred at shallower levels, thus allowing a higher content of juvenile kimberlite ash and lapilli, and lower content of accidental lithic clasts.

Edwards et al. (1992) interpreted the current level of exposure of the Aries diatremes to be within the root zone, based on the presence of hypabyssal kimberlite dykes, including globular segregationary-textured kimberlite and breccias. However, this interpretation is contradicted by the more recent discovery of a sequence of bedded volcanoclastic breccias, of possible sediment gravity-flow origin, in the upper part of the north lobe, indicating that the level of exposure extends to far higher regions of the diatremes. In addition, the presence of widespread juvenile kimberlite lapilli, large volumes of basalt clasts—that were derived from higher stratigraphic levels—and the well-mixed nature of clast types within

the lithic kimberlite breccias, are diagnostic of diatreme facies volcanoclastic rocks rather than root-zone breccias. Overall, the distribution of volcanic lithofacies within the diatremes and dykes indicates that the drill core has exposed a diatreme sequence that extends from the upper into the lower diatreme, and is intruded by hypabyssal kimberlite dykes and sills at all levels up to the current surface.

8. Conclusions

The Neoproterozoic Aries kimberlite forms a N–NNE-trending series of diatremes and hypabyssal dykes. Diatremes are infilled with massive, chaotic, clast-supported accidental lithic-rich breccias that are intruded by hypabyssal kimberlite dykes and plugs, with variably uniform- to globular segregationary-textured ground-masses. Globular segregationary textures within hypabyssal kimberlite dykes, that occur over a large vertical extent, from the surface to ~ 210 m depth, may have been produced through volatile exsolution from the kimberlite magma. However, there is no preserved evidence to suggest that volatile exsolution of this type played any role in the development of fragmental rocks within the diatremes. The massive, lower-diatreme accidental lithic-rich breccias (LKB) probably were produced by fall-back of ejecta into the vent, along with a major contribution from the collapse of the vent walls. They are overlain by a laterally restricted sequence of bedded, accidental lithic-rich breccias (BLKB), and juvenile ash and lapilli-rich, volcanoclastic kimberlite breccia (VKB) in the upper part of the north lobe diatreme. These are interpreted to be the deposits of density currents derived from the collapse of the maar crater walls and/or the redeposition of tephra ring deposits surrounding the crater. The volcanoclastic kimberlite breccia unit (VKB) within this upper-diatreme sequence contains abundant, poorly vesicular to non-vesicular, juvenile kimberlite ash and lapilli with morphologies that are consistent with phreatomagmatic fragmentation mechanisms. This evidence for phreatomagmatism, along with the nature of the country rocks, the very lithic-rich nature of the diatreme-filling breccias and the morphology of the diatremes, suggests that diatreme-forming eruptions may have been initiated by magma–water interactions along joint and fracture-controlled aquifers within the King Leopold Sandstone.

The upper-diatreme sequence of bedded volcanoclastic breccias derived from sediment gravity flows indicates that the current level of exposure at Aries extends from the upper diatreme into the lower diatreme. This indicates that the Aries kimberlite is not as deeply eroded as previously thought (cf. Edwards et al., 1992), and, along with the

Argyle lamproite, shows the potential for Proterozoic lamproite and kimberlite diatremes to be well preserved in the Kimberley region of Western Australia.

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References

- Aranda-Gomez, J.J., Luhr, J.F., 1996. Origin of the Joya Honda Maar, San Luis Potosi, Mexico. *Journal of Volcanology and Geothermal Research* 74, 1–18.
- Boxer, G.L., Lorenz, V., Smith, C.B., 1989. The geology and volcanology of the Argyle (AK1) lamproite pipe, Western Australia. In: Ross J. et al. (Eds), *Kimberlites and Related Rocks, Volume 1. Their Composition, Occurrence, Origin and Emplacement. Proceedings of the Fourth International Kimberlite Conference, Perth 1986*. Geological Society of Australia Special Publication 14, pp. 140–152.
- Cas, R.A.F., Wright, J.V., 1987. *Volcanic successions: modern and ancient*. Allen and Unwin, London. 528 pp.
- Clement, C.R., 1982. A comparative geological study of some major kimberlite pipes in the northern Cape and Orange Free State. PhD thesis, 2 volumes, University of Cape Town, South Africa, 432 pp., unpublished.
- Clement, C.R., Reid, A.M., 1989. The origin of kimberlite pipes: an interpretation based on a synthesis of geological features displayed by southern African occurrences. In: Ross J. et al. (Eds), *Kimberlites and Related Rocks, Volume 1. Their Composition, Occurrence, Origin and Emplacement. Proceedings of the Fourth International Kimberlite Conference, Perth 1986*. Geological Society of Australia Special Publication 14, pp. 632–646.
- Clement, C.R., Skinner, E.M.W., 1985. A textural-genetic classification of kimberlites. *Transactions of the Geological Society of South Africa* 88, 403–409.
- Dellino, P., La Volpe, L., 2000. Structures and grain size distribution in surge deposits as a tool for modelling the dynamics of dilute pyroclast density currents at La Fossa di Vulcano (Aeolian Islands Italy). *Journal of Volcanology and Geothermal Research* 96, 57–78.
- Dellino, P., Liotino, G., 2002. The fractal and multifractal dimension of volcanic ash particles contour: a test study on the utility and volcanological relevance. *Journal of Volcanology and Geothermal Research* 113 (1–2), 1–18.

- Derrick, G.M., 1966. Geology of the Ashton 1:250000 sheet area SD52/13 Western Australia. Australian Bureau of Mineral Resources, Record 1966/81, 48 pp.
- Edwards, D., Rock, N.M.S., Taylor, W.R., Griffin, B.J., Ramsay, R.R., 1992. Mineralogy and petrology of the Aries diamondiferous kimberlite pipe, central Kimberley block, Western Australia. *Journal of Petrology* 33, 1157–1191.
- Field, M., Scott Smith, B.H., 1999. Contrasting geology and near-surface emplacement of kimberlite pipes in southern Africa and Canada. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.R. (Eds.), *The J.B. Dawson Volume—Proceedings of the Seventh International Kimberlite Conference*, vol. 1. Red Roof Design, Capetown, South Africa, pp. 214–237.
- Field, M., Gibson, J.G., Wilkes, T.A., Gababotse, J., Khutjwe, P., 1997. The geology of the Orapa A/K1 kimberlite, Botswana: further insight into the emplacement of kimberlite pipes. *Russian Geology and Geophysics* 38 (1), 24–39.
- Gale, S.J., 1992. Long-term landscape evolution in Australia. *Earth Surface Processes and Landforms* 17, 323–343.
- Gellatly, D.C., Soufoulis, J., 1966. Geology of the Drysdale and Londonderry 1:250000 sheet areas SD52-5 and 9, Western Australia. Australian Bureau of Mineral Resources, Record 1966/55, 53 pp.
- Gellatly, D.C., Derrick, G.M., Plumb, K.A., 1970. Proterozoic palaeocurrent directions in the Kimberley region, northwestern Australia. *Geological Magazine* 3, 249–257.
- Gellatly, D.C., Derrick, G.M., Plumb, K.A., 1975. The geology of the Lansdowne 1:250 000 sheet area, Western Australia. Australian Bureau of Mineral Resources, Report 152, 100 pp.
- Graham, I., Burgess, J.L., Bryan, D., Ravenscroft, P.J., Thomas, E., Doyle, B.J., Hopkins, R., Armstrong, K.A., 1999a. Exploration history and geology of the Diavik Kimberlites, Lac de Gras, Northwest Territories, Canada. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.R. (Eds.), *The J.B. Dawson Volume—Proceedings of the Seventh International Kimberlite Conference*, vol. 1. Red Roof Design, Capetown, South Africa, pp. 262–279.
- Graham, S., Lambert, D.D., Shee, S.R., Smith, C.B., Reeves, S., 1999b. Re–Os isotopic evidence for Archaean lithospheric mantle beneath the Kimberley block, Western Australia. *Geology* 27 (5), 431–434.
- Griffin, T.J., Grey, K., 1990. Kimberley Basin. Geology and Mineral Resources of Western Australia Geological Survey, Memoir, vol. 3, pp. 293–304.
- Griffin, T.J., Tyler, I.M., Playford, P.E., 1993. Lennard River, W.A. (3rd edition). Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 56 pp.
- Grimley, M., Scott, R., White, M., 2002. Phillips Range Joint Venture Project, Western Australia. Combined annual report, December, 2001. BHP Billiton Combined Report C22/1993, unpublished.
- Gunn, P.J., Meixner, A.J., 1998. The nature of the basement of the Kimberley block, northwestern Australia. *Exploration Geophysics* 29, 506–511.
- Heiken, G., Wohletz, K., 1985. *Volcanic Ash*. University of California Press, Berkeley, California. 246 pp.
- Hetman, C.M., Scott Smith, B.H., Paul, J.L., Winter, F., 2004. Geology of the Gahcho Kue kimberlite pipes, NWT, Canada: root to diatreme magmatic transition zones. Selected papers from the Eighth International Kimberlite Conference. Volume 1: The C. Roger Clement Volume. *Lithos* 76, 51–74.
- Houghton, B.F., Hackett, W.R., 1984. Strombolian and phreatomagmatic deposits of Ohakune Craters, Ruapehu, New Zealand: a complex interaction between external water and rising basaltic magma. *Journal of Volcanology and Geothermal Research* 21, 207–231.
- Houghton, B.F., Schmincke, H.-U., 1989. Rothenberg scoria cone, East Eifel: a complex strombolian and phreatomagmatic volcano. *Bulletin of Volcanology* 52, 28–48.
- Houghton, B.F., Wilson, C.J.N., Smith, I.E.M., 1999. Shallow-seated controls on styles of explosive basaltic volcanism: a case study from New Zealand. *Journal of Volcanology and Geothermal Research* 91, 97–120.
- Jaques, A.L., Lewis, J.D., Smith, C.B., 1986. Kimberlites and lamproites of Western Australia. Western Australia Geological Survey. Bulletin, vol. 132. Perth, Western Australia. 268 pp.
- Kohn, B.P., Gleadow, A.J.W., Brown, R.W., Gallagher, K., O'Sullivan, P.B., Foster, D.A., 2002. Shaping the Australian crust over the last 300 million years: insights from fission track thermotectonic imaging and denudation studies of key terranes. *Australian Journal of Earth Sciences* 49 (4), 697–718.
- Kurszlaukis, S., Barnett, W., 2003. Volcanological and structural aspects of the Venetia kimberlite cluster—a case study of South African kimberlite maar-diatreme volcanoes. *South African Journal of Geology* 106, 145–172.
- Kurszlaukis, S., Lorenz, V., 1997. Volcanological features of a low-viscosity melt: the carbonatitic Gross Brückarros Volcanic Field, Namibia. *Bulletin of Volcanology* 58, 421–431.
- Kurszlaukis, S., Franz, L., Lorenz, V., 1998. On the volcanology of the Gibeon Kimberlite Field, Namibia. *Journal of Volcanology and Geothermal Research* 84, 257–272.
- Lorenz, V., 1985. Maars and diatremes of phreatomagmatic origin: a review. *Transactions of the Geological Society of South Africa* 88, 459–470.
- Lorenz, V., 1986. On the growth of maars and diatremes and its relevance to the formation of tuff rings. *Bulletin of Volcanology* 48, 265–274.
- Lorenz, V., Zimanowski, B., Buttner, R., Kurszlaukis, S., 1999. Formation of kimberlite diatremes by explosive interaction of kimberlite magma with groundwater: field and experimental aspects. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.R. (Eds.), *The P.H. Nixon Volume—Proceedings of the Seventh International Kimberlite Conference*, vol. 2. Red Roof Design, Capetown, South Africa, pp. 522–528.
- Lorenz, V., Zimanowski, B., Buttner, R., 2002. On the formation of deep-seated subterranean peperite-like magma–sediment mixtures. *Journal of Volcanology and Geothermal Research* 114, 107–118.
- Ludemann, C., 1999. Xenoliths from the Suomi 7 Kimberlite, northern Finland, and the Aries kimberlite, central Kimberley block, Western Australia: implications for mantle conditions and processes. BSc (Hons) thesis, University of Western Australia, 69 pp., unpublished.
- Mainkar, D., Lehmann, B., Haggerty, S.E., 2004. The crater-facies kimberlite system of Tokapal, Bastar District, Chhattisgarh, India. Selected papers from the Eighth International Kimberlite Conference. Volume 1: The C. Roger Clement Volume. *Lithos* 76, 201–217.
- Martin, U., Nemeth, K., 2004. Mio/Pliocene phreatomagmatic volcanism in the western Pannonian Basin. *Geologica Hungarica Series Geologica*, vol. 26. Geological Institute of Hungary, Budapest. 198 pp.
- McNaughton, N.J., Rasmussen, B., Fletcher, I.R., 1999. SHRIMP uranium–lead dating of diagenetic xenotime in siliciclastic sedimentary rocks. *Science* 285, 78–80.
- Mitchell, R.H., 1986. *Kimberlites: Mineralogy, Geochemistry and Petrology*. Plenum Press, New York. 442 pp.
- Mitchell, R.H., 1995. *Kimberlites, Orangeites and Related Rocks*. Plenum Press, New York. 410 pp.

- Nemeth, K., 2003. Calculation of long-term erosion in Central Otago, New Zealand, based on erosional remnants of maar/tuff rings. *Zeitschrift für Geomorphologie* 47 (1), 29–49.
- Nemeth, K., White, J.D.L., 2003. Reconstructing eruption processes of a Miocene monogenetic volcanic field from vent remnants: Waipiata Volcanic Field, South Island, New Zealand. *Journal of Volcanology and Geothermal Research* 124, 1–21.
- Nemeth, K., Martin, U., Harangi, Sz., 2001. Miocene phreatomagmatic volcanism at Tihany (Pannonian Basin, Hungary). *Journal of Volcanology and Geothermal Research* 111, 111–135.
- Nowicki, T., Crawford, B., Dyck, D., Carlson, J., McElroy, R., Oshurst, P., Helmstaedt, H., 2004. The geology of kimberlite pipes of the Ekati property, Northwest Territories, Canada. Selected papers from the Eighth International Kimberlite Conference. Volume 1: The C. Roger Clement Volume. *Lithos* 76, 1–27.
- Ollier, C.D., Gaunt, G.F.M., Jurkowski, I., 1988. The Kimberley Plateau, Western Australia. A Precambrian erosion surface. *Zeitschrift für Geomorphologie* 32, 239–246.
- Plumb, K.A., Gemuts, I., 1976. Precambrian geology of the Kimberley region, Western Australia. 25th International Geological Congress Excursion Guide, vol. 44C. 69 pp.
- Plumb, K.A., Derrick, G.M., Needham, R.S., Shaw, R.D., 1981. The Proterozoic of northern Australia. In: Hunter, D.R. (Ed.), *Precambrian of the Southern Hemisphere*. Elsevier, Amsterdam, pp. 205–307.
- Ramsay, R.R., Edwards, D., Taylor, W.R., Rock, N.M.S., Griffin, B.J., 1994. Compositions of garnet and spinel from the Aries diamondiferous kimberlite pipe, central Kimberley block, Western Australia—implications for exploration. *Journal of Geochemical Exploration* 51, 59–78.
- Roberts, H.G., Perry, W.J., 1969. Mt Elizabeth, W. A. 1:250 000 Geological Series. Australian Bureau of Mineral Resources Explanatory Notes, SE/52-5, 16 pp.
- Ruddock, I., 2003. Mineral occurrences and exploration potential of the north Kimberley. Western Australia Geological Survey, Report 85, 58 pp.
- Sheridan, M.F., Wohletz, K.H., 1983. Hydrovolcanism: basic considerations and review. *Journal of Volcanology and Geothermal Research* 17, 1–29.
- Skinner, E.M.W., Marsh, J.S., 2004. Distinct kimberlite pipe classes with contrasting eruption processes. Selected papers from the Eighth International Kimberlite Conference. Volume 1: The C. Roger Clement Volume. *Lithos* 76, 183–200.
- Smith, C.B., Lorenz, V., 1989. Volcanology of the Ellendale lamproite pipes, Western Australia. In: Ross, J. et al. (Eds.), *Kimberlites and Related Rocks, Volume 1. Their Composition, Occurrence, Origin and Emplacement*. Proceedings of the Fourth International Kimberlite Conference, Perth 1986. Geological Society of Australia Special Publication 14, pp. 505–519.
- Stiefenhofer, J., Farrow, D.J., 2004. Geology of the Mwadui kimberlite, Shinyanga district, Tanzania. Selected papers from the Eighth International Kimberlite Conference. Volume 1: The C. Roger Clement Volume. *Lithos* 76, 139–160.
- Stoppa, F., 1996. The San Venanzo maar and tuff ring, Umbria, Italy: eruptive behaviour of a carbonatite-melilitite volcano. *Bulletin of Volcanology* 57, 563–577.
- Taylor, W.R., Tompkins, L.A., Haggerty, S.E., 1994. Comparative geochemistry of West African kimberlites: evidence for a micaceous kimberlite endmember of sublithospheric origin. *Geochimica Cosmochimica Acta* 58 (19), 4017–4037.
- Thorne, A.M., Sheppard, S., Tyler, I.M., 1999. Lissadell, W.A. (2nd edition). Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 68 pp.
- Towie, N.J., Marx, M., Bush, M., Manning, E.R., Ramsay, R.R., 1994. The Aries diamondiferous kimberlite pipe, central Kimberley region, Western Australia: exploration, setting and evaluation. In: Meyer, H.O.A., Leonardos, O.H. (Eds.), *Proceedings of the Fifth International Kimberlite Conference, Araxa, June 1991. Volume 2: Diamonds: Characterization, Genesis and Exploration*. CPRM Special Publication, vol. 1B, pp. 319–328.
- Twidale, C.R., 1994. Gondwanan (Late Jurassic and Cretaceous) palaeosurfaces of the Australian craton. *Palaeogeography, Palaeoclimatology, Palaeoecology* 112, 157–186.
- Twidale, C.R., 1998. Antiquity of landforms: an ‘extremely unlikely’ concept vindicated. *Australian Journal of Earth Sciences* 45, 657–668.
- Tyler, I.M., Page, R.W., Griffin, T.J., 1999. Depositional age and provenance of the Marboo Formation from SHRIMP U–Pb zircon geochronology: implications for the early Palaeoproterozoic tectonic evolution of the Kimberley region, Western Australia. *Precambrian Research* 95, 225–243.
- White, J.D.L., 1991. Maar-diatreme phreatomagmatism at Hopi Buttes, Navajo Nation (Arizona), USA. *Bulletin of Volcanology* 53, 239–258.
- Williams, H., McBirney, A.R., 1979. *Volcanology*. Freeman, Cooper and Company, San Francisco. 397 pp.
- Wohletz, K.H., 1983. Mechanisms of hydrovolcanic pyroclast formation: grain-size, scanning electron microscopy, and experimental studies. *Journal of Volcanology and Geothermal Research* 17, 31–63.
- Zonneveld, J-P., Kjarsgaard, B.A., Harvey, S.E., Heaman, L.M., McNeil, D.H., Marcia, K.Y., 2004. Sedimentologic and stratigraphic constraints on emplacement of the Star Kimberlite, east-central Saskatchewan. Selected papers from the Eighth International Kimberlite Conference. Volume 1: The C. Roger Clement Volume. *Lithos* 76, 115–138.