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Kimberlite-hosted diamond deposits of southern Africa: A review

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ABSTRACT

Following the discovery of diamonds in river deposits in central South Africa in the mid nineteenth century, it was at Kimberley where the volcanic origin of diamonds was first recognized. These volcanic rocks, that were named “kimberlite”, were to become the corner stone of the economic and industrial development of southern Africa. Following the discoveries at Kimberley, even more valuable deposits were discovered in South Africa and Botswana in particular, but also in Lesotho, Swaziland and Zimbabwe.

A century of study of kimberlites, and the diamonds and other mantle-derived rocks they contain, has furthered the understanding of the processes that occurred within the sub-continental lithosphere and in particular the formation of diamonds. The formation of kimberlite-hosted diamond deposits is a long-lived and complex series of processes that first involved the growth of diamonds in the mantle, and later their removal and transport to the earth's surface by kimberlite magmas. Dating of inclusions in diamonds showed that diamond growth occurred several times over geological time. Many diamonds are of Archaean age and many of these are peridotitic in character, but suites of younger Proterozoic diamonds have also been recognized in various southern African mines. These younger ages correspond with ages of major tectono-thermal events that are recognized in crustal rocks of the sub-continent. Most of these diamonds had eclogitic, websteritic or lherzolitic protoliths.

In southern Africa, kimberlite eruptions occurred as discrete events several times during the geological record, including the Early and Middle Proterozoic, the Cambrian, the Permian, the Jurassic and the Cretaceous. Apart from the Early Proterozoic (Kuruman) kimberlites, all of the other events have produced deposits that have been mined. It should however be noted that only about 1% of the kimberlites that have been discovered have been successfully exploited.

In this paper, 34 kimberlite mines are reviewed with regard to their geology, mantle xenolith, xenocryst and diamond characteristics and production statistics. These mines vary greatly in size, grade and diamond-value, as well as in the proportions and types of mantle mineral suites that they contain. They include some of the world's richest mines, such as Jwaneng in Botswana, to mines that are both small and marginal, such as the Frank Smith Mine in South Africa. They include large diatremes such as Orapa and small dykes such as those mined at Bellsbank, Swartruggens and near Theunissen. These mines are all located on the Archaean Kalahari Craton, and it is apparent that the craton and its associated sub-continental lithosphere played an important role in providing the right environment for diamond growth and for the formation of the kimberlite magmas that were to transport them to the surface.

1. Introduction

Diamond is one of the most sought after gemstones on earth. They are formed mainly in the earth's lithosphere where pressure conditions are appropriate for carbon to crystallize as diamond, and they are brought to the surface, mostly through the eruption of alkaline igneous rocks such as kimberlites and lamproites. Stachel (this volume) provides a more comprehensive explanation about diamond growth in the sub-continental lithosphere. Southern Africa is endowed with considerable deposits of diamonds (Fig. 1), and it was here that the igneous origin was first recognized. In this paper the occurrence of these so-called “primary” diamond deposits are reviewed and described. The first part of this paper deals with a short history of diamonds and the discovery of kimberlites as important hosts of diamonds. It also deals with the discovery of the older diamond mines in South Africa such as Koffiefontein, Jagersfontein and the archetypical Kimberley pipes. This is followed by a summary of kimberlite geology. Thereafter 14 large mines are described in detail in the chronological order in which they were discovered. For each

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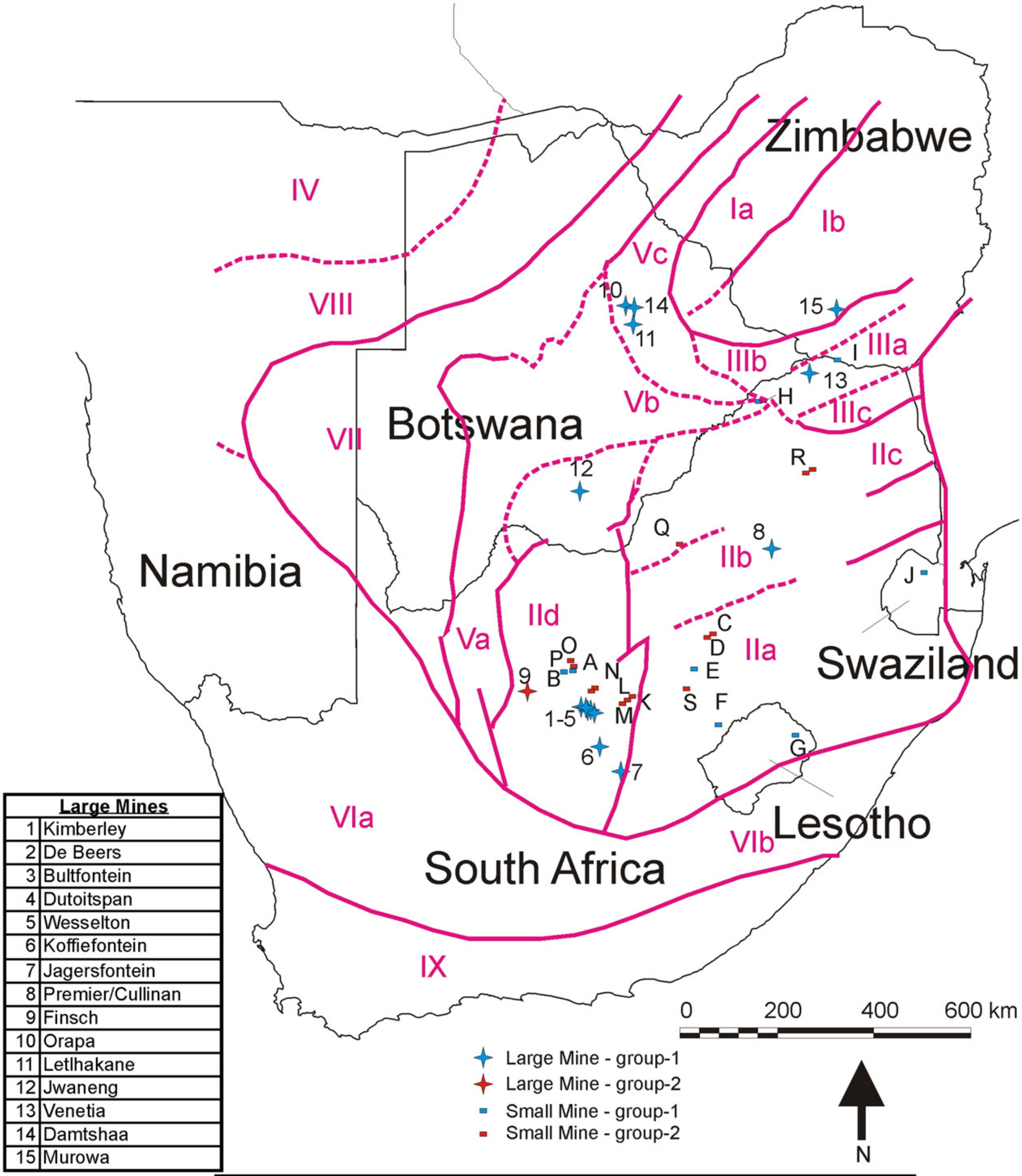


Large Mines	
1	Kimberley
2	De Beers
3	Bultfontein
4	Dutoitspan
5	Wesselton
6	Koffiefontein
7	Jagersfontein
8	Premier/Cullinan
9	Finsch
10	Orapa
11	Letlhakane
12	Jwaneng
13	Venetia
14	Damtshaa
15	Murowa

Small Mines									
A	Frank Smith	G	Letseng	M	Blaauwbosch	S	Star
B	Newlands	H	The Oaks	N	Loxtondal		
C	Voorspoed	I	River Ranch	O	Bellsbank		
D	Crown/Lace	J	Dokolwayo	P	Doornkloof-Sover		
E	Kaalvallei	K	Roberts Victor	Q	Swartruggens		
F	Monastery	L	New Elands	R	Marsfontein-Klipspringer		

Fig. 1. Map showing the location of kimberlite-hosted diamond mines in southern Africa superimposed on the structural units of Griffin et al. (2003b). Structural units: I: Archean Zimbabwe craton; II: Archean Kaapvaal craton; III: Archean Limpopo microcontinent; IV: Archean Angolan craton; V: Early Proterozoic crust (passive margin of Kalahari Continent); VI: Early-middle Proterozoic crust — Namaqua–Natal belt (accretionary fold belts); VII: Early-middle Proterozoic crust — Rehobothian subprovince; VIII: Late-Proterozoic crust — Damara province; IX: Saldanian province. Subdivisions of structural units: Ia: Tokwe terrane; Ib: North-western terrane; IIa: South-Eastern terrane; IIb: Central terrane; IIc: Pietersburg terrane; IId: Western terrane; IIIa: Central zone; IIIb: Northern marginal zone; IIIc: Southern marginal zone; Va: Kheis fold belt; Vb: Okwa inlier; Vc: Makondi foldbelt.

locality the main geological features are described, this includes a description of the geology of the kimberlites themselves as well as a brief review of the nature of the mantle xenoliths, diamond inclusions and diamonds that are characteristic of each mine. A section covering 19 smaller-scale mines is then presented. These are divided into two main groups' viz. "pipe" mines and "fissure" mines. In this paper an attempt has been made to review published information, and only in a few cases where there is a dearth of published information, are unpublished reports quoted.

2. History and discovery of kimberlite

Mankind's fascination with diamonds dates as far back as 2000 BC. Prior to 1720 all known diamonds originated from India where alluvial deposits in the Krishna River of Madhya Pradesh had been mined since ancient times and fuelled many legends of the so-called "valley of diamonds" (Wannenburgh and Johnson, 1990). It was only after the exploration of the 'New World' began that diamonds were found elsewhere. The first of these new discoveries was in Brazil in rivers in the Minas Gerais district near the town of Tijuco in 1726. These diamonds were also of alluvial origin, meaning that they were no longer in their host volcanic rocks, but rather eroded from their hosts and re-deposited in more recent river gravel and aeolian deposits.

Diamonds were first discovered in southern Africa in 1866. The first diamond to be found was credited to a 15-year old boy, Erasmus Jacobs whose discovery near Hopetown on the Orange (now Gariep) river was subsequently identified as a 21.25 carat (ct) diamond and became known as the "Eureka". In 1869 a Griqua shepherd named Swartbooi offered a 83.5 ct diamond to Schalk van Niekerk who purchased it for a considerable sum of sheep, oxen and a horse (Lynn et al., 1998). This diamond became known as the "Star of South Africa" and sparked a major rush of European and American prospectors to South Africa. Later in 1869 diamonds were discovered in gravels along the Vaal River near the current town of Barkly West (Wagner, 1914). A large number of "diggers" began exploiting these gravels for diamonds and these workings became known as the "wet diggings". All these diamonds were of alluvial origin.

There is some contention as to where the first diamonds from igneous rocks were discovered, but evidence seems to point to the recovery of a 50 ct diamond at Jagersfontein in the Orange Free State Republic (Lynn et al., 1998). An alternative explanation given by Bruton (1978) is that diamonds were discovered at nearby Koffiefontein before the events at Jagersfontein took place. Both occurred in 1870. It is not entirely certain whether diamonds discovered on the farms Dorstfontein and then Bultfontein (near the modern city of Kimberley), were discovered before those at Koffiefontein and Jagersfontein. Roberts (1976) indicates that these Kimberley diamonds were discovered in 1869 (i.e. a year before). Mitchell (1986) stated that these initial Kimberley discoveries were considered insignificant by most diggers, and it was only with the discovery of the much higher-grade deposits on the farm Vooruitzicht in 1871 that serious interest was paid to these non-alluvial deposits. Roberts (1976) suggested that this had more to do with a lack of surface water in the area that was required to sustain life and the washing of ground to recover diamonds. Later, two deposits were found on the farm owned by the De Beer brothers. Initially De Beers "Rush" was discovered, and some months later another deposit was discovered at Colesberg Kopje that became known as De Beers New Rush. These two deposits were to become known as De Beers and Kimberley Mines respectively. Collectively these deposits away from the rivers became known as the "dry diggings". The settlements that developed around these diggings were later renamed Kimberley in honour of Lord Kimberley, the British Secretary of State for the colonies (Roberts, 1976).

Around 1872 (Mitchell, 1986) it became apparent that these diamond deposits were not alluvial but hosted by a rock of igneous origin. This discovery is credited to Prof. Ernest Cohen who described the host rock as an eruptive tuff (Janse, 1985). The igneous host rock for these diamonds was named "kimberlite" after the town. The original proposer of this name was Prof. Henry Carvil Lewis who presented a paper to the British Association for the Advancement of Science in Manchester in 1887 (Lewis, 1887; Wagner, 1914).

Early mining of the kimberlites around Kimberley was a chaotic business with many claim-holders digging small individual claims of 31 by 31 ft. Later, as mining reached deeper levels and became more difficult, claims were consolidated into numerous companies. In 1888 De Beers Consolidated Mining Company was created by Cecil John Rhodes. This company consolidated all mining operations under the one company, thereby creating the leading diamond producer in the world for the next 90 years. The discovery of diamonds in the Kimberley area of South Africa initiated a general mineral exploration rush, which, as a consequence, resulted in the discovery of many more diamond mines in southern Africa as well as other mineral deposits such as gold and platinum.

3. Some definitions

For the purposes of this review some definitions are provided to clarify certain terms used in the diamond industry and in this paper:

Southern Africa: The southern portion of the African continent, usually defined as being that area south of the Cunene and Zambezi rivers and encompassing the countries of Namibia, Botswana, Zimbabwe, southern Mozambique, South Africa, Swaziland and Lesotho. No kimberlites have been mined for diamonds in Namibia or Mozambique.

Mine: A kimberlite deposit that has seen sustained mining for a continuous period of at least 2 years. Deposits meeting this criterion are shown in Fig. 1.

Large and small mines: This is a difficult concept to quantify as it does not necessarily represent diamond grade, diamond quality or the size or value of the mineral resource or reserve. It rather has to be defined by the rate of production and life of the operation. All of the kimberlites defined as "large mines" in this review have been mined wholly or partly by the De Beers Group of companies for a sustained period (five or more years) at high production rates, mostly in excess of one million tons per annum. Most of the "small mines" have been mined by other mining companies, many discontinuously, and at rates of below one million tons per annum. Recently De Beers has mined at least two kimberlites that fall into the "small mine" category, namely Marsfontein and The Oaks in South Africa. There are a number of other kimberlites that have been subjected to mining, but that could not sustain much activity. Published information concerning these kimberlites is scant, and therefore they are not described here. Examples of the latter include St. Augustine's, Kamfersdam and Olifantsfontein near Kimberley, and Makganyene, West End and Postma near Postmasburg in the Northern Cape.

Diamond grades: Diamond grades are most frequently expressed as a carat per unit mass or unit volume. The most commonly used measure is carats per hundred tons (cpht), but older figures were quoted as carats per hundred loads (cphl). A load represented the mass of ore carried by typical mining trucks often referred to as "skips" or "cocopans". This was a non-standard measure and therefore comparative figures should be treated with caution.

Diamond-specific terms:

Melee: diamonds below 1 carat (0.2 g) in weight.

Macle or maccle: a twinned diamond, with crystal rotation through 180° along an octahedral plane.

Boart or bort: This term was defined by Bruton (1978) to include minutely and randomly crystallized, and usually yellowish-green or grey to black masses of diamond which are extremely hard and when crushed are valuable as an abrasive. It also refers in general terms to diamonds of poor quality.

Cleavage or cleavage fragments: a term used to describe diamonds which have a very flat octahedral cleavage surface (Bruton, 1978).

Type-I and Type-II diamonds: Diamonds can be classified according to the aggregation state of nitrogen in their crystal structure. About 98% of all natural diamonds have detectable nitrogen, and in most of these diamonds the nitrogen occurs as aggregates, although diamonds also contain a proportion of non-aggregated nitrogen. These diamonds are referred to as Type-I diamonds. There are several sub-types depending on where the nitrogen atoms are aggregated. Type-II diamonds contain little or no detectable nitrogen. The interested reader is referred to the work by Wilks and Wilks (1994) and Evans (1997) for more detail.

Gem diamonds: Gem diamonds are defined as those that can be used by industry to manufacture jewellery.

4. Summary of kimberlite geology

Before the major kimberlite deposits in southern Africa are described, it is necessary to summarize the current state of knowledge regarding kimberlite geology. In this section four main topics will be summarized, the definition of kimberlite, Group 1 and 2 kimberlites, kimberlite nomenclature and kimberlite pipe formation models. Whilst it is recognized that work was and is still being conducted on kimberlites (*sensu stricto* and *sensu lato*) elsewhere, this section will focus on the characteristics of southern African kimberlites only.

4.1. Kimberlite definition

Skinner and Clement's (1979) definition of kimberlite highlighted the complex nature of this rocktype and is repeated here for the sake of completeness: "Kimberlite is a volatile-rich, potassic ultrabasic igneous rock which occurs as small volcanic pipes, dykes and sills. It has a distinctive inequigranular texture resulting from the presence of macrocrysts set in a fine grained matrix. This matrix contains as prominent primary phenocrystal and/or groundmass constituents, olivine and several of the following minerals: phlogopite, carbonate (commonly calcite), serpentine, clinopyroxene (commonly diopside), monticellite, apatite, spinels, perovskite and ilmenite. The macrocrysts are anhedral, mantle-derived, ferromagnesian minerals which include olivine, phlogopite, picroilmenite, chromian spinel, magnesian garnet, clinopyroxene (commonly chromian diopside) and orthopyroxene (commonly enstatite). Olivine is extremely abundant relative to the other macrocrysts, all of which are not necessarily present. The macrocrysts and relatively early-formed matrix minerals are commonly altered by deuteric processes, mainly serpentinization and carbonatization. Kimberlite commonly contains inclusions of upper mantle-derived ultramafic rocks. Variable quantities of crustal xenoliths and xenocrysts may also be present. Kimberlite may contain diamond but only as a very rare constituent". This definition highlighted two of the major problems with these rocks, namely their hybrid nature and their high propensity for alteration. This combination of features has hampered a fuller petrogenetic understanding of the rocks and complicated estimations of the chemical composition and physical characteristics of kimberlite magma. Mitchell's (1986) definition is similar, but is considered petrologically more complete, as it highlighted the compositional characteristics of the constituent minerals.

4.2. Group 1 and 2 kimberlites

Wagner (1914) was the first to recognize that there were at least two varieties of diamond-bearing kimberlites in South Africa, which he referred to as "basaltic" and "lamprophyric" kimberlites. This major difference was later quantified geochemically by Smith (1983a) and petrologically by Skinner (1989b). Mitchell (1995) found Group-2 kimberlites to be so different from Group-1 (or archetypical) kimberlites that he proposed the new name "orangeites" for them. According to the IUGS classification for igneous rocks (Woolley et al., 1996) either name can be used, but it should be recognized that Group-1 and 2 kimberlites are petrologically distinct. Group-2 is preferred in this review for historic reasons.

The defining difference between the two groups is their isotope geochemistry (Smith, 1983a,b). Group-1 kimberlites have Sr–Nd isotopic signatures that are slightly depleted relative to bulk earth, whereas Group-2's are significantly enriched relative to bulk earth. The Group-1's possess radiogenic Pb isotopic signatures, whereas Group-2's have unradiogenic Pb isotopic signatures.

The primary magmatic minerals in Group-1 kimberlites are diverse and consist of combinations of olivine, monticellite, calcite, phlogopite, spinel, perovskite, apatite and ilmenite. Spinel and perovskite grains tend to be relatively coarse-grained (up to 0.1 mm, but commonly less than 0.05 mm; Skinner, 1989b). As pointed out by Skinner (1989b) phlogopite does occur as a primary matrix mineral in many Group-1 kimberlites, and some can indeed be described as micaceous. Group-2 kimberlites have phlogopite as the dominant groundmass mineral. Olivine, diopside, spinel, perovskite, apatite and melilite are the other typical rock-forming minerals, although melilite is mostly altered and relatively less common. Perovskite and spinel grains tend to be much finer-grained in these rocks (averaging 0.01 mm — Skinner, 1989b). In some extreme Group-2 kimberlites (e.g., the Muil dyke at Helam Mine, Swartruggens) other potassium-bearing minerals such as sanidine, K-richterite and leucite have also been recognized. In all known cases these extreme rocks do not appear to contain significant quantities of diamonds.

Group-1 kimberlites have diverse radiometric ages (for example see Allsopp et al., 1989), that include Cretaceous (e.g., Kimberley and Orapa), Permian (e.g., Jwaneng), Cambrian (e.g., Venetia) and Proterozoic (Premier-Cullinan) groups. Details of ages and references are provided in the descriptions of each mine in the section below. Group-2 kimberlites are confined to a narrow time period ranging between 114 and 200 Ma (Smith et al., 1985).

The geochemistry of the two groups is also distinct (Skinner, 1989b; Mitchell, 1995). Notably Group-2's are enriched in SiO_2, K_2O, Pb, Rb, Ba and light rare earth elements and depleted in Cr and Nb relative to Group-1's.

It is important to note that Group-2 kimberlites (*sensu stricto*) are confined to southern Africa and to a narrow geological time period. Other, isotopically enriched kimberlite-like rocks do occur on other continents, for example lamproites in Western Australia, Europe and North America. In fact Mitchell (1995) stated that Group-2 kimberlites have a greater affinity with lamproites than with Group-1 kimberlites. Mitchell (2006) suggested that potassic igneous rocks (including Group-2 kimberlites) are derived from metasomatised lithospheric mantle that is unique to each continent, whereas Group-1 kimberlites are derived from the asthenospheric mantle and therefore have similar isotopic signatures wherever they occur. Mitchell (2006) refers to the former as metasomatized lithospheric mantle (MLM) magmas.

A further difference between the two groups is the suite of mantle xenoliths and xenocrysts that are contained in them. Group-1 kimberlites typically contain a wide variety of mantle xenoliths, including peridotites, metasomatised peridotites, sheared peridotites, MARID suite rocks (MARID is an acronym for Mica-Amphibole-Rutile-Ilmenite-Diopside), eclogites, wherlites and discrete minerals of the megacryst suite such as olivine, orthopyroxene, clinopyroxene, ilmenite, garnet and other minerals. Group-2 kimberlites are generally devoid of metasomatized xenoliths and sheared peridotites, and megacryst suite crystals are uncommon.

A significant proportion of the Group-2 kimberlites that are diamondiferous are dykes, although important exceptions are the Finsch, Lace and Voorspoed mines which are pipes. A number of Group-2 mines also have enlargements on dykes known as blows. There is no general consensus whether these represent highly eroded pipes, or whether they are some other unique structure peculiar to Group-2 kimberlite dykes (Bosch, 1971; Tainton, 1992; Mitchell, 1995). All of the Group-1 kimberlites that are economically significant in southern Africa are pipes.

4.3. Kimberlite lithofacies nomenclature

The recognition that kimberlite pipes are the product of volcanic processes was an important early observation. Early workers such as Lewis (1887, 1888), Wagner (1914) and Williams (1932) recognized pipes, dykes, sills and "blows" as the various styles of kimberlites. They noted that the various dykes had differing age relationships with respect to the pipes, being either "antecedent" or "consequent". Wagner (1914) stated that the kimberlite pipes were volcanoes of "maar-type" and he noted further that the two main components of the kimberlite pipes were foreign inclusions, including large "floating reefs", and "pipe rock proper". The latter type was described as varying (from top to bottom) from "yellow ground" to "blue ground" to "hardebank" with depth in most pipes. This described the state of alteration that diminished with depth. Blue ground was shown to be variable in character and kimberlite tuff, kimberlite breccia and injection breccias were recognized. At great depth "hardebank" was thought to represent the "parent rock" with no trace of fragmentary texture. These early workers clearly recognized that individual pipes are composed of numerous "chimneys" of different kimberlite types. Further they realized that these different zones were related to the semi-circular outlines of the pipes (for example see the discussion on Kimberley Mine in the next section) and to the quantities and types of diamond present within them.

Hawthorne (1975) published the first model of a kimberlite pipe, in which he depicted this lithological zonation. His model has been widely quoted and used since, and is shown in Fig. 2. It also illustrated the stratigraphy through which most of the Cretaceous-aged kimberlites of southern Africa were emplaced.

The work of Clement (1979, 1982), Clement and Skinner (1979, 1985) and Clement and Reid (1989) formed the basis for the subdivisions used for the southern African kimberlite mines. These authors proposed that typical kimberlite pipes consist of three distinctive zones, which they named the crater, diatreme and root zones, which were filled with texturally and compositionally unique varieties of kimberlites which they termed crater-facies, diatreme-facies and hypabyssal-facies kimberlite respectively. The textural-genetic classification proposed for these rocks in particular was unique to kimberlites. The term "tuffisitic" was used to describe the poorly sorted, clastic rocks that comprise the diatreme zone. The word "tuffisite" is applied to tuffs of intrusive origin, which these rocks were deemed to be (Clement, 1979, 1982; Clement and Reid, 1989; Field and Scott Smith, 1999). The most common rocktype seen in the diatreme zone of most kimberlite pipes were termed tuffisitic kimberlite breccias or "TKB". Where these rocks contained fewer crustal xenoliths they were termed tuffisitic kimberlite or "TK". Those rocks that occurred in the root zones of kimberlites, as well as those that occur in dykes and sills at any level, were termed hypabyssal-facies kimberlite (HK).

Much of the work done during this period focused strongly on the petrographic characteristics of kimberlites. Clement (1982) demonstrated that it was possible to sub-divide the kimberlites at Kimberley, Finsch and Koffiefontein mines into distinctive zones based on their petrographic character, and that this sub-division correlated well with diamond grade distributions within these mines. Clement and Skinner's (1979, 1985) classification scheme was adopted widely for kimberlites (Mitchell, 1986, 1995; Field and Scott Smith, 1999).

Later work at Orapa (Field et al., 1997), Venetia (Kurszlaukis and Barnett, 2003), Koffiefontein (Naidoo et al., 2004) and Finsch (Ekkerd et al., 2003) showed that some of the rocks at these localities were inconsistent with their previous classification as TKB. Sparks et al. (2006) addressed this issue further and recommended that the term TKB should be discontinued on the basis that it is an incorrect description of the rocks and because the name has genetic connotations that cannot be substantiated. A general, non-genetic term, "massive volcaniclastic kimberlite" (MVK) was suggested as an alternative.

Furthermore, Stripp et al. (2006) found that some of the distinctive mineralogical and textural features of the "TKB", specifically the serpentine–diopside matrix of these rocks, could be interpreted as the products of hydrothermal metamorphic processes at temperatures well below magmatic limits. In addition, they found that these textural features were similar to those of pore-space crystallization or cementation at low temperatures.

Standardized volcanological nomenclature and terminology (Fisher, 1961, 1966; Cas and Wright, 1987; McPhie et al., 1993) have not been used to describe kimberlites, and this has led to considerable confusion and the inconsistent application of terminology. A kimberlite working group has been established under the auspices of IAVCEI, and a nomenclature sub-committee has been created that is currently deliberating over an appropriate nomenclature. It is recognized that a non-genetic approach is most appropriate, and that two main end-member textural varieties exist, namely clastic rocks where evidence of magma fragmentation is apparent, and coherent rocks where there is little evidence for magma fragmentation. These rocks can occur at any level within a pipe system. It has been suggested by Sparks et al. (2006) that the coherent kimberlites may not be intrusive rocks, but rather agglutinated or welded pyroclastic rocks, that as a consequence of welding have an appearance that is similar to intrusive dykes and sills. Some rocks of this type have also been termed "magmatic kimberlite" (MK) e.g., at Jwaneng (see Fig. 14).

In an attempt to clarify the different geological terms that have been used historically (textural-genetic), and to draw comparisons with terms that are volcanologically more acceptable (non-genetic) a schematic diagram is presented in Fig. 3 that demonstrates the variety of deposits found in the various kimberlite pipes of southern Africa. These are drawn from the true sections that are presented in Figs. 4 to 19. This figure is for illustrative purposes only, and it should not be considered as a model for all kimberlite pipes.

In this paper the rocktype names and facies descriptions that were originally proposed (i.e. Clement and Skinner, 1979) will be used so as to not cause further confusion.

4.4. Kimberlite pipe formation models

The processes that led to the formation of kimberlite pipes are still being debated. This is the consequence of the fact that no modern kimberlite eruption has been witnessed, and a complete volcanic edifice has not been preserved in the geological record. Volcanic processes are best understood by studying modern deposits that have been largely undisturbed since deposition. In most cases this involves detailed study of materials deposited outside the volcanic vent. With the possible exception of the Fort a la Corne kimberlites in Saskatchewan in Canada, such kimberlite deposits are not known, and even in the case of Fort a la Corne, they are mostly only exposed in drill holes. In addition, kimberlites are highly susceptible to alteration and weathering, and therefore primary volcanic textures may be difficult to distinguish from alteration overprints. Furthermore, the hybrid nature of the rocks has made it difficult to determine the chemical and physical properties of kimberlite magma, especially at low pressures. Several attempts have been made to estimate primary kimberlite magma compositions (Danchin et al., 1975; Price et al., 2000; Golovin et al., 2003; Le Roex et al., 2003; Harris et al., 2004) using quenched autoliths, aphanitic dykes and olivine melt inclusions. There appears to be general agreement that kimberlite melts are volatile-rich, but the composition and concentrations of these volatiles are difficult to ascertain (Sparks et al., 2006).

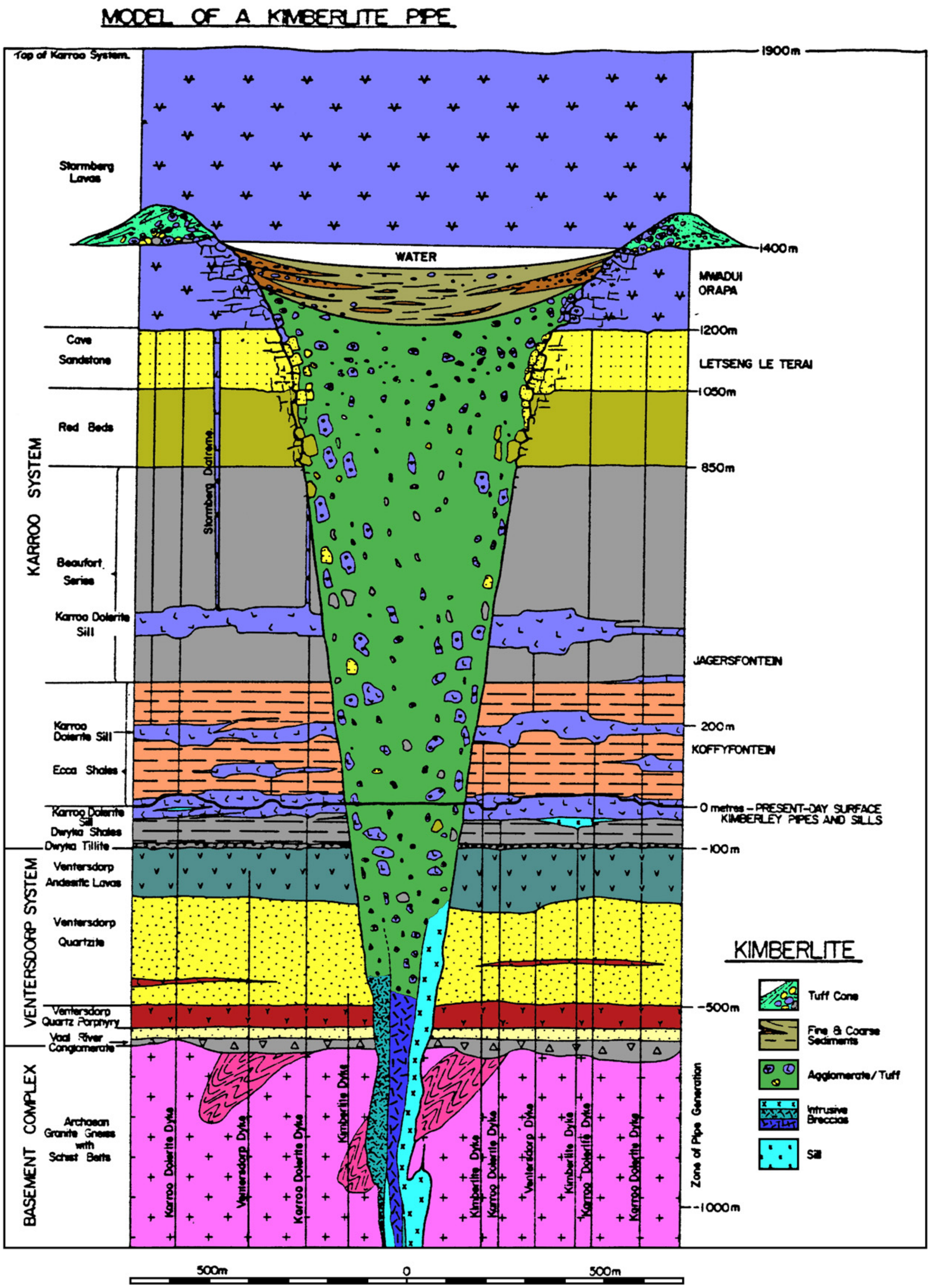
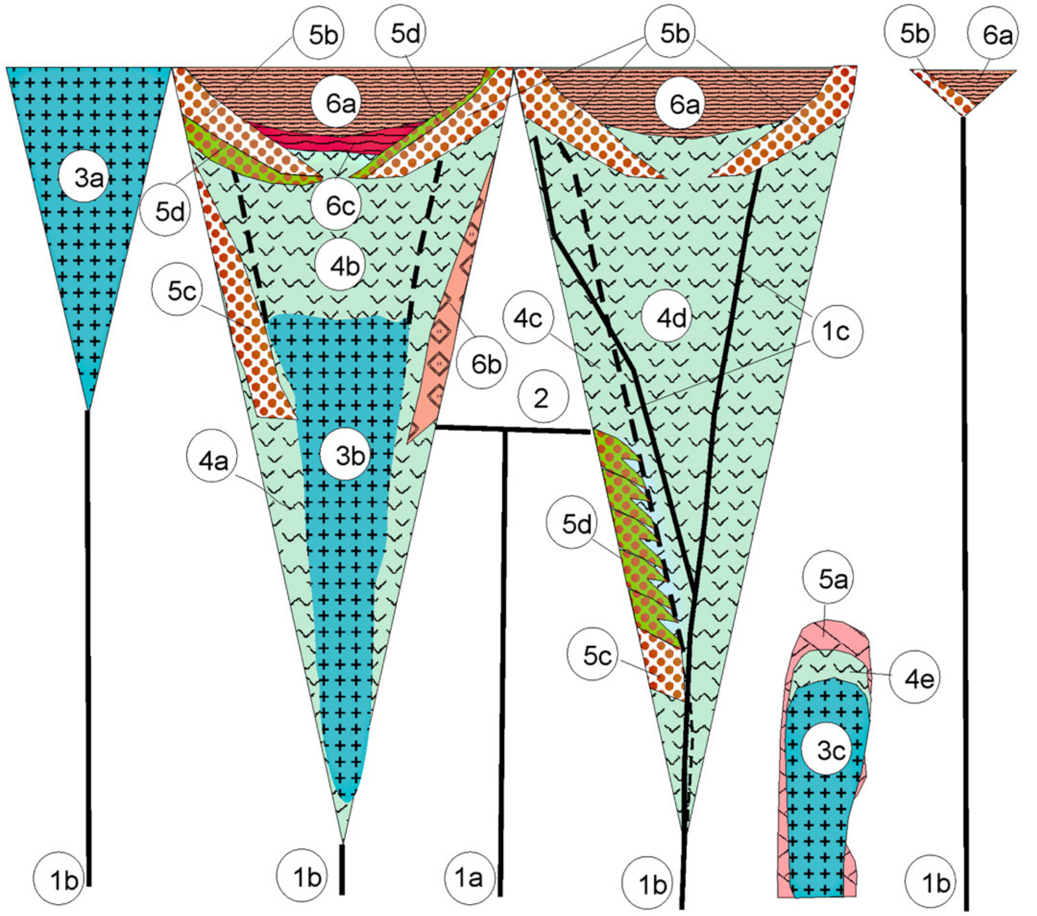


Fig. 2. Hawthorne's (1975) model of a kimberlite pipe.

Theories on proposed kimberlite pipe formation processes can be split into two main schools, namely those that favour the role of juvenile gases as the main driving force (magmatic model), and those that favour the interaction between magma and near-surface water (the phreatomagmatic or hydro-volcanic model) as the main process.



Unit	Old Nomenclature (Textural-genetic)	Preferred Nomenclature (Non-genetic)	Examples
1a	HK	Dyke - Pre-pipe	Finsch, Letseng
1b	HK	Dyke - Pipe-age	Bultfontein Mine
1c	HK	Dyke - Post-Pipe	Venetia K1, Finsch, Koffiefontein
2	HK	Sill	Wesselton Mine Water Tunnel Sills
3a	HK	CK	Damtshaa Mine BK9
3b	HK	CK	Jwaneng North Pipe / Venetia K1
3c	HK	CK	Wesselton Mine W7
4a	VK / TKB	MVK	Jwaneng North Pipe / Venetia K1
4b	TKB	MVK	Venetia K1 / Finsch F8
4c	TKB	MVK	Letlhakane DK1
4d	TKB	MVK	Orapa NPK
4e	HKB-TKB	MVK	Wesselton Mine W7 / De Beers DB5
5a	Contact Breccia	CRBr	Wesselton WCB1 / Venetia K1
5b	Talus Breccia	CRBr	Orapa, Damtshaa, Venetia K2
5c	Floating Reef	CRBr	Koffiefontein, Jagersfontein
5d	Floating Reef	VKBr	Venetia K2, Orapa AK1
6a	Epiclastic Kimberlite	RVK	Orapa
6b	Floating Reef / Crystal TK	RVK	Jwaneng / Venetia K1
6c	Pyroclastic Kimberlite	PK	Orapa AK1

Fig. 3. A schematic summary of the geology southern African kimberlite pipes. The table compares old textural-genetic nomenclature with modern non-genetic nomenclature. HK: hypabyssal kimberlite; TKB: tuffisitic kimberlite breccia; HKB: hypabyssal kimberlite breccia; CK: coherent kimberlite; MVK: massive volcaniclastic kimberlite; CRBr: country-rock breccia; VKBr: volcaniclastic kimberlite breccia; RVK: re-sedimented volcaniclastic kimberlite; PK: pyroclastic kimberlite.

4.4.1. Magmatic models

The magmatic model was proposed as early as 1914 by Wagner, but has undergone several changes over the last century. Wagner (1914) considered that the pipes formed as a result of the violent explosion caused by the sudden release of highly compressed vapour and gases of magmatic origin.

Several Russian scientists proposed an explosive-boring process that was the culmination of volatile build-up in magma chambers (see Mitchell, 1986 for detailed explanation).This process has been largely discounted by modern petrological studies (Mitchell, 1986).

Fluidization was proposed as an alternative to the explosive-boring hypothesis by Dawson (1962, 1967, 1971, 1980). This model expanded the ideas developed by Cloos (1941) to explain the occurrence of "tuffisitic" rocks in the diatremes of the Swabian Alb melilitites. Dawson (1971) believed that a CO_2-charged kimberlite magma would break through explosively from a depth of 2–3 km, and that the vent would be enlarged and filled by fluidized fragmental kimberlite. Woolsey et al. (1975) conducted experimental studies that supported this model, although the experimental results were largely dismissed by Mitchell (1986). McCallum (1976) used the experimental results to explain the development of blind intrusions in kimberlite root zones. Similar models were proposed by Davidson (1967), Kennedy and Nordlie (1968), McGetchin and Ulrich (1973), McGetchin et al., (1973), Ellis and Wyllie (1980), and Wyllie (1980). Mitchell (1986) pointed out that there were some difficulties associated with these emplacement models, particularly regarding the proposed speed of emplacement, which was regarded to be supersonic.

Clement (1982), Clement and Reid (1989) and Field and Scott Smith (1999) presented a magmatic emplacement model that was somewhat modified from that originally proposed by Dawson (1971). In this model, an embryonic pipe was formed as a result of the relatively slow upward migration of a breccia front created by exsolved magmatic gases that exploited pre-existing structures in the country rocks. The upward moving magma and breccia column was temporarily stalled by resistant barriers in the country-rock sequence such as dolerite sills and thick basalt lava sequences. Explosive breakthrough took place from about 500 m below the surface, and it was proposed that the diatreme was formed as a result of the downward modification of the embryonic pipe as a consequence of short-lived fluidization and authigenic brecciation.

Sparks et al. (2006) proposed a four-stage model for the formation of kimberlite pipes. According to this model, kimberlite eruption commenced near surface, initially from a fissure as a consequence of the magma being severely over-pressured due to its high volatile content. The initial eruption created a crater, but due to continued overpressure of the magma most of the erupted material was ejected from the crater. The second stage was that of pipe formation as the crater widened and deepened, and thus this stage was seen largely as an erosive phase. Stage 3 commenced when the crater widened to a critical point when the erupting mixture reached 1 atm. Beyond this point material was no longer ejected from the crater, and deposition within the pipe commenced. Fluidization of the deposited pyroclastic materials could then occur if conditions were correct. This fluidization could produce the characteristic mixed, massive character of typical diatreme zone "TKB" (*sensu* Clement and Skinner, 1979, 1985) or "MVK" (*sensu* Sparks et al., 2006). Importantly, fluidisation was seen as a process that modified unconsolidated pyroclastic debris in the vent, and was not proposed to be the process that formed the pipe. The final stage involved post-emplacement hydrothermal metamorphism and alteration. These different stages, particularly stages 2 and 3, were not envisaged to be simple two-stage processes, but processes that could be repeated frequently resulting in overlapping episodes of pipe widening, emptying and filling. It is therefore implied that the formation of a pipe could be a long-lived process, similar to that witnessed in almost any other type of volcano.

Wilson and Head (2007) proposed a model that by contrast to that of Sparks et al. (2006) could be formed in a very short time period (approximately 1 h). They proposed CO_2-charged magma rose from the mantle as a dyke, where CO_2-rich foam formed behind the dyke tip. This CO_2 was a supercritical fluid that had a vast pressure differential from the magma to the dyke tip. This resulted in the magma rising in a turbulent manner at a speed of 30–50 ms^{-1}. When the dyke tip breached the surface, CO_2 was vented and the walls imploded as a consequence of a downward propagating depressurization wave. This wave imploded the dyke walls, fragmented the magma and created a ringing fluidization wave that formed the diatreme. The magma in the dyke was instantly chilled.

4.4.2. Phreatomagmatic model

This model has been applied to kimberlites because phreatomagmatism is recognized as the predominant process in the formation of diatremes of a diverse suite of magma types (McBirney, 1963; Lorenz, 1973, 1975, 1979, 1984, 1985; Wolfe, 1980). In these maar-diatreme volcanoes it was possible to demonstrate phreatomagmatism on the basis of the location of maars, which were associated with river valleys and fracture zones, the presence of base-surge beds within the crater-rim and extra-crater pyroclastic deposits and the presence of accretionary lapilli in some of the pyroclastic beds. In addition, direct observation of the eruption of the Ukinrek maars in Alaska (Kienle et al., 1980) and detailed studies of the extra-crater deposits provided strong evidence for phreatomagmatic mechanisms in the formation of these volcanoes.

The proposed emplacement model is that rising kimberlite magma encountered groundwater in the near-surface environment that lead to repeated hydro-volcanic eruptions. These explosions initially excavate an explosion crater. The diatreme was formed as a consequence of the lowering of the groundwater table, and thus successively deeper magma-water contact points and explosive centres. Lorenz and Kurszlaukis (2003) demonstrated further that pipes of differing shape and depth could form as a result of different aquifer geometry as well as by variable supply rates of both magma and groundwater. Kurszlaukis and Barnett (2003) applied this model to the Venetia kimberlite cluster. Recent publications (Lorenz and Kurszlaukis, 2003, 2006, 2007) have proposed how this model can be used to explain root zone characteristics of kimberlite pipes, and that the root zones may be the location of major phreatomagmatic interaction. It was further suggested that phreatomagmatism could cause fluidisation that homogenised the tephra contained within the diatreme, thus producing the characteristic massive nature of the rocks that occupy these parts of diatremes. Water vapour could also cause hydrothermal alteration and mineralization of the pyroclastic materials.

In essence, the magmatic model of Sparks et al. (2006) and the phreatomagmatic model have much in common, with the major difference being the cause of explosive eruption. The magmatic model suffers from difficulties associated with determining the volatile content of kimberlite magma in the near-surface environment, and the apparent paucity of vesicles in non-fragmented rocks such as dykes. The phreatomagmatic model lacks direct evidence for characteristic phreatomagmatic pyroclastic deposits that are so obvious in the extra-crater deposits of volcanoes of other magma types.

5. Large mines

5.1. The Kimberley Mines

The discovery of the Kimberley Mines (Fig. 1) has been described above. The final one of five major mines to be discovered was the Wesselton Mine (previously called the Premier Mine, and not be confused with the Premier Mine (now Cullinan Mine) at Cullinan near Pretoria. Wesselton was discovered in 1891. These five mines, together with Jagersfontein and Koffiefontein were the major producers of diamonds in the world for the next 25 years (>90%, Lynn et al., 1998). The locations of the Kimberley mines, as well as a number of other kimberlites in the immediate area are shown in Fig. 4. The surface outlines of the five mines and vertical sections of the pipes cutting across the local stratigraphy are shown in Fig. 5.

5.1.1. Kimberley Mine

5.1.1.1. Discovery. Kimberley Mine (often referred to as "the Big Hole"), was discovered by Fleetwood Rawstorne's Red Cap Party in July 1871 (Roberts, 1976). It was originally called Gilfillian's and Colesberg Kopje.

5.1.1.2. Geology. The original surface outcrop was approximately 4 ha in area, and from historic descriptions it formed a low hill of whitish coloured rock, today interpreted to be the calcretized cap of surface kimberlite. There are several geological descriptions of the early mine from visiting European geologists, e.g., Patterson (1872), Shaw (1872), Cooper (1874), Maskelyne and Flight (1874), Lewis (1887, 1888). These descriptions reflect the authors' attempts of dealing with highly weathered near-surface rocks (so-called yellow ground), whilst also trying to provide a unified model that also explained the nearby alluvial deposits.

Rapid mining led to the kimberlite being mined-out and the mine closed by 1914. This means that no modern geological investigations were ever carried-out on probably the “archetypical” kimberlite. Maps of the mine show that it had a pipe-like shape, and that it probably consisted of diatreme-facies kimberlite (Clement, 1982). Lewis (1888) described the rock as “a volcanic breccia, but not an ash or a tuff”. He also noted that a large amount of the surrounding bituminous shale was enclosed in the rock and that this was variably baked and altered. Lewis (1887) also noted that it was the outer portions of the pipe that had the most abundant shale inclusions, and that it was these zones which contained the largest quantities of diamonds.

Moulle (1885; quoted by Clement, 1982) recognized five distinct columns of kimberlite in the upper parts of the Kimberley Mine. Wagner (1914) noted that the Kimberley pipe was in fact the coalescence of at least three distinct pipes arranged along a fissure having an E.N.E–W.S.W orientation. One of these pipes, the so-called “west-end” variety possessed a considerably lower diamond grade, and was associated with dykes which were thought to be connected to the low-grade St. Augustine's pipe about 1 km to the west of the Kimberley pipe. This lower grade kimberlite was distinctively enriched in phlogopite (Wagner, 1914). Wagner also observed large mega-blocks (the so-called floating reefs) of Karoo sedimentary rocks in the kimberlite down to a depth of 660 m below the current surface. Some of these Karoo-derived lithic clasts were interpreted to be derived from stratigraphic horizons above those currently exposed at the surface. Wagner also noted that although the kimberlite became fresher with depth, that it was still fairly altered at a depth of 1073 m below the surface.

Clement (1982) showed that the Kimberley pipe changed from diatreme to root zone at a depth of approximately 225 m below the current surface whilst Mitchell (1986) suggested that the Kimberley pipe, like Bultfontein, graded directly from a diatreme into a dyke without a root zone.

The kimberlite is of the Group-1 variety, although no formal dating has been conducted on it. Recent geochemical analyses of fresh kimberlite obtained from one of the Kimberley Mine dumps (Le Roex et al., 2003) confirmed its Group-1 character.

5.1.1.3. Mantle xenoliths and diamond inclusions. Specific studies of mantle xenolith studies for Kimberley Mine have not been conducted, and these are assumed to be similar to those from the other nearby mines, where specific suites have been studied. Similarly, diamond-inclusion studies have not been undertaken.

5.1.1.4. Diamonds. Wagner (1914) noted that the nature of the diamonds that were derived form the various parts of the Kimberley Mine at upper levels were well documented. The “west-end” portion of the mine yielded abundant brown stones of generally inferior quality as well as smoky, cracked sharp-edged octahedral diamonds. The northern portion of the pipe produced mostly boart, the north-western sector peculiar brown stones, and the central and southern portions yielded high proportions of cleavage fragments. At the time of writing, Wagner (1914) noted that the hard kimberlite being mined at depth in the Kimberley Mine yielded considerable quantities of boart and boart aggregates, numerous macles (twins), peculiar pinkish-brown diamonds, white octahedra, and small percentages of white cleavage fragments. Octahedral and hexoctahedral habits predominated.

5.1.1.5. Production. This kimberlite was without doubt the best economic prospect of the Kimberley pipes, which explains why it was mined-out so rapidly. It is difficult to reconcile the total production of diamonds from Kimberley Mine due to chaotic mining practices in its early days. The quoted figure (Lynn et al., 1998) is that 32.7 million carats were recovered from this pipe. Grade figures provided by Wagner (1914) are combined grades for Kimberley and De Beers Mines. Kimberley Mine was closed in 1914 due to prevailing economic circumstances. Williams (1932) stated that the mine was closed due to increased mining costs at depth. Flooding of the mine and the small size of the remaining ore at depth has not permitted its re-opening.

5.1.2. De Beers Mine

5.1.2.1. Discovery. It is not entirely clear who was responsible for the discovery of De Beers Mine (Fig. 4). A river diamond digger, Richard Jackson, was alerted to the fact that another digger named Cornelia was already recovering diamonds from a dry digging on the farm Vooruitzig that belonged to a farmer named De Beer. On investigating, Jackson found this to be true, and he pegged a claim on the property, soon to be followed by many others (Roberts, 1976).

5.1.2.2. Geology. Lewis (1887) described two varieties of “blue ground” from De Beers Mine, one of which was diamondiferous, and the other barren of diamonds. Both were described as peridotites (this before “kimberlite” had been formerly proposed), with the diamond-bearing rock being distinguished from the barren rock by the presence of abundant inclusions of black carbonaceous shale. Wagner (1914) also recognized two major types of kimberlite within the pipe at upper levels, and described the presence of a large diabase (dolerite) “floating reef”. Williams (1932) described and illustrated the presence of floating reefs of basalt and Karoo sediments. He also drew attention to the western mining limit outlined by Rhodes and the demarcation of this limit by the presence of a prominent internal kimberlite dyke. These were no doubt the barren and rich zones referred to by Lewis (1887) and Wagner (1914).

Clement (1982) described the geology of this pipe between the 245 and 785 m levels below surface. He noted that this pipe is a good example of a rapid transition between root and diatreme zones, and that the pipe increased in size below 455 m level as it passed downwards from the diatreme into the root zone (Fig. 6). He sub-divided the De Beers kimberlite into 6 petrographic varieties (which he named DB1–DB6) all of which were hypabyssal-facies kimberlite (K) or kimberlite breccias (KB). He noted that at surface only two varieties were likely to have been present, namely DB3 and DB5, which corroborated the earlier work of Lewis (1887), Wagner (1914) and Williams (1932). Clement also highlighted the presence of breccia zones associated with the pipe, which he termed “contact breccias”. Clement demonstrated a close correlation between the DB-varieties and diamond grade, and noted that the DB5 and DB3 types contained significantly higher grades than the intervening DB2 type. He noted that the DB2 variety was a monticellite-rich kimberlite, while the DB5 was a distinctive phlogopite-rich kimberlite. A comprehensive account of the geology, mining history and diamond characteristics of De Beers Mine is provided by Clement et al. (1986).

De Beers is considered a typical Group-1 kimberlite. It has been radiometrically dated using several methods (Allsopp et al., 1989) that have produced age ranges of 84±3 Ma using Rb–Sr on phlogopite, (Allsopp and Barrett, 1975); 78±3 Ma using fission tracks on zircon (Green, 1985); 87±2 Ma using the Ar–Ar method on phlogopite (Fitch and Miller, 1983); and ~92 Ma using U–Pb systematics on zircon (Davis, 1977). Whole-rock geochemistry and groundmass mineral chemistry data are provided by Clement (1982) and Pasteris (1980, 1982, 1983).

5.1.2.3. Xenoliths. The xenoliths from this mine were described as consisting mostly of peridotites (lherzolites, harzburgites, wherlites and dunites), with less common mica-rich rocks (the MARID suite) and rare eclogites (Lawless et al., 1979). Bishop et al. (1975) described sulphide-bearing spinel lherzolites from the mine.

5.1.2.4. Diamonds. The diamonds from De Beers were described by Wagner (1914) as bearing a close resemblance of those from

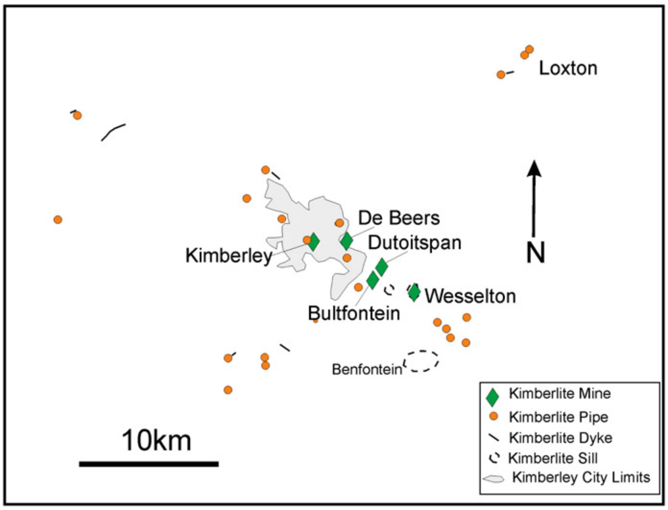


Fig. 4. The Kimberley area showing the location of kimberlites relative to the city limits of Kimberley. Kimberlites shown in green are the large mines, those in orange have undergone only small scale mining.

Kimberley Mine. The distinctive features being the low abundance of boart, the rarity of white stones with white cleavage, the rarity of large macles, the presence of dodecahedral fancy stones with a deep yellow colour and a greater abundance of large yellow diamonds. He also noted that the low-grade western portion of the mine yielded a considerable proportion of brown stones of inferior quality. Harris et al. (1984) in a quantitative analysis of bulk-sample diamonds from all of the Kimberley mines suggested that overall the primary growth characteristics of the diamonds from the different mines were similar, however they noted some peculiarities with respect to the diamonds from De Beers mine. These included a high proportion of irregular stones and a small number of octahedral stones, as well as a high proportion of stones exhibiting weak blue fluorescence under UV light. They also noted lower levels of plastic deformation in De Beers diamonds compared to those from other Kimberley mines.

Clement et al. (1986) made a comparison between diamonds obtained from the DB1, DB2 and DB3 kimberlite varieties. Very minor differences were noted, and it was generally concluded that the diamonds in all types had similar primary growth forms and subsequent histories. A notable feature was the high proportion of broken crystals and irregular fragments, most of which were etched, thus indicating that the breakage process must have been natural.

5.1.2.5. Diamond inclusions. The study by Harris et al. (1984) showed that peridotitic inclusions dominated (79.8%) over eclogitic (7.8%) and sulphides (12.4%). Of the peridotitic inclusions, olivine and enstatite (33.7%) were the most abundant together with chromite (31.5%) and garnet was relatively uncommon (9%).

5.1.2.6. Production. De Beers had a sporadic life as a mine. It was worked by open-cast methods from 1871 until 1908 and then closed until 1963 when it was re-opened. During the pre-1908 period, approximately 40 million tons of ore was treated from which approximately 23 million carats were recovered at an average grade of 64 carats per hundred tons (cpht). When the mine re-opened in 1963 as an underground operation, the grade peaked at about 27 cpht, and then declined steadily with time and depth of mining. This also

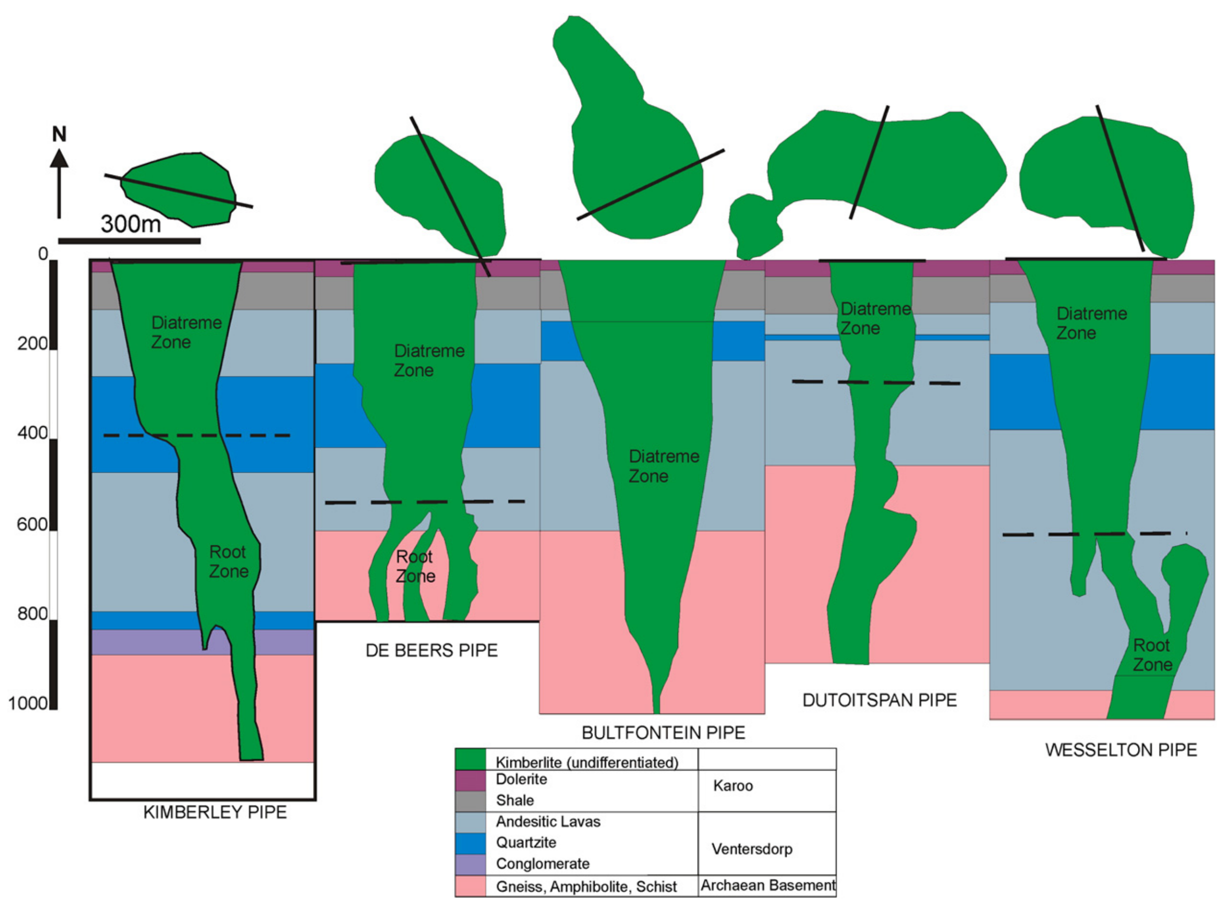


Fig. 5. Surface outlines and vertical cross-sections through the five Kimberley mines showing the stratigraphy through which the pipes were emplaced, and the transition lines between diatreme and root zone kimberlite, after Clement (1982).

corresponded with an ever decreasing proportion of the higher graded DB3 and DB5 varieties, and the non-selectivity of underground mining methods. Clement et al. (1986) demonstrated from sampling exercises that the grades of the individual kimberlite types varied greatly. The DB2 variety had an average grade of 3.57 cpht, whereas the DB3 variety has an average grade of 60.88 cpht. Further they demonstrated that the grade of the DB3 variety declined with depth at a rate of 18 cpht per 100 vertical metres. De Beers Mine was finally closed in 1990.

5.1.3. Bultfontein Mine

5.1.3.1. Discovery. The discovery of Bultfontein (Fig. 4) is described above. At discovery, the outcrop appears to have been obscured by the presence of a pan, a low depression filled during the wet season by ephemeral water.

5.1.3.2. Geology. Wagner (1914) noted two kimberlite varieties in this pipe. Williams (1932) described a brecciated column containing abundant fragments of sandstone, shale and dolerite that extended from surface down to the 410 m level. Clement (1982) described this as a non-coherent floating reef. Clement (1982) divided Bultfontein into three varieties, which he termed B1, B2 and B3. B1 was a diatreme-facies TKB which dominated volumetrically, whilst B2 enveloped B1 and was classified as a kimberlite breccia (hypabyssal-facies). B3 formed part of what was known as the NNW Extension, an enlargement on a dyke.

Bultfontein was notable for the fact that it possessed no root zone (Clement, 1982) having a very regularly shaped diatreme that tapered continuously downwards until it turned into a dyke. Recent drilling (2000–2003) confirmed that this is indeed the case.

Bultfontein is considered a typical Group-1 kimberlite. It has been dated using a variety of techniques, all of which confirm its Cretaceous age. Kramers et al. (1983a) obtained an age of 84±0.9 Ma on phlogopites from veined metasomatized xenoliths. Allsopp and Barrett (1975) analyzed phlogopites for Rb–Sr isotopes and obtained an age of 84±3 Ma. Various U–Pb ages were obtained from zircons by Davis (1977) that range from ~81.7 to ~91.2 Ma.

5.1.3.3. Xenoliths. The xenoliths from this mine are described as consisting mostly of peridotites (lherzolites, harzburgites, wherlites and dunites), with less common mica-rich rocks (the MARID suite) and rare eclogites (Lawless et al., 1979). Rare polymict peridotites were also described that were interpreted by Lawless et al. (1979) to represent remnant conduit filling left behind in the mantle by earlier phases of kimberlite intrusion. They consisted of a mixture of peridotite, eclogite and megacryst fragments, cemented by ilmenite, phlogopite, rutile and sulphides. An age of 82.8 Ma has been obtained for them (Lawless et al., 1979). Wyatt and Lawless (1984) interpreted these rocks to be formed as a consequence of a brecciation event in the mantle by fluids that were enriched in H_2O, TiO_2 and K_2O. These xenoliths have contributed greatly to developing our understanding of metasomatic processes in the mantle. The interested reader is referred to papers by Aoki (1974), Dawson and Smith (1977), Jones et al. (1982), Erlank et al. (1982), Kramers et al. (1983b), Erlank et al. (1987), Waters (1987a, 1987b), Waters and Erlank (1989), Waters et al. (1989), Hawkesworth et al. (1990), Konzett et al. (1998), and Gregoire et al. (2002) for further detail.

5.1.3.4. Diamonds. The diamonds from the main part of Bultfontein (Clement's B1) were described by Wagner (1914) as being characterized by "peculiarly" rounded white or pale-greenish octahaedra which are pitted and spotted. The mine also produced some clear, sharp-edged octahedra, as well as occasional smooth, yellow octahedra and hex-octahedra. The latter were the only stones similar to those found in nearby Dutoitspan Mine. Wagner further noted that diamonds form the "stalk-end" area of the pipe (Clement's B3) differed in colour and crystallization form from those of the main pipe. Williams (1932) confirmed Wagner's observations adding that Bultfontein diamonds were uniformly roughened by minute flutes, and that nearly every stone had some defect. He also noted that the average size of Bultfontein diamonds was small and that the predominant colour was white. Both Wagner and Williams noted that Bultfontein's diamonds are completely different from those recovered at nearby Dutoitspan. The study by Wilding et al. (1995) found that most of the inclusion-bearing diamonds they studied were macles of brown colour, and that these were predominantly of Type IaA, with rare Type-II diamonds being present.

5.1.3.5. Diamond inclusions. Diamond-inclusion studies conducted by Harris et al. (1984) and Wilding et al. (1995) found that the vast majority of inclusions (80%) were of peridotitic chemistry, whilst less common eclogitic inclusions and sulphides made up the remaining 20%. A high proportion (41%) of the peridotitic inclusions were chromites, and it was found that the chemistry of these inclusions varied according to the location within the diamond, those located near the periphery being more Fe- and Ti-rich.

5.1.3.6. Production. The diamond grade of Bultfontein Mine proved to be remarkably consistent over the long period that it was mined, and for most of its life it was the mine with the highest grade of the Kimberley pipes, especially after the closure of Kimberley Mine. Following chaotic open-pit mining, instabilities of the Karoo sedimentary rocks in the mine walls forced mining underground, where initially inclined chambering was used as the mining method. Later block-cave and sub-level block-caving methods were used. The deepest mining level was 848 m below surface. Bultfontein Mine closed in 2005 as economic conditions made it no longer profitable.

5.1.4. Dutoitspan Mine

5.1.4.1. Discovery. The Dutoitspan pipe (Fig. 4) was like Bultfontein, overlain by an ephemeral pan. This pipe though had an elongated shape and far more complex geology than Bultfontein, which is only 500 m away.

5.1.4.2. Geology. Shaw (1872) described the highly altered kimberlite from the early days of mining as a fine clayey detritus. Wagner (1914) recognized four kimberlite varieties in this pipe. Wagner (1914) and Williams (1932) noted the presence of an extremely large floating reef in the upper portion of the pipe (known as Mount Ararat). Wagner thought it to be large autolith of kimberlite, and Williams claimed that it was a large piece of upwardly transported Ventersdorp lava.

Clement (1982) paid particular attention to Dutoitspan, as an extensive array of sampling tunnels were excavated through the kimberlite during the 1970's. These provided unprecedented exposure of kimberlite. From his mapping and petrographic work, he described 18 varieties of kimberlite which he named D1-18 (Fig. 7). These were mostly varieties of diatreme-facies and hypabyssal-facies kimberlite and breccias. Dutoitspan was interpreted by Clement to be a root zone, cut by a number of diatremes. A notable feature of Dutoitspan was the presence of the so-called Auxilliary Pipe, which is partly attached to the south-western part of the main pipe, but, part of this pipe is blind and does not extend through to the current surface. What is also evident is that this auxiliary pipe contained numerous varieties of hypabyssal kimberlite (K) and kimberlite breccia (KB).

Dutoitspan is a typical Group-1 kimberlite of Cretaceous age. Allsopp and Barrett (1975) determined an age of 84±3 Ma using the Rb–Sr method on phlogopite which was confirmed by Davis (1978) using the U–Pb method on zircon when he produced an age of ~83.8 Ma. Green (1985) used the fission-track technique on zircon to determine an age of 82±3 Ma.

There are no published specific accounts of xenoliths from Dutoitspan.

5.1.4.3. Diamond inclusions. Harris et al. (1984) conducted a diamond-inclusion study on a suite of diamonds from Dutoitspan. They found that these were predominantly peridotitic (81.3%) with low abundances of eclogitic (5%), sulphides (8.8%) and clouds (5%). The peridotitic inclusions were predominantly olivine/enstatite (32.5%) and chromite (30%), with low abundance of garnet (7.5%) and clinopyroxene (1.3%). The "clouds" referred to above are inclusions of grey-coloured, extremely fine-grained inclusions (1–5 5 μm in size) of uncertain paragenesis. These are typical of Kimberley diamonds (Harris et al., 1984).

5.1.4.4. Diamonds. There was a wide variation in diamond quality of the different geological zones, with the eastern D13 and D14 varieties yielding high proportions of large, high-quality stones, particularly coloured stones (Dunn, 1874). Wagner (1914) noted that Dutoitspan produced the best quality diamonds of all the Kimberley mines. It produced an unusual abundance of large yellow stones and fine silver capes and brilliant white stones with the faintest tinge of yellow. It was also notable for very large macles, a fair proportion of Bultfontein-like stones and very little boart. The presence of Bultfontein stones was taken as an indication that the two pipes are located on the same dyke system. Furthermore, he noted that the Dorstfontein variety (Clement's D11) produced clear white stones which were quite different to those from the eastern parts of the mine. Williams' (1932) description of Dutoitspan diamonds concurred largely with those of Wagner (1914), and he also noted the much larger average size of the stones, and the occurrence of several stones larger than 100 carats each. The largest diamond ever found in the Kimberley mines was the "616" (of 616 carats) or Kimberley Octahedron (Bruton, 1978), which was "picked-up" by a miner in Dutoitspan in 1974. This diamond is the largest ever octahedral diamond that has been recovered.

5.1.4.5. Production. From the earliest mining it was obvious that Dutoitspan had a highly variable distribution of diamond grades. Most of the mining activity focused on two kimberlite varieties (D13 and D14) which occurred on the eastern side of the mine. Although the other varieties contained diamonds, none ever proved significant. The D11 variety, known to Wagner and subsequent miners as the "Dorstfontein" was notably lower in its diamond tenor. Wagner showed that this was the consequence of a completely different "outburst" of kimberlite. Early mining utilized open-cast methods, but later various underground methodologies were employed, including inclined chambering, sub-level caving and block-caving. The deepest mining level was 870 m below surface. Dutoitspan Mine was closed in 2005 due to prevailing economic conditions.

5.1.5. Wesselton Mine

5.1.5.1. Discovery. Wesselton (Fig. 4) was the last of the Kimberley mines to be discovered in 1890. The discovery was credited to a prospector named Fabricius who picked up shiny minerals in the veldt that turned out to be a diamond and garnets (Roberts, 1976). This attracted a "rush" of diggers but also the interests of De Beers, who eventually took over the mine in 1891.

5.1.5.2. Geology. The geology of the early mine was described by Wagner (1914) who highlighted the presence of floating reefs within the north-eastern sector of the pipe, and noted that these consisted of a breccia of materials derived from the adjacent wallrocks and from formations above those currently exposed at Kimberley. The latter included mudstones containing fish fossils from the Beaufort Series. He also provided evidence for dykes and sills in the immediate surrounding country rock.

Clement (1982) and Shee (1985) conducted detailed studies of the kimberlites at Wesselton. Clement divided the kimberlite into 10 varieties (W1–10), consisting of diatreme- and hypabyssal-facies kimberlites and breccias (Fig. 8). Clement also described the root zone of the mine, which remains one of the best documented examples of such a zone. The widening of the pipe below the diatreme zone and the presence of blind intrusions of kimberlite are noteworthy features, as are the presence of contact breccias. The complexity of the root zone can be contrasted with the simplicity of the overlying diatreme. The upper diatreme consisted of two main varieties W4 and W9. These varieties also hosted floating reefs down to a depth of 800 m, whilst the root zone kimberlites were free of such inclusions. The complexity of the root zone is illustrated in Fig. 8.

Shee (1985) described in detail the petrography, mineralogy, mineral chemistry and bulk-rock and isotope geochemistry of the various Wesselton kimberlite varieties. From this he developed a petrogenetic model for the emplacement of the kimberlite. He showed that the pipe contained multiple small batches of kimberlite melt that formed by low degrees of partial melting of a depleted garnet-free harzburgite source that was metasomatically enriched by C, H and O. Isotopically the kimberlite is a Group-1 type, which he speculated was formed in the asthenosphere. Shee also highlighted the occurrence of pre-pipe sills and dykes surrounding the kimberlite. Shee (1984) showed that the oxide minerals, particularly spinels and ilmenites could be used to trace the geochemical evolution of the magma batches that produced the Wesselton kimberlite and that for instance the W2 and W3 kimberlite varieties had almost identical groundmass spinel compositions with well-developed titanomagnetite evolutionary trends, whereas the W7 lacked this evolutionary trend and the W3a and W8 were considerably less iron-rich. The surrounding sills were the most evolved (despite being earlier intrusive phases) and had a substantially different geochemical evolution when compared to rocks in the main pipe.

The Cretaceous age of the pipe has been confirmed by several different dating methods, that included U–Pb in perovskite (88 ± 2 Ma — Smith et al., 1985; ~90 ± 14 Ma — Kramers and Smith, 1983), Rb–Sr in phlogopite (81 ± 4 Ma — Allsopp and Barrett, 1975), U–Pb in zircon (90 ± 3 Ma — Davis, 1977) and fission-track in zircon (86 ± 3 Ma — Green, 1985).

5.1.5.3. Xenoliths. Shee (1985) conducted an analysis of run-of-mine concentrate to attempt to quantify the proportions of various mantle xenolith types at Wesselton. He showed that the majority were harzburgites (36%), followed by ilmenite macrocrysts (18%), garnet lherzolites (16%), lherzolites (13%) and MARID suite rocks (5%). Notably absent were clinopyroxene and garnet macrocrysts.

5.1.5.4. Diamond inclusions. Harris et al. (1984) found that the diamond-inclusion suite at Wesselton was predominantly peridotitic (90%) with only minor eclogitic (3.2%), sulphide (4.2%) and cloud-like inclusions (2.7%) represented. Amongst the peridotitic inclusions olivine/enstatite (37.9%) and garnet (29.2%) predominated, whereas chromite (6.5%) and clinopyroxene (1.4%) were rare. This low abundance of chromite relative to garnet served to distinguish the Wesselton diamond-inclusion suite from those found in the other Kimberley mines where higher chromite abundances were noted.

5.1.5.5. Diamonds. The diamonds from Wesselton were described by Wagner (1914) as being characterized by the presence of large numbers of small octahedral stones, the rarity of cleavage fragments and the abundance of small stones below 2 carats in size. These characteristics served to distinguish them from the diamonds from any of the other mines in Kimberley. Yellow diamonds were noted to be absent, but fancy golden-coloured irregular stones were present. There were also a considerable proportion of brown stones of inferior quality. Williams' (1932) observations concurred largely with those of

Wagner. In addition he noted that diamond sizes ranged up to 20 carats but that these large stones (>20 carats) appeared to be rare. The higher proportion of octahedral stones at Wesselton when compared to the other Kimberley mines was also noted by Harris et al. (1984). Variations in the ratio of octahedral to dodecahedral stones with size seen at other mines was not observed at Wesselton. In addition, Wesselton had the highest proportion of stones exhibiting strong blue ultraviolet fluorescence in the Kimberley cluster. Robinson et al. (1989) compared the diamond characteristics of the W2, W3, W5 and W7 kimberlite varieties within a single sieve class. This showed that diamonds from the various facies have similar colours, main crystal forms and shapes, but that they had different surface textures. Diamonds from the two hypabyssal-facies kimberlites (W2 and W3) had more common corrosion sculptures and shallow depressions than the diamonds from the W5 (TKB) and W7 (transitional) types.

5.1.5.6. Production. The diamond grade in Wesselton was highly variable, and closely linked to the varieties of kimberlite identified by Clement (1982) and Shee (1985). Wesselton was mined by open-cast methods and then later by various underground methods. The deepest mining level at Wesselton was 995 m below surface, the deepest diamond mine in the world. Wesselton Mine closed in 2005.

In addition to the details listed above, there have been many studies of mantle xenoliths and at least one study of diamond-inclusions (Phillips et al., 2004) that refer to all of the Kimberley mines (sometimes also called De Beers Pool) without differentiation as to which pipe the materials were derived from. The study by Phillips et al. (2004) provided a comprehensive account of diamond-inclusion chemistry and thermobarometry. This demonstrated the predominant harzburgitic paragenesis of the inclusion suite and provided some constraints on the temperatures and pressures of diamond formation (1082–1320 °C and 4.6–7.7 Gpa). The study of mantle xenoliths is summarized by Nixon (1987) and the other references therein.

5.2. Koffiefontein Mine

5.2.1. Discovery

The discovery of Koffiefontein (Fig. 1) is credited to a transport driver named Bam (Bruton, 1978) who discovered the first diamond there in 1870. The prospect was worked by diggers until it became too deep to mine by manual means. It was then purchased by Alfred Mosely who formed a company that worked it until 1891 when De Beers bought the mine. De Beers worked it until 1931 and then closed it. It was re-opened in 1971 to replace Jagersfontein Mine. De Beers subsequently closed it again in 1982 and re-opened it again in 1986. It was closed again in 2005, and has recently been sold to Petra Diamonds.

5.2.2. Geology

Wagner (1914) described two main kimberlite varieties, as well as examples of late-stage internal dykes. Clement (1982) recognized three varieties of kimberlite in the main pipe, which he named KOF1-3. These comprised two diatreme-facies (KOF1 and 2) and a hypabyssal-facies kimberlite (KOF3). The KOF-1 variety was a TKB that occupied the main pipe, whereas KOF-2 was a TKB that occupied the “West Fissure”. The KOF-3 variety was the hypabyssal intrusion that occurred as the “East Fissure”. A further notable feature was the presence of a large floating reef comprising various Karoo lithologies in the main pipe. A satellite kimberlite pipe named Ebenhaezer, which also contained diatreme-facies kimberlite, is located close to the main pipe. Clement speculated that these two pipes once coalesced to form a single large crater.

Mapping of deeper levels by Naidoo et al. (2004) found evidence for at least two main volcaniclastic kimberlite varieties in the main pipe, and demonstrated that these were geochemically distinct based on their groundmass spinel compositions. They described the layered nature of the “floating reef” as well as intermixing between layered breccias and relatively lithic-poor volcaniclastic kimberlite (Fig. 9). They also demonstrated that the kimberlite between the floating reef and the eastern contact at depth to be geochemically distinct from the main kimberlite variety that had been mined throughout the life of the mine. They called into question the appropriateness of the “TKB” classification of Clement (1982).

The only published radiometric age for Koffiefontein is that of Davis (1978) who obtained an age of ~90.4 Ma using the U–Pb method on zircons.

5.2.3. Xenoliths

The only recorded study of xenoliths from Koffiefontein is that by Hanrahan et al. (2003) who recorded the presence of five varieties of peridotites, namely spinel peridotites, low *P–T–T* coarse peridotites, high *P–T* coarse peridotites, high *P–T* transitional peridotites and high *P–T* sheared peridotites.

5.2.4. Diamond inclusions

Rickard et al. (1989) studied a suite of 58 diamonds from Koffiefontein. They found that the majority of these (93%) were peridotitic, and the remainder were either eclogitic or sulphides. The major peridotitic suite were found to be harzburgitic or dunitic in composition, with lesser quantities of lherzolitic and eclogitic varieties. Some of the peridotitic minerals were noted to be unusually K-rich, and ferro-periclase was recorded as an inclusion. Pearson et al. (1998) conducted an Re–Os isotopic study of sulphide inclusions in peridotitic and eclogitic diamonds from Koffiefontein. These showed that several periods of diamond formation had occurred; including Archaean and Proterozoic growth periods but that some of the sulphide inclusions produced ages that were close to the emplacement age of the kimberlite.

5.2.5. Diamonds

The diamonds from Koffiefontein were described by Wagner (1914) as being characterized by “very good average quality of its melee'”, which rendered it unique amongst kimberlites pipes. The stones are mostly pure blue-whites and octahedral-shaped crystals predominated. Wagner further noted that similar quality diamonds occurred in the Ebenaezer satellite as well as the nearby Klipfontein Mine, all of which were proposed to lie along a connected dyke system. Williams (1932) confirmed the high quality of Koffiefontein stones and noted that a peculiarity was the abundance of stones with laminated structure. Harris et al. (1979) examined diamonds obtained from the 244 and 488 m sampling tunnels, as well as from production between 100 and 160 m below surface. They concluded that the diamonds showed only minor variations in morphology with depth but that there were significant changes in colour with depth, for example the proportion of colourless stones declined from 60% on the 244 level to 40% on the 488 level, whereas yellow and brown stones increased from 30 to 50% over the same interval. They also showed that the relative proportion of yellow to brown stones increased with size at all levels. A comparison with diamonds obtained from the nearby Ebenhaezer pipe was also made. This showed only slight differences, namely the presence of a few cubo-octahedral stones at smaller sizes and slightly higher proportions of flattened dodecahedra. Deines et al. (1991) conducted a carbon-isotope and nitrogen study of both lithospheric and asthenospheric diamonds from Koffiefontein and they found that the two populations were indistinguishable in terms of carbon-isotopic signature, but that the asthenospheric variety were mostly Type-II in terms of their nitrogen aggregation state.

5.2.6. Production

The diamond grade at Koffiefontein is very much lower than that seen in the Kimberley mines and this was further complicated by the presence of the barren or near-barren “floating reef”. The low grade was compensated for by high average diamond values. Its history clearly illustrates the marginal character of the mine, and although it

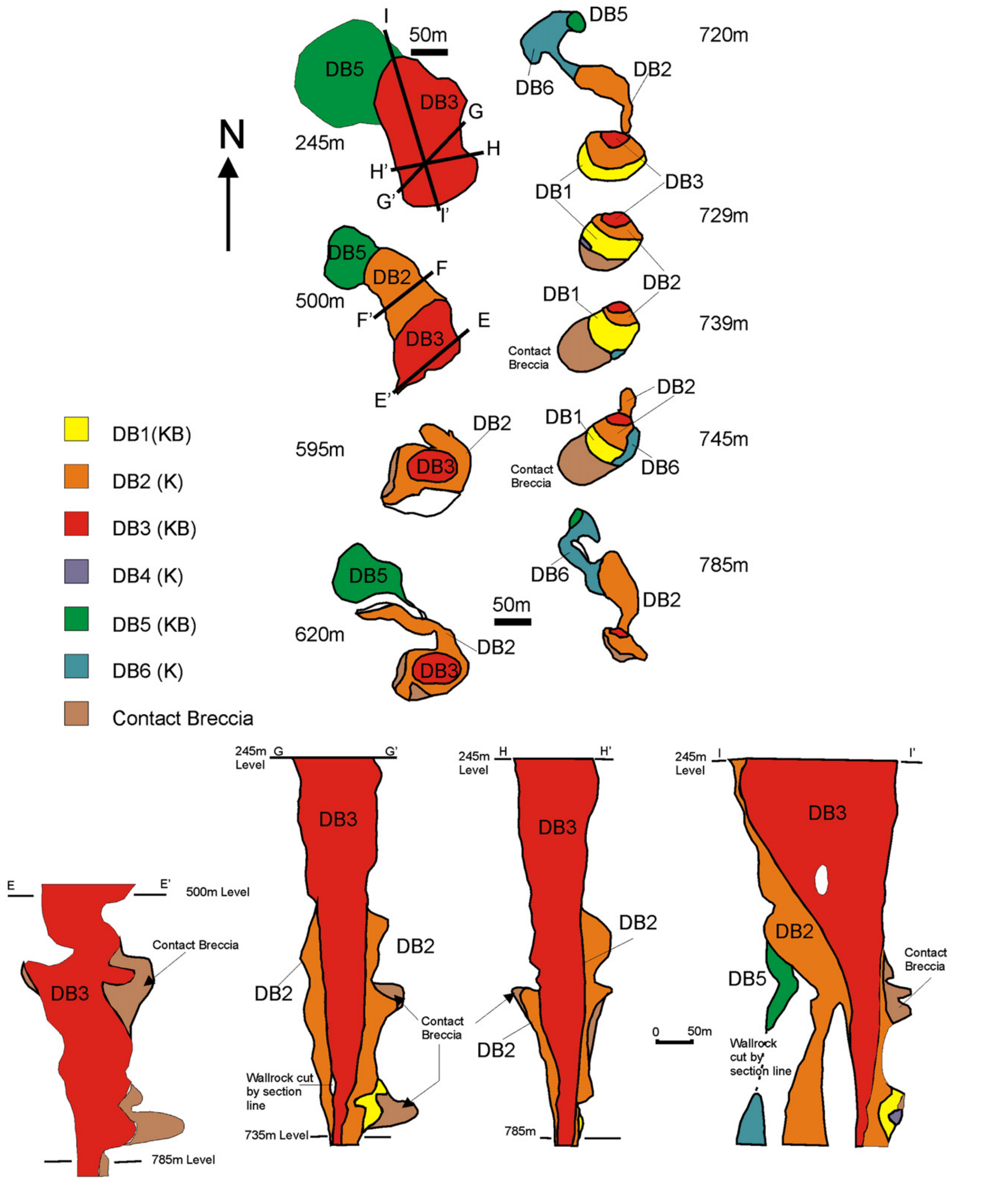


Fig. 6. A summary of the internal geology of De Beers Mine, adapted from Clement (1982). K refers to hypabyssal kimberlite and KB to hypabyssal kimberlite breccia as defined by Clement and Skinner (1979, 1985).

produced diamonds of exceptional quality, the diamond grade was too low to sustain the mine at times when the diamond market was weak.

5.3. Jagersfontein Mine

5.3.1. Discovery

Diamonds were discovered at Jagersfontein (Fig. 1) in 1870. This discovery is credited to a farm foreman known as De Klerk, who, having heard from passing diamond diggers about how to prospect for diamonds tried his luck on a small, ephemeral stream running through the farm Jagersfontein. In August 1870 he found a 50-carat diamond (Bruton, 1978). This event sparked a minor rush to the area, but the occurrence of diamond was found to be sporadic, and the local farmer charged the diggers high fees for the privilege of prospecting on his farm. It was only in 1878 that it was realized that this diamond occurrence was indeed a pipe (Bruton, 1978). The main pipe is the only kimberlite to have been mined in the area. A further six pipes and dykes have been tested but found to be un-economic.

5.3.2. Geology

The main kimberlite pipe intrudes sedimentary rocks of the Karoo Supergroup and a Stormberg-aged dolerite sill of 245 m thickness. The pipe is slightly inclined to the east (Wagner, 1914). Wagner noted the presence of extensive breccias derived from Karoo sediments above the current erosion level. These breccias were referred to by Williams (1932) as "grey-ground" and had very low diamond grades. Williams stated that these breccias consisted of abundant red and grey mudstone fragments, which in places contained little or no kimberlitic matrix. This "grey-ground" occurred from the surface to the greatest depths of the mine. Jagersfontein was also noted as a key location where Stormberg basalts were preserved as down-rafted fragments. The remainder of the kimberlite was termed "blue-ground". No modern studies have been carried-out on this kimberlite since the mine closed in 1971.

The only published age for Jagersfontein is 85.6 ± 1.0 Ma obtained by Smith et al. (1985) using the Rb–Sr method on phlogopite.

5.3.3. Xenoliths

Jagersfontein has attained legendary status as a prime locality for mantle xenoliths. The suite includes peridotites, eclogites, pyroxenites, metasomatised peridotites (Field et al., 1989; Stiefenhofer, 1998) and rocks of the megacryst suite (Hops et al., 1989). In addition, unusual corundum-bearing rocks have also been discovered (Mazzone and Haggerty, 1989). Haggerty and Sautter (1990) and Sautter et al. (1991) found mantle xenoliths that are interpreted to have been derived from 300–500 km depths. These xenoliths contain garnets that have exsolved rods of clinopyroxene that are proposed to have originally formed as silicon-rich majoritic garnet.

5.3.4. Diamond inclusions

A study by Tsai et al. (1979) showed that both peridotitic and eclogitic inclusions occur within diamonds from Jagersfontein. The relative abundance of the two varieties is however not recorded.

5.3.5. Diamonds

Williams (1932) described the diamonds as "superior". Wagner (1914) described it as a "cleavage-mine" as over 50% of its production consisted of cleavage fragments. The high quality of the stones is due to a high proportion of pure blue-white stones. Another notable feature was the presence of large black spots on the surfaces of the diamonds. Jagersfontein produced a number of the world's largest diamonds including the 971.75 carat Excelsior and 640 carat Jubilee (previously named "Reitz"). Bruton (1978) described the discovery of the Excelsior diamond, and how it was almost stolen. At the time of its discovery it was the largest diamond ever recovered. Wagner also noted the recovery of un-named stones of 567 and 537 carats. Bruton also lists 572.3 and 350 carat un-named stones from Jagersfontein that were discovered in 1955 and 1951 respectively. Bruton (1978) noted that the colour description "blue-white" was devised to describe specific Jagersfontein diamonds. These diamonds owe their colour to a strong blue fluorescence. However, this colour was exceptionally rare and often misused in the description of diamonds from other localities. The study by Deines et al. (1991) demonstrated that at least six different diamond sources could be recognized in Jagersfontein diamonds (both in the lithosphere and asthenosphere) on the basis of carbon isotope studies and nitrogen aggregation states. Tappert et al. (2005) provide further evidence for the asthenospheric origin of eclogitic diamonds, and related these to deep subduction processes that started 200 Ma ago.

5.3.6. Production

The diamond grade of Jagersfontein was always very low (<10 cpht), but it produced diamonds of extremely high quality. Early open-cast mining of Jagersfontein was assisted by the presence of the thick dolerite sheet, which made the side walls of the mine much more stable than those at Kimberley or Koffiefontein. Underground mining only commenced in 1910 when a shaft was sunk. The mine only closed during the great depression of the 1930's and during the Second World War. Jagersfontein was the first kimberlite mine where block-cave mining was used as the only mining method. This happened in 1958 following trials on a portion of Bultfontein Mine (Bruton, 1978). The mine finally became uneconomic and was closed in 1971. This was attributed to a declining grade as a result of increasing proportions of grey ground and increasing mining costs.

5.4. Premier (Cullinan) Mine

5.4.1. Discovery

The Premier diamond mine (Fig. 1) was the first major discovery in the old Transvaal Province of South Africa. This pipe is the largest (32 ha at surface) ever found in South Africa (Bartlett, 1998). It was discovered as a consequence of prospecting for heavy minerals in the nearby Pienaars River and its tributaries, where diamonds were found and traced back to their source in the hills at Cullinan, east of Pretoria. Ten other kimberlites were found in the immediate area, but none have proven to be economically sustainable.

5.4.2. Geology

The pipe intruded rocks of the Transvaal Supergroup as well as igneous rocks of the Bushveld Igneous Complex. The kimberlite has been radiometrically dated at 1179 ± 36 Ma (Smith, 1983b) using Rb–Sr in clinopyroxene and 1202 ± 72 Ma using U–Pb in perovskite (Kramers and Smith, 1983). The pipe is itself intruded by a gabbro sill of 1150 Ma (Bartlett, 1998).

The internal geology of the pipe was first described by Wagner (1914) who noted the presence of a "floating reef" of Waterberg quartzite which occurred in the middle of the pipe and was associated with a considerable rubble zone of rounded quartzite and sandstone boulders. These Waterberg quartzite inclusions indicated the presence of this formation at the time of emplacement, but which has since been eroded from the area. Later geological work identified the presence of a number of discrete kimberlite varieties (Robinson, 1973; Bartlett, 1998) that included two major types of TKB, named the "Brown" and "Grey" kimberlites (Fig. 10). The large floating reef referred to above occurred within the Grey Kimberlite along the boundary with the Brown. In addition, a central complex that consisted of several phases of kimberlite occurred within the Grey. This was referred to as the Black Kimberlite, which has an associated variety called the Piebald Kimberlite. The last phase of magmatism was the intrusion of carbonate-rich dykes. Robinson (1973) demonstrated that these magnetite–serpentine–calcite-rich rocks were indeed igneous, and that although they could qualify to be called "carbonatite" on a purely petrographic basis, geochemically they were very different from typical alkaline carbonatites. This geological arrangement has been confirmed to a depth of 1000 m below the current surface, where the kimberlite has an area of 5 ha (Bartlett, 1998).

5.4.3. Xenoliths

Premier has yielded an array of mantle-derived rocks and minerals, although it is the garnet harzburgites and lherzolites that have received most attention (Danchin, 1979; Boyd and Mertzman, 1987; Boyd et al., 1993). Bartlett (1998) listed five main varieties, namely coarse garnet lherzolites, deformed garnet lherzolite and types I, II and III harzburgites. Bartlett further noted that although eclogites are rare at Premier, over 80 had recently been collected. Viljoen et al. (2004) have described a rare diamond-bearing lherzolite from Premier.

5.4.4. Diamond inclusions

Tsai et al. (1979) analysed diamond inclusions from Premier, and found that the majority were eclogitic in character. They also analysed a unique acmitic diopside inclusion. Gurney et al. (1985) found a peridotitic to eclogitic ratio of 40:60. Inclusions were dated by Richardson (1986) who found that the eclogitic inclusions were of a similar age to the kimberlite, namely 1150±60 Ma. Lherzolitic inclusions were found to be 1930 Ma and a link to Bushveld Complex magmatism is suggested by Viljoen et al. (2004), whereas harzburgitic inclusions were dated at 3200 Ma, and are similar to other old inclusions found at other southern African locations (Richardson et al., 1993).

5.4.5. Diamonds

Premier is renowned for its large diamonds. The world's largest diamond, the 3106 carat Cullinan, was discovered at Premier in 1905. Wagner (1914) noted that Premier had a very varied assortment of diamonds, most of which (80%) were cleavage fragments of inferior quality. Less common however were a small proportion of exceptional quality blue-white stones. A common feature of Premier diamonds was their opalescence, referred to by Williams (1932) as “oily brilliance”. Harris et al. (1975) conducted a comprehensive quantitative study of Premier diamonds and compared these to diamonds from Finsch and Koffiefontein. They noted that Premier had a low proportion of octahedral stones, and that relative proportions of octahedral, dodecahedral and flattened dodecahedral diamonds remained roughly constant with varying size. No cubo-octahedaral stones were found, but spherical stones and rare blue stones were a feature of Premier diamonds. They also noted that Premier diamonds were commonly frosted and a high proportion had graphite coatings. Bartlett (1998) suggested that a small proportion of Premier's diamonds were of Type-II (nitrogen-free) variety, and that some of these were Type-IIb boron-bearing stones that had blue colouration. Apart from the Cullinan, Premier continued to produce a considerable proportion of the world's largest diamonds (up to a quarter — Bartlett, 1998). Recent notable large stones were the 599 carat “Centenary” diamond and the 1083 carat “Unknown Brown” (Bartlett, 1998).

5.4.6. Production

The diamond grade of Premier Mine varied between 40 and 80 cpht, and increased with depth, possibly as a result of diminishing proportions of country-rock inclusions. According to Williams (1932) there was considerable surface enrichment of diamonds, and early reported grades were as high as 170 cpht (Bartlett, 1998). It is interesting to note that the intrusive gabbro sill not only metamorphosed the kimberlite, but also destroyed diamonds within a metre of it, although metamorphism of the kimberlite was detected up to 30 m from the contact.

Premier has had a chequered production history. It started producing in 1903 and ceased in 1915, but recommenced in 1916, only to close again in 1932 as a consequence of the economic depression. It reopened after the Second World War with production commencing in 1950. It has been operating continuously since then. Mining started as an open-pit operation between 1903 and 1932, and underground mining from 1950 onwards. Underground mining methods that have been used include sub-level open benching, cave-mining using scrapers, sub-level open-stoping and mechanized trackless block-caving as ground conditions have changed. In 2005 Premier produced 1.3 million carats from 4.6 million tons of ore at an average grade of 28 cpht (Damarupurshad, 2006).

5.5. Finsch Mine

5.5.1. Discovery

The Finsch kimberlite pipe (Fig. 1) was discovered in 1960 by two prospectors, Fincham and Schwabel (after whom it was named) who were prospecting for asbestos in the Asbestos Hills approximately 150 km west of Kimberley. They discovered a depression on top of the hills, which with further investigation yielded garnets and diamonds. They established Finsch Diamonds in 1960, but De Beers gained a controlling interest in the prospect in 1963 and production commenced in 1965 (Viljoen and Lawless, 1988).

5.5.2. Geology

Finsch has an age of 118±2.8 Ma (Smith et al., 1985), and is a Group-2 kimberlite (Smith, 1983a; Fraser and Hawkesworth, 1992). The geology of Finsch Mine in the open-pit and on the 348 m underground sampling level was described by Clement (1982). The pipe was emplaced through a thick sequence of Proterozoic, Griqualand West sequence sedimentary rocks comprising dolomites, banded iron formation and shales. Preserved within the pipe are large fragments of Karoo-aged sediments, lavas and dolerite which were clearly present at the time of emplacement, but have been subsequently eroded away.

Clement (1982) defined eight kimberlite varieties in the mine which he called F1–F8. F1 was described as being the most significant volumetrically and was classified as a diatreme-facies TKB. This variety hosted numerous very large blocks of down-rafted Karoo basalt lava and sedimentary rocks. The F5 variety was also described as TKB, but occurred within a satellite portion of the pipe called “the precursor”. The other varieties were classified as hypabyssal kimberlite or kimberlite breccia. The F4 variety formed a late-stage plug intruded into the central portions of the pipe, whilst F2 was a number of late-stage dykes (Fig. 11).

Exploration of deeper levels of the mine (Ekkerd et al., 2003) found that the F8 variety increased in size with depth, and that the lithic-content of the F1 declined with depth. Mapping of deeper levels has also revealed the presence of steeply-dipping bedding planes within both the F1 and F8 varieties. Ekkerd et al. (2003) suggested that the F1 and F8 could be the same kimberlite, varying only in lithic content and alteration. The F7 variety was also described as having a gradational contact with F8 and it had a distinctly more coherent or magmatic texture. The nature of the south-west precursor remains enigmatic. It became detached from the main pipe at depth, with the two bodies being separated by intensely shattered dolomite. The kimberlite itself consisted of two sub-types F5 and F6. One of the characteristics of this unit was the presence of large orbicular magma clasts (or globular segregations) of crystallized kimberlite groundmass minerals, with interstitial carbonate. It was also characterized by the presence of abundant amygdaloidal basalt clasts of undoubted Karoo origin. This suggested that the precursor was emplaced as far as the original palaeo-surface, perhaps as a fully developed pipe. The precursor pipe was cross-cut and partly cored out by the later main pipe (Ekkerd et al., 2003).

The petrogenesis of various components (pipe and dyke rocks) of the Finsch kimberlite was investigated by Fraser and Hawkesworth (1992). They concluded that the different kimberlite melts could not be explained by different degrees of partial melting or by fractional crystallization. They speculated that the Group-2 melts were formed by low degrees of partial melting of old sub-continental lithospheric mantle that was enriched in trace elements by metasomatic processes.

5.5.3. Xenoliths

The majority of the xenoliths that have been found are peridotitic (Skinner, 1989a) and rare diamond-bearing varieties were described by Shee et al. (1982) and Viljoen et al. (1992).

5.5.4. Diamond inclusions

A systematic examination of over 200,000 diamonds by Gurney et al. (1979a) produced 1024 that contained inclusions. Approximately half of these were graphite, sulphides and clouds. Of the remaining stones, 98% contained peridotitic minerals and 2% eclogitic. The study of a smaller number of diamond-inclusions by Tsai et al. (1979) also confirmed a peridotitic paragenesis. Boyd et al. (1985) provided evidence that the peridotitic diamonds at Finsch crystallized at depths of 120–150 km, while Richardson et al. (1984) calculated a model age for the peridotitic inclusions of 3.3 Ga. Richardson et al. (1990) and Smith et al. (1991) demonstrated that the eclogitic inclusions were of Proterozoic age (1580±50 Ma and model ages of 1443 to 2408 Ma respectively). A further study of eclogitic diamonds from Finsch by Appelyard et al. (2004) showed that the eclogitic garnets in these diamonds are unusually enriched in FeO and MnO, and that the clinopyroxenes are unusually depleted in K_2O, relative to eclogitic inclusions from other localities. Diamonds from two different eclogitic sources were also identified.

5.5.5. Diamonds

The diamonds from Finsch Mine were described by Harris et al. (1973) and Harris et al. (1979). These studies showed that Finsch diamonds are characterized by a high proportion of irregular stones (30–35%), followed by dodecahedra (22–33%) and octahedra (7–20%). The predominant colours were colourless, yellow and brown of roughly equal proportions (20–30%). Grey stones were more common at larger sizes. A high proportion of larger stones were opaque (up to 25%). Harris et al. (1979) demonstrated that green-coated diamonds were more common at shallower levels than at depth, and related this to the alteration of the kimberlite at higher levels. Proportions of green-coated stones diminished considerably below approximately 100 m depth once less oxidized kimberlite was mined. The study by Appleyard et al. (2004) showed that all the eclogitic diamonds analysed were of Type IaAB with respect to their nitrogen aggregation state and that no Type-II diamonds were found.

5.5.6. Production

The mine started as a conventional open-cast mine in 1964. In 1980 a shaft was sunk to access deeper ore and the transition to an underground mine commenced in 1990. The mining method changed to a blast-hole open-stoping operation and in 2005 into a trackless mechanized block-caving operation. The diamond grade of the Finsch pipe is relatively high when compared to the Kimberley, Koffiefontein and Jagersfontein pipes (Clement, 1982), and by 1978 it was South Africa's major producer (Bruton, 1978). In 2005 Finsch produced 2.2 million carats from 5.9 million tons of ore at an average grade of 37.3 cpht (Damarupurshad, 2006).

5.6. Orapa Mine

5.6.1. Discovery

Orapa A/K1 pipe (Fig. 1) was discovered by De Beers geologists using traditional heavy-mineral (indicator-mineral) sampling in 1967. This pipe actually outcropped at surface, with a surface area of 110 ha, making it second in size to the Mwadui pipe in Tanzania.

5.6.2. Geology

Early mapping soon showed that the pipe contained crater-facies kimberlite (Hawthorne, 1975; Clement, 1979; Clement and Skinner, 1979; Clement, 1982; Clement and Skinner, 1985). Field et al. (1997) showed that Orapa actually consists of two pipes which coalesce near the surface (Fig. 12). The older northern pipe contains crudely layered pyroclastic kimberlite (NPK) which has distinctive gas-escape pipes and a textural characteristic not unlike those of the diatreme-facies TKB's described by Clement (1982) for the South African pipes. The south pipe by contrast has a far more varied geology. The upper portions contained a sequence of epiclastic kimberlite composed of shales, grits, sandstones and debris flows that were formed in a crater-lake. These deposits contained a variety of Cretaceous fossils, including plants and insects, none of which were aquatic (McKay and Rayner, 1986; Rayner and McKay, 1986; Rayner, 1987; Rayner and Waters, 1989, 1990, 1991; Rayner et al., 1991). A paleo-environmental reconstruction indicated that that in the Cretaceous Orapa experienced a temperate climate, being seasonal with cool winters, and that it was a region which experienced high rainfall (Rayner et al., 1991). Below the epiclastics there is a sharp unconformity, below which are rocks which are predominantly green-coloured volcaniclastics (SVK). It was clear from drill holes though that at least three phases of SVK are present, each separated by a sequence of basalt-rich breccias. The associated basalt-rich breccias are linked with those exposed in the western side of the crater, as well as with steeply-dipping, well-sorted and graded grain-flow deposits. The basalt-rich breccias are interpreted to represent rock-avalanche deposits that originated from the crater side walls, and the grain-flow deposits talus fan that sourced kimberlitic materials from the tuff-ring surrounding the crater. The lower SVK is underlain by a heterolithic breccia of basalt and sandstone clasts with variable quantities of included kimberlitic material. This breccia has a sharp contact with dark volcaniclastic kimberlite — DVK (previously classified as TKB by Field et al., 1997). This dark rock resembles the kimberlite from Letlhakane Mine. Surrounding the DVK on the western and northern sides of the south pipe is a collar of breccia which has very little kimberlite matrix. The distinctive feature of this breccia is that it contained only locally derived clasts of mudstone, coal and granitic basement. Basalt and upper Karoo sedimentary lithologies were notably absent. This unit has been named the Deep Heterolithic Breccia or DHB. Some late-stage kimberlite dykes have been intersected in deep drill cores.

Orapa is a Group-1 kimberlite of Cretaceous age that intruded Archaean basement rocks overlain by a sequence of Phanerozoic Karoo sedimentary rocks and Jurassic basalts of the Stormberg Formation. The age has been confirmed by a radiometric U–Pb age of ~93.1 Ma obtained from zircons (Davis, 1977; Allsopp et al., 1989) and fission-track dating of zircons that yielded ages of 92±6 Ma and 87 ±6 Ma (Raber, 1978; Allsopp et al., 1989).

5.6.3. Xenoliths

Orapa has been recognized as an eclogite-dominated xenolith locality (Shee, 1978; Shee and Gurney, 1979). Amongst this eclogite suite both graphite- and diamond-bearing varieties were found. Megacrysts of garnet, clinopyroxene and ilmenite have also been described by these authors. The apparent absence of peridotites at this locality may be due to the highly weathered nature of the kimberlite because altered peridotites have been recognized by the authors.

5.6.4. Diamond inclusions

Gurney et al. (1984b) conducted a diamond-inclusion study on 268 <2 mm diamonds. They found that eclogitic minerals were the most common inclusions (68%) whereas peridotitic inclusions comprised just 14%. The remainder were sulphides, as well as a single websteritic inclusion. Richardson (1989) dated eclogitic garnet inclusions at 990±50 Ma using Sm/Nd methods. Burgess et al. (2004) provide further evidence for the age of Orapa diamonds using the Ar–Ar technique. They obtained ages of 906–1032 Ma from clinopyroxene inclusions. Some ages of >2500 Ma were also obtained. The study by Deines and Harris (2004) showed that the eclogitic component at Orapa is even greater than that previously reported, being around 87%. This study also demonstrated the difference between Orapa and nearby Letlhakane diamonds. Stachel et al. (2004) considered the major and trace element compositions of the minor peridotitic inclusions and found that these differed from localities within the craton interiors (Orapa is near the western edge). This study suggested that peridotitic diamonds survived the tectono-thermal events that created the dominant eclogitic suite.

5.6.5. Diamonds

Bruton (1978) noted that Orapa produced 15% gem-quality diamonds. Harris et al. (1986) studied a large number of diamonds (mostly > 1500 stones from each of 10 sieve classes) from Orapa's 1983 production. They found that aggregated diamonds comprised about 60% of the production, but that cubic and cube-related diamonds comprised an important minor component. Flattened dodecahedra were notably absent. Yellow diamonds were the most common, comprising around 50% in all size classes, while the remainder comprised colourless, brown, transparent green-coated and steel-grey and grey colours. Colourless stones decreased in proportion with increasing size, whilst proportions of grey and steel-grey increased with size. A characteristic feature of the Orapa diamonds was the high proportion that exhibited light blue fluorescence in ultraviolet light. This can be correlated directly with the predominance of yellow colours. Plastic deformation was found to be present in 12% of the stones, and this feature was found to be independent of diamond size. It was noted that this level of deformation was lower than that recorded for other southern African kimberlites. Gurney and Boyd (1982) described polycrystalline aggregates (or framesites) that are relatively common at Orapa. A rare gas, carbon isotope and nitrogen study of framesites from Orapa by Gautheron et al. (2005) provided evidence for the mantle-derivation of these stones. Deines et al. (1993) conducted a carbon isotope and nitrogen concentration study on Orapa diamonds. They found that cubic diamonds were derived from relatively shallow mantle depths, that the peridotitic diamonds were formed close to the wet peridotite solidus and that the eclogitic diamonds formed under the highest *P–T* conditions. They also found that the diamond-bearing eclogites could not account for all the eclogitic diamonds, and that a websteritic variety of diamond population exists that had inclusions whose chemistry is transitional between peridotitic and eclogitic varieties. Cartigny et al. (1999) argued that the eclogitic diamonds could not have been formed by recycling of sedimentary carbon.

5.6.6. Production

Orapa is currently one of the largest producers of diamonds and in 2004 produced over 16.9 million carats, (approximately 15% of world production) at an average grade of 95 cpht. In 2006 the production rose to 17.3 million carats. It is a conventional open-cast mining operation.

5.7. Letlhakane Mine

5.7.1. Discovery

This mine is located 40 km south-east of Orapa (Fig. 1), and was discovered soon after Orapa in 1970. It consists of two kimberlite pipes, named D/K1 and D/K2. The larger D/K1 (11.6 Ha) has been mined continuously since discovery, but D/K2 (3.6 Ha) was only mined for a much shorter period (June 1985 to May 1986).

5.7.2. Geology

The D/K1 kimberlite pipe mainly consisted of massive volcaniclastic kimberlite, which has been divided into three units, named LM1, LM2E and LM2 W and a basalt-rich breccia zone (Fig. 13) in which sedimentary structures have been recognized (Kilham et al., 1998). The D/K2 pipe contains both volcaniclastic kimberlite and hypabyssal-facies kimberlite.

The Letlhakane kimberlites intruded the same suite of country rock as those described at Orapa, and it has been assumed that they are of similar age, as no radiometric ages have been published for Letlhakane. Both are typical Group-1 kimberlites.

5.7.3. Xenoliths

Letlhakane hosts a varied suite of mantle xenoliths including peridotites, pyroxenites, eclogites, megacrysts, MARID and glimmerites (Stiefenhofer, 1993; Stiefenhofer and Marsh, 1993; Stiefenhofer et al., 1997; Van Achterbergh et al., 1998, 2001). Thermobarometry calculations showed that the underlying mantle is thick (150 km) and had a typical continental geothermal gradient at the time of kimberlite emplacement of 40 mW/m^2.

5.7.4. Diamond inclusions

Deines and Harris (2004) quote unpublished figures as well as their own that show that Letlhakane's diamond-inclusion population has a significantly higher peridotitic component than that at Orapa, being 37% peridotitic, 29% eclogitic and 39% sulphides. They demonstrated further that the peridotite protolith at Letlhakane suffered a greater degree of partial melting than that of Orapa, and that there were significant differences in the carbon-isotope compositions of diamonds from the two pipes. Eclogitic diamonds between the two localities are also significantly different with respect to ^{13}C concentrations.

5.7.5. Production

Letlhakane is a significantly smaller operation than Orapa, and the diamond grade is considerably lower. De Beers annual reports indicate a range of 25 to 30 cpht for the annual recovered grade over the last seven years. In 2004, 1.03 million carats were recovered from 3.4 million tons of ore at an average grade of 30 cpht. The quality of diamonds recovered from this mine are considerably better than those at Orapa, with 40% being of gem-quality (Bruton, 1978).

5.8. Jwaneng Mine

5.8.1. Discovery

The world's premier diamond mine was discovered in the Naledi Valley in central western Botswana (Fig. 1) in 1974 using traditional heavy-mineral sampling techniques. This mine consists of three interconnected pipes, termed the south, central and north-east pipes (or lobes). At the time of discovery they were covered by approximately 40 m of Recent to Cretaceous-aged Kalahari sediments.

5.8.2. Geology

Petrographically, the Jwaneng kimberlites are considered typical Group-1 kimberlites, although they have unique Permian emplacement ages that have not been recorded elsewhere in southern Africa. Bristow et al. (cited by Allsopp et al., 1989) obtained ages of 206 ± 8 Ma from fission-track dating of zircons and 250 ± 7 Ma from Rb–Sr dating of phlogopite from the nearby DK7 kimberlite pipe. Kinny et al. (1986, 1989) obtained an age of 235 ± 2 Ma from U–Pb analysis of zircons. The latter work showed that both Archaean and Permian zircon xenocrysts are present within the pipes. The pipes intruded rocks of the Proterozoic Transvaal Sequence including quartzitic shales and dolomites. Inclusions of middle and lower Karoo sediments within the kimberlite indicate that these rocks and unconsolidated sediments were present at the time of emplacement. The geology of the kimberlite pipes is complicated. It has been recognized that they are not typical Type-1 pipes (Field and Scott Smith, 1999; Skinner and Marsh, 2004) meaning that the pipes are steep-sided diatremes that are filled with re-sedimented volcaniclastic kimberlite. The detailed geology of the south pipe was described by Machin (2000) and Webb et al. (2003). These studies showed that the south and central pipes comprise a central zone of bedded to massive volcaniclastic kimberlite with marginal breccias comprised of Karoo- and Transvaal-derived clasts. The north pipe contains a central zone of dark, dense pyroclastic kimberlite and a marginal zone of volcaniclastic kimberlite (Fig. 14). In all cases, the kimberlite is discontinuously bedded. In some cases the bedding planes are clearly not primary and are parts of down-rafted and rotated blocks. In other places spectacular accretionary lapilli beds are preserved. A geological model of the three pipes was constructed by Farrow et al. (2004) and is displayed in Fig. 14.

5.8.3. Xenoliths

There is a general lack of xenolith studies from Jwaneng. This is largely because the xenoliths are extremely altered.

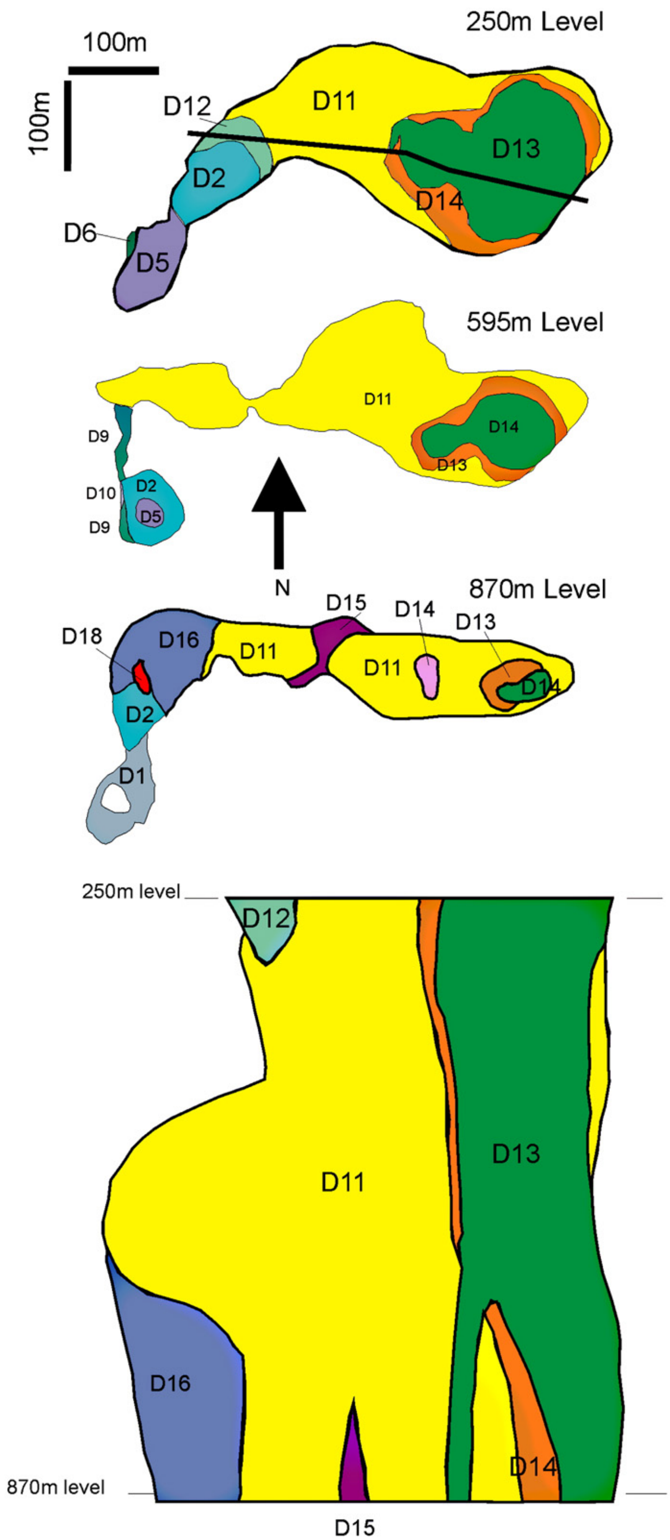


Fig. 7. Plan views and a cross-section of Dutoitspan Mine (after Clement, 1982) showing the distribution of various kimberlite varieties.

5.8.4. Diamond inclusions

Gurney et al. (1995) examined 52 diamonds with inclusions from Jwaneng Mine, and found that 67% were eclogitic and 33% peridotitic. Of the peridotitic inclusions most were lherzolitic in composition. Dating of the eclogitic inclusions by the ^{40}Ar–^{39}Ar technique (Burgess et al., 1992) produced the emplacement age of the kimberlite (233 ± 22 Ma to 417 ± 44 Ma). A maximum age for the inclusions however pointed to ages much older than the kimberlites and thus confirmed the xenocrystic character of the diamonds. Sm–Nd dating of eclogitic inclusions by Richardson et al. (1999) produced an age of 1540 Ma that is close to the age of similar inclusions dated at Finsch and also confirmed their xenocrystic character. Stachel et al. (2004) demonstrated that there is a difference between the peridotitic inclusions that were only mildly affected by metasomatism, and that the interpreted lithospheric profile for this portion of the craton (Griffin et al., 2002, 2003a) showed that a high proportion of the mantle had been affected by metasomatic processes. This indicated that some of the peridotitic diamonds survived the tecto-thermal events that metasomatised the mantle, and also produced the dominant eclogitic component seen amongst the diamond inclusions.

5.8.5. Diamonds

The characteristics of the diamonds from Jwaneng were described by Harris et al. (1986). This study showed that Jwaneng has a high proportion of aggregated stones, and a relatively high proportion of cubic and cube-related diamonds. The latter comprised about 8% of a sample of over 17 000 stones examined from production during 1982. The largest proportion of these stones (over 50%) were classified as yellow, whilst a significant proportion were transparent green-coated stones, and smaller proportions were classified as colourless, brown and grey. The predominant yellow stones resulted in a distinctive light blue fluorescence under ultraviolet light. Only 8% of the stones displayed plastic deformation features. This is the lowest value recorded for kimberlites studied by these authors. Kirkley et al. (1994) described the carbon isotope and intergrowth compositions of framesite (microcrystalline aggregates of diamond) from Jwaneng. They found these aggregates to be intergrown with spinel, diopside and garnet. Some of the garnets were eclogitic in composition, whilst others had a peridotitic character. They were interpreted to have formed in Cr-rich subducted materials that were subsequently invaded by fluids that altered the mineralogy and produced secondary products. Schrauder and Navon (1994, 1996) examined fluid inclusions trapped within the fibrous coats of cubic diamonds from Jwaneng and found evidence for two end-member fluid compositions, one that was carbonate-rich and the other hydrous, and that these fluids were in equilibrium with minerals of eclogitic composition, while peridotitic inclusions in the diamonds provided no evidence for interaction with these fluids.

5.8.6. Production

Jwaneng is a large open-cast mine. In 2004 the mine produced 13.6 million carats from 8.7 million tons at an average recovered grade of 143 cpht. During 2006 a record 15.6 million carats were produced. Jwaneng is currently the world's largest producer of diamonds by value and is a conventional open-cast mining operation.

5.9. Venetia Mine

5.9.1. Discovery

The Venetia mine kimberlites (Fig. 1) were discovered by De Beers in 1980 through heavy-mineral sampling techniques. In all, 14 kimberlite bodies have been discovered in the immediate area. The two largest, named K1 and K2 are being mined, whilst a number of smaller bodies such as K8 and K16 are included within the large open-pit that is designed and centred on K1 and K2 (Fig. 15).

5.9.2. Geology

These kimberlites have been classified as Group-1 kimberlites on the basis of petrography, geochemistry and isotope geochemistry (Seggie et al., 1999). The kimberlites are of Cambrian age. Allsopp et al. (1995) determined ages of 530 ± 4 Ma and 510 ± 16 Ma using the Rb–Sr technique on phlogopite separates. Phillips et al. (1999) determined an

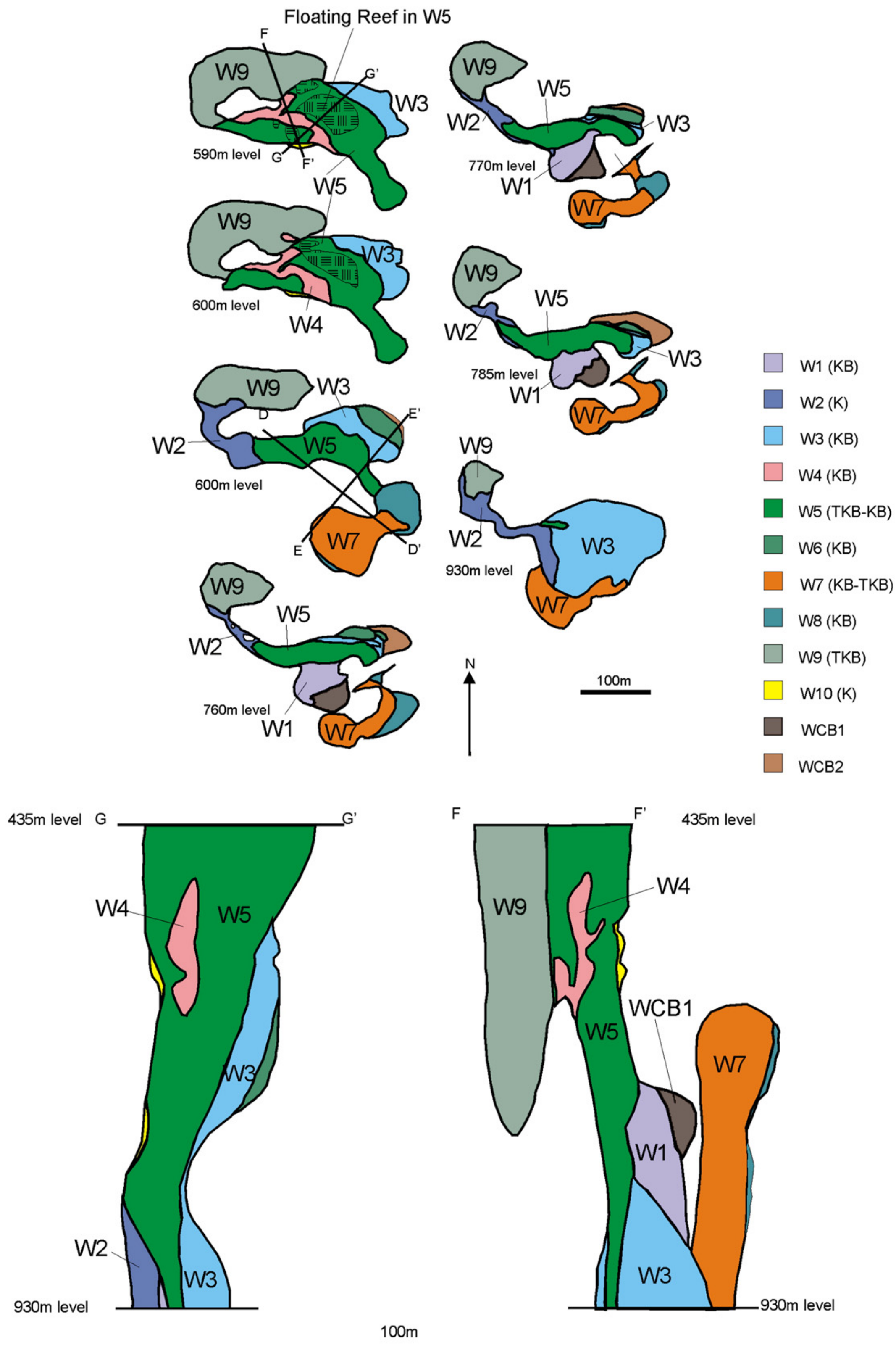


Fig. 8. Horizontal plan sections (above) and vertical cross-sections (below) of Wesselton Mine. The geological sub-divisions are after Clement (1982). K: Kimberlite (hypabyssal-facies); KB: Kimberlite breccia (hypabyssal-facies): TKB: Tuffistic Kimberlite Breccia (diatreme-facies); WCB1 and WCB2: Country-rock breccias.

age of 519.2±0.6 Ma using the $^{40}Ar–^{39}Ar$ technique on groundmass phlogopites. The kimberlites were intruded into Precambrian rocks of the Limpopo Mobile Belt (Barton et al., 2003). There are inclusions of Proterozoic Waterberg sediments and igneous rocks within the kimberlites which indicate that these rocks were present at the time of intrusion, but have subsequently been removed by erosion.

The K1 kimberlite has an elongated, boot-shaped outline at surface that has been shown by Kurszlaukis and Barnett (2003) to be

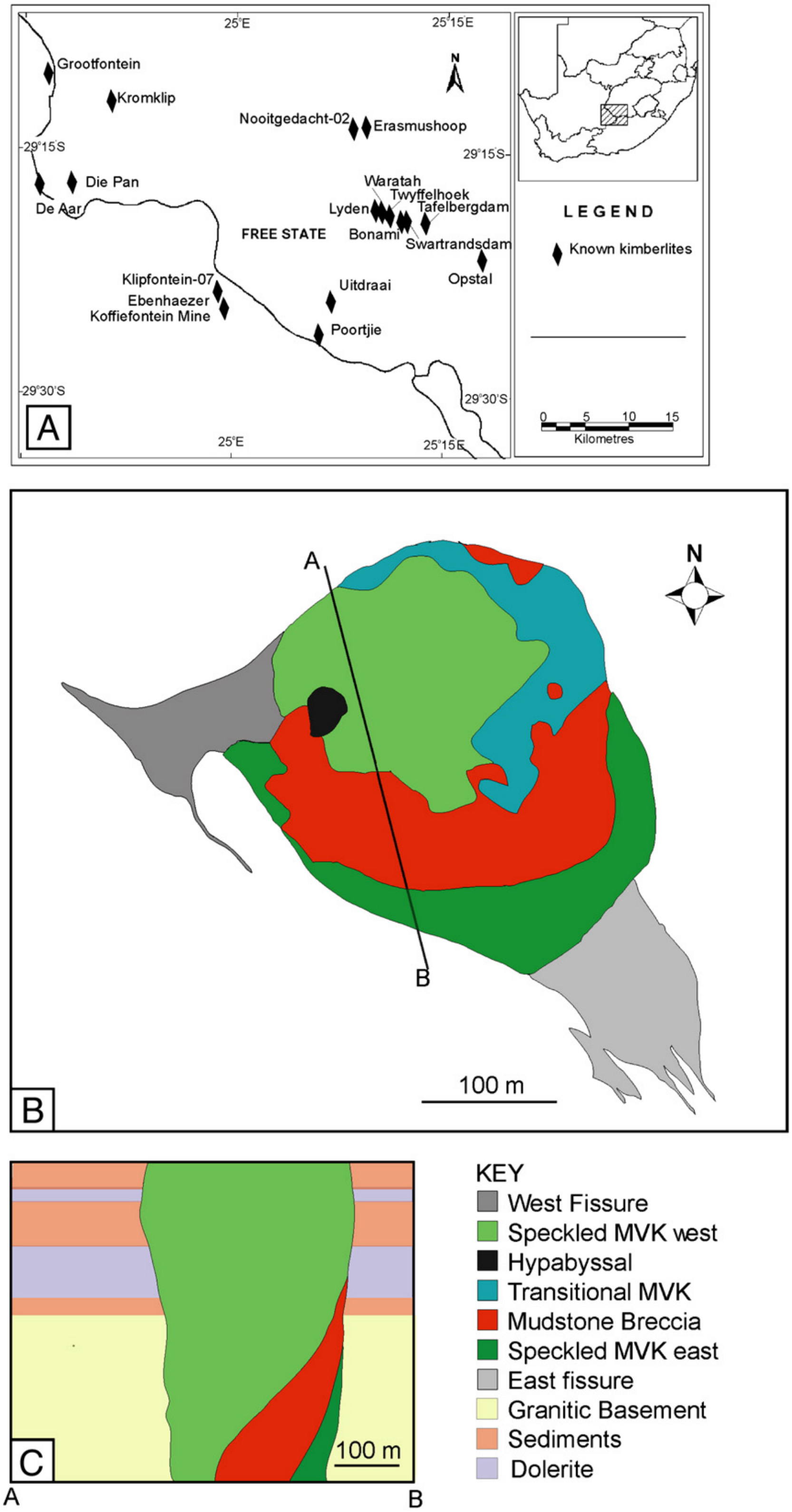


Fig. 9. A: Locality map showing Koffiefontein mine and the surrounding kimberlites (from Naidoo et al., 2004). B: Plan view of the 480 m production level showing the internal geology (from Sparks et al. 2006). C: Vertical cross-section showing the internal geology (from Naidoo et al., 2004, Sparks et al., 2006).

the consequence of the influence of pre-existing structures in the country rock. The internal geology was originally divided into diatreme-facies TKB's and hypabyssal-facies intrusions (Seggie et al., 1999). Subsequent work by Kurszlaukis and Barnett (2003) and Tait et al. (2006) showed (Fig. 15) that the so-called TKB's cannot be "intrusive tuffs" but rather volcaniclastics which are either pyroclastic deposits or reworked volcaniclastics. The so-called hypabyssal rocks were found to have gradational boundaries with the volcaniclastics. In places, these deposits have spectacular globular pelletal magma clasts which have been interpreted to be pyroclasts (Medlin, 2005), some of which exhibit evidence for welding. In certain parts of the reworked volcaniclastic kimberlite, Kurszlaukis and Barnett (2003) described the presence of accretionary lapilli, and take this to indicate a possible phreatomagmatic origin for some of the diatreme infill.

The geology of the K2 pipe is clearly divisible into two litho-facies associations. Seggie et al. (1999) recognized a western sector composed of hypabyssal-facies kimberlite and an eastern sector of TKB. Two distinct textural varieties were recognized in the hyabyssal-facies sector, namely globular segregationary kimberlite associated with breccias near the western margin and uniform hypabyssal kimberlite located more centrally. The investigation by Kurszlaukis and Barnett (2003) identified layering in the so-called hypabyssal-facies kimberlite that strongly indicated that this was not an intrusive kimberlite at all. Recent mapping of the open-pit exposures and logging of drill cores by Brown et al. (in press) confirmed the observations of Kurszlaukis and Barnett, and further identified the presence of three main litho-facies in the upper portions of K2 (Fig. 16), namely a peripheral country-rock breccia (CRBr), an associated zone of volcaniclastic kimberlite breccia (VKBr) and then a cross-cutting zone of volcaniclastic kimberlite with much lower lithic abundances. The latter corresponds roughly with the TKB of Seggie et al. (1999). The CRBr is composed largely of country-rock clasts ranging from sub-millimetre fragments to large mega-blocks in excess of 20 m in diameter. These country-rock clasts constitute more than 80% of the rock by volume. The VKBr is intimately associated with the CRBr, but contains a higher abundance of kimberlite-derived components. These deposits appear to comprise a series of breccia fans which were deposited by sector collapse of the pipe sidewall. The VK facies is considered a later-stage deposit that was blasted through the breccia-dominated facies. This VK deposit is interpreted to have undergone post-depositional fluidization that has resulted in a highly homogenized deposit. The geology of the other kimberlites will not be considered further here as they are currently not being mined.

5.9.3. Xenoliths

Stiefenhofer et al. (1999) described a suite of 100 xenoliths from Venetia. These were identified as peridotites and pyroxenites. The peridotite collection contained spinel and garnet-bearing peridotites of shallow and deep origin, calcic and sub-calcic garnet harzburgites and coarse- and sheared-textured garnet lherzolites and megacrystalline garnet-bearing dunites. Metasomatised peridotites were absent, but cryptic metasomatism was recognized in the mineralogy of some xenoliths. The pyroxenite xenoliths derived from above the diamond stability field, whereas the peridotite xenoliths defined a fairly continuous depth profile between 20 and 77 kb.

5.9.4. Diamond inclusions

Viljoen et al. (1999) examined over 220,000 diamonds for inclusions. The most common inclusion found was sulphide. Of the silicate and oxide inclusions, the vast majority (76–99%) were found to be peridotitic, whilst eclogitic and websteritic inclusions were rare. The study concluded that most of the diamonds at Venetia crystallized in thick, ancient cratonic lithosphere, which consisted predominantly of highly depleted peridotite, with minor eclogite and websterite veins or lenses. Aulbach et al. (2002) analysed eclogitic and websteritic inclusions from the above study and showed that the precursor protolith to eclogite must have suffered some melt depletion before being incorporated into the diamonds, whereas the websterites must have had a more mafic precursor that resulted from mixing between mantle peridotite and slab-derived melts.

5.9.5. Production

Venetia is currently the largest producer of diamonds in South Africa. It is a conventional open-pit mining operation that in 2005 produced 7.18 million carats from 5.8 million tons of ore, at an average grade of 122 cpht.

5.10. Damtshaa Mine

5.10.1. Discovery

Damtshaa is the most recent mine to be opened in Botswana by Debswana. It is located approximately 15 km east of Orapa Mine (Fig. 1) and comprises a number of kimberlite pipes. The two largest pipes are the B/K9 and B/K12 pipes which are located close together and are currently being mined. The B/K1 and B/K15 pipes are further away and will only be mined later in the mine's life. All of these pipes were discovered in the mid-1970's soon after the discovery of Orapa and Letlhakane. Discovery was due to a combination of geophysical surveys and heavy-mineral sampling.

5.10.2. Geology

The B/K9 pipe was approximately 15 ha at surface. The geology of the kimberlite was investigated through a number of drilling programmes, and this culminated in the development of a geological model (Field and Selfe, 1996). The pipe has three main geological zones, a central portion comprising a layered sequence dominated by basalt-rich breccias, and two "intrusive" dark coherent kimberlite varieties previously referred to as "hypabyssal" kimberlite (Fig. 17). Recent mapping, since mining has commenced, suggests that this "hypabyssal kimberlite" is indeed pyroclastic kimberlite. Deep drilling showed that the body splits into three pipes with depth, and that the basalt-rich breccia basin is underlain by several volcaniclastic kimberlite varieties (previously classified as TKB) and various breccias comprising specific Karoo sedimentary fragments.

The B/K12 kimberlite is slightly smaller than B/K9 (8 ha), and comprises three volcaniclastic units and a central zone of basalt-rich breccia (Fig. 17).

No xenolith, diamond-inclusion or diamond characteristic studies have been conducted on these kimberlites.

5.10.3. Production

Damtshaa Mine was opened in 2001. The published annual recovered grade between 2002 and 2004 varied between 6 and 26 cpht (De Beers Annual Reports 2002–2004). No distinction was drawn about the source of these diamonds.

5.11. Murowa

5.11.1. Location and discovery

The Murowa kimberlites were discovered by Rio Tinto in 1997 40 km south-east of the town of Zvishavane in southern Zimbabwe (Fig. 1; Rio Tinto 2005).

5.11.2. Geology

Three kimberlite pipes of Cambrian age were intruded into the Chibi granite batholith of the Zimbabwe Craton, just north of the boundary with the Limpopo Mobile Belt (Smith et al., 2003). According to Smith et al. (2003) these pipes are deeply eroded and have complex outlines. They contain various hypabyssal- and diatreme-facies kimberlites and fenitised wall-rock breccias.

5.11.3. Production

Two of the pipes have been mined since late 2004 and a reserve of 19 million tons at a grade of around 90 cpht has been declared (HRD, 2007). Mining is by conventional open-cast methods. In 2005 around 251,000 carats were produced (HRD, 2007).

6. Small mines

6.1. Frank Smith

6.1.1. Discovery

The Frank Smith Mine is located approximately 80 km north of Kimberley (Fig. 1). It is not recorded when or how this mine was discovered, but Wagner (1914) records that the Company formed to mine it was constituted in 1900.

6.1.2. Geology

Wagner (1914) described Frank Smith Mine as consisting of older dykes cut by two later pipes (Frank Smith main pipe and the Weltevreden pipe). Both Wagner (1914) and Williams (1932) recorded that the dyke had a completely different petrographic character from the pipes, being more micaceous, whilst the pipe was more "basaltic". Frank Smith is considered to be a Group-1 kimberlite (Smith, 1983a; Skinner, 1989b) although it has isotopic characteristics which are slightly different from those of other Cretaceous Group-1 kimberlites. It has been dated at ~114 Ma (Smith, 1983a,b) and 113.7±1.8 Ma (Smith et al., 1985) which is older than Kimberley Group-1 kimberlites, but very similar to the nearby Newlands Group-2 kimberlite. The kimberlite intruded Archaean basement and Ventersdorp sequence rocks and Karoo sedimentary rocks and a Jurassic–age Karoo dolerite sill. The kimberlite also contained Stormberg lava fragments in the diatreme, which indicated that the pipe has suffered considerable erosion since it was emplaced. The pipe is connected to the nearby Weltevreden pipe by a wide dyke (40 m maximum width and 180 m long) that was known as the Windsor Block. Mapping and petrographic examination by Van der Spuy (1984) identified five varieties of kimberlite in the main pipe with a dominant "TKB" facies and three smaller hypabyssal kimberlites. He also recognized contact breccias, large floating reefs and late-stage internal dykes. He found two varieties of kimberlite in the Windsor Block.

6.1.3. Xenoliths

Frank Smith is well-known for its mantle xenolith and xenocryst populations. Boyd (1973) recorded the presence of eclogite, kyanite-eclogite, corundum-diamond eclogite, dunite, harzburgite, lherzolite (both granular and sheared), garnet harzburgite, and various intergrowths and megacrysts. The latter include Mg-rich ilmenite megacrysts with lamellae of either pleonaste or titanomagnetite, ilmenite-enstatite and ilmenite-diopside lamellar intergrowths (Pasteris et al., 1979), unique megacrysts of enstatite that contained both Cr-rich and Cr-poor garnet intergrowths as well as ilmenite inclusions (Meyer and Tsai, 1979), quench-textured ilmenite-pyroxene megacrysts (Rawlinson and Dawson, 1979) and pyroxene-ilmenite megacrysts with potassic-rich sulphides (Clarke, 1979).

6.1.4. Diamonds

The diamonds from Frank Smith are considered to be of excellent quality, where white, sharp-edged octahedral diamonds or "glassies" predominated. It also produced a greater proportion of "close goods" (pure crystals of regular form) and a small proportion of "rubbish" (impure and imperfectly crystallized stones not fit for cutting) and boart (Wagner, 1914).

6.1.5. Production

Frank Smith Mine has had a sporadic life due mainly to a very low grade (3.92 carats per hundred loads). Williams (1932) noted that it was worked intermittently over many years. Field (1988) noted that the mine was closed in the following periods 1907–1913, 1914–1920 and 1929–1964, but that it was operational in 1988. Lynn et al. (1998) record that it was still being worked in the 1990's and that other mining companies were considering ways of mining it economically. The mine is currently owned by Good Hope Diamonds Pty Ltd, and is under care and maintenance (Damarupurshad, 2006).

6.2. Newlands

6.2.1. Location

This small mine is located north of Barkly West in the Northern Cape (Fig. 1).

6.3. Geology

The mine consists of five small pipes or "blows" located along a dyke. Wagner (1914) noted that petrographically the kimberlite is intermediate between "micaceous" and "basaltic varieties". It is classified as a Group-2 kimberlite (Smith, 1983a; Skinner, 1989b) and has been dated at 114±1.6 Ma (Smith et al., 1985).

6.3.1. Xenoliths

Newlands has produced a wide variety of mantle xenoliths, including diamond-bearing sub-calcic harzburgites and eclogites (Gurney and Menzies, 1998). Menzies et al. (1999) identified three diamond growth periods by Re–Os isotopic analysis of diamond-bearing garnet macrocrysts from Newlands, namely 3.1–3.4 Ga, 2.7–2.8 Ga and 1.8–2.1 Ga.

6.3.2. Diamonds

Wagner described diamonds from Newlands as being very similar to those from Frank Smith. Menzies et al. (1998) conducted an FTIR study of diamonds from eclogites and peridotites as well as run-of-mine diamonds. They found that about 75% of the latter diamonds were eclogitic. They also found that harzburgitic diamonds had much lower nitrogen concentrations than the eclogitic diamonds, and that about half of the harzburgitic diamonds could be classified as Type-II.

6.3.3. Production

Newlands was purchased by Dwyka Diamonds Limited during 2005 and production from both tailings and underground commenced in the same year (Dwyka Diamonds Limited, 2006). Current production levels are around 6000 tons per month (Damarupurshad, 2006).

6.4. Voorspoed

6.4.1. Location and discovery

Voorspoed Mine is located north of Kroonstad in the Free State Province (Fig. 1). This kimberlite pipe was discovered in 1906 by H.S. Harger. The Voorspoed kimberlite forms the eastern-most limit of a cluster of eleven intrusions, of which Lace, 9 km south-west of Voorspoed, is the most famous. Voorspoed and Lace represent the only known bodies of economic interest.

6.4.2. Geology

Wagner (1914) noted the presence of antecedent and consequent dykes with respect to the pipe. He further described the presence of a Stormberg basalt floating reef. This very large floating reef occupies more than half of the pipe at surface, and has contributed greatly to the pipe's sub-economic character (Clement, 1982). Wagner (1914) was the first to note the micaceous nature of the rocks, although he noted that the pipe rocks were less micaceous than the antecedent dykes. It is a Group-2 kimberlite pipe (Phillips et al., 1998, 1999), which has been dated at 131.3±0.6 Ma using the $^{40}Ar/^{39}Ar$ technique on groundmass phlogopite grains. These authors also described the pipe as containing two distinct varieties of "TKB" and seven varieties of hypabyssal kimberlite. Subsequent work by one of the authors (unpublished data — J. Stiefenhofer) demonstrated the presence of graded bedding and textures of probable pyroclastic origin within the pipe, and suggested that Voorspoed should be more appropriately

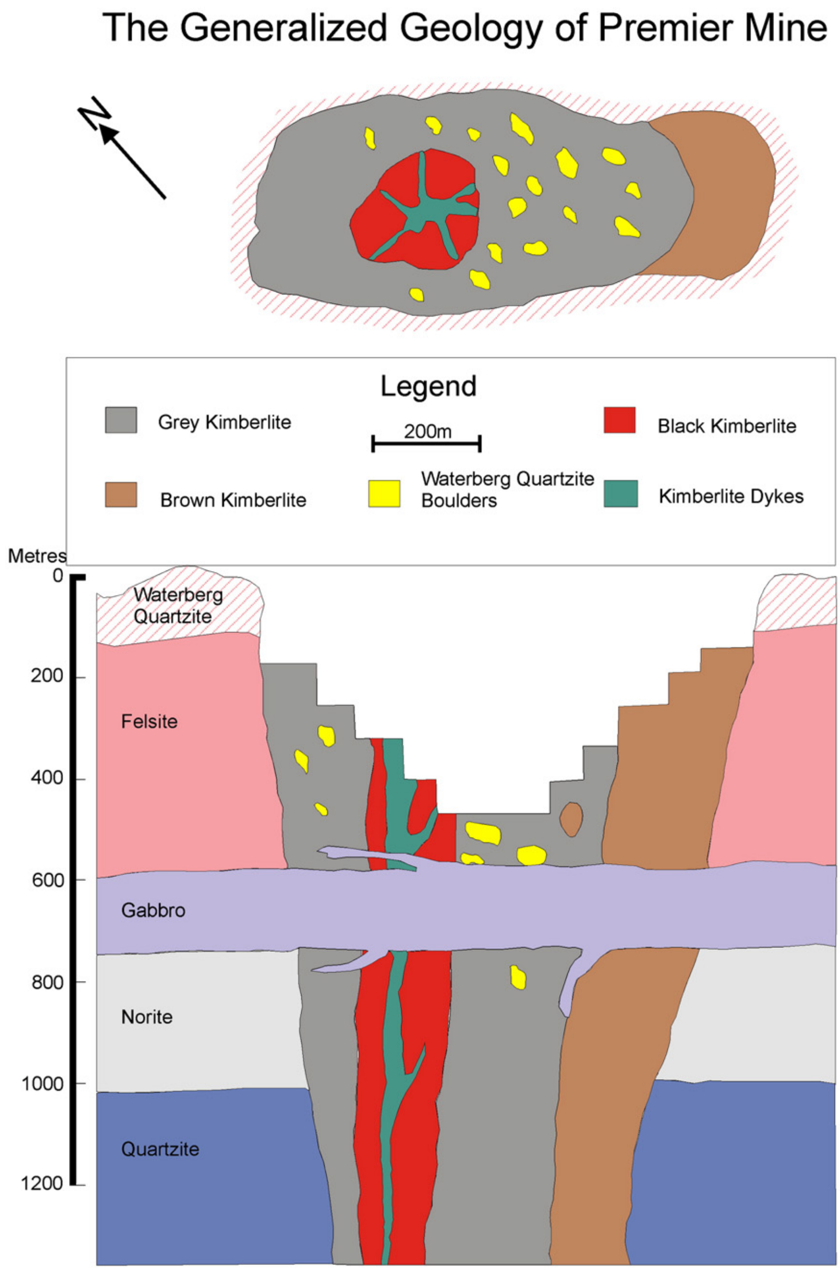


Fig. 10. Simplified plan and section of the Premier kimberlite pipe, modified from Bartlett (1998). Note that the country-rock profile includes Waterberg Quartzite, which is a reconstruction of the profile that probably existed at the time of emplacement.

considered as a volcaniclastic kimberlite. The geometry and distribution of basalt-rich breccias was also more consistent with a volcaniclastic setting.

No mantle-xenolith or diamond-inclusion studies have been carried-out on the Voorspoed kimberlite.

6.4.3. Diamonds

Wagner (1914) described the diamonds from Voorspoed and noted the presence of cubic diamonds in which the cube faces were covered by roughened surfaces and corrosion markings. He stated that Voorspoed diamonds were renowned by cutters as being the hardest of all diamonds, and difficult to cut. He described the diamonds from the mine as being largely dull and lustreless, of poor quality, and that there were a large proportion of small stones. Most of the diamonds were coloured, with white being rare. Among the fancies there were fine rose-pinks. Dodecahedra, mostly distorted, dominated production, whilst octahedra were rare.

6.4.4. Production

The mine was worked extensively for five and half years after discovery through weathered yellow ground and a near-surface concentration zone. During this time 4.19 million tons were treated at an average grade of 21.4 cpht. The diamond grade dropped dramatically below 40 ft as fresher hard kimberlite was encountered, and the mine closed in 1912. It was subsequently purchased by De Beers. It is currently being re-developed by De Beers as a new mine. A new mining license was granted to De Beers during 2006.

6.5. Crown/Lace

6.5.1. Discovery and history

The Crown or Lace Mine is located close to Voorspoed, in the Free State Province (Fig. 1). It was discovered in 1896 and after testing by De Beers it was considered to be uneconomic. It was then acquired and worked by Lace Diamond Mining Company between 1902 and 1907. It

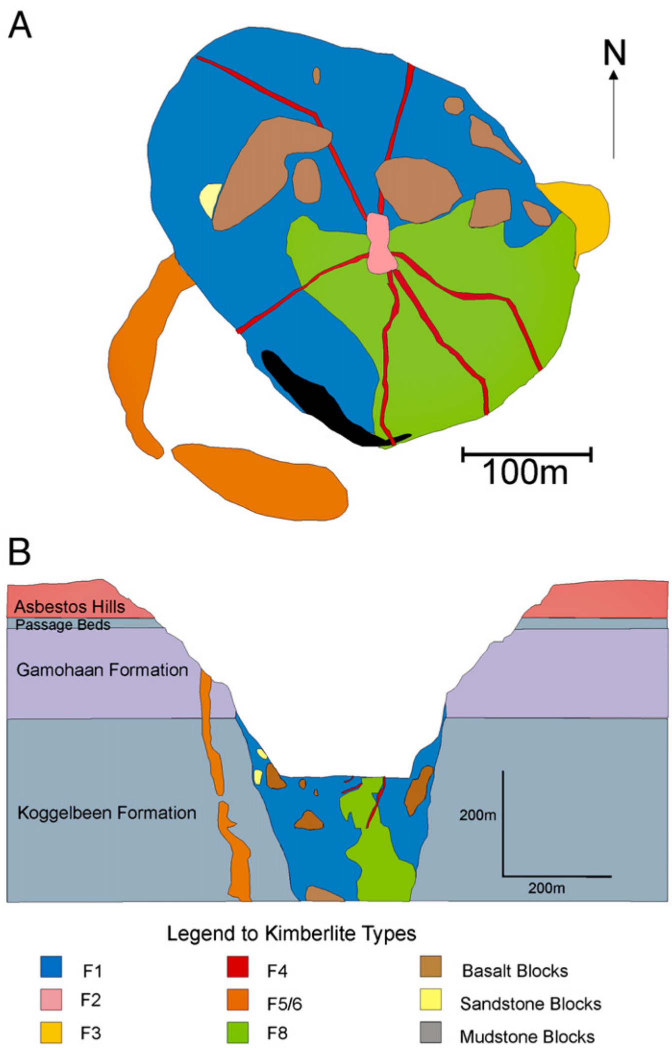


Fig. 11. A: The geology of the 610 m level at Finsch Mine. B: A West-East cross-section across Finsch Mine illustrating the country-rock stratigraphy and kimberlite varieties. Unpublished geological model — De Beers Consolidated Mines — also see Ekkerd et al. (2003).

was taken over by the Crown D.M. and E. Company in 1908. Operations were suspended in 1910, but continued in 1913 until 1931(Lynn et al., 1998). De Beers subsequently re-acquired the property, and then sold it again in the late 1990's. The current owner is DiamondCorp, who are presently investigating the viability of re-opening the underground mine. Dump re-treatment was due to start in 2007.

6.5.2. Geology

The mine exploited a small Group-2 kimberlite pipe. Wagner (1914) noted that at Crown country-rock fragments were evenly scattered throughout the kimberlite and were very abundant (90% of the rock in places). Stormberg basalt was noted as the main lithic type, whilst indurated shale, sandstone and granite inclusions were also recorded. Dixon (1979) noted the presence of five major kimberlite types, one of which was probably mined-out because it contained the highest diamond grade. Clement (1982) presented a cross-section of the pipe which showed that it increased in size with depth. He also indicated the presence of a small blind satellite pipe to the west of the main pipe. Clement (1982) noted that the diatreme-facies kimberlite at Lace is a rare example of a crystallinoclastic TK because of the presence of abundant quartz and feldspar grains scattered throughout the rock (that were smaller than 4 mm and so that the rock could not be termed breccia according to the Clement and Skinner (1979, 1985) textural-genetic classification scheme). Phillips et al. (1999) reported that the pipe contained TKB and a late-stage hypabyssal plug. Phlogopite grains from the latter were dated using $^{40}Ar/^{39}Ar$ to obtain an age of 133.2 ± 2.8 Ma.

6.5.3. Xenoliths

Lace was well-known for its garnet granulite xenoliths, but garnet megacrysts, eclogites and kyanite eclogites and rare diamondiferous eclogites were also found (S.R. Shee pers. comm.).

6.5.4. Diamonds

Wagner (1914) noted that octahedral diamonds dominated production at Lace, in complete contrast to those at nearby Voorspoed. The mine yielded fine yellow and brilliant blue-white stones, but due to the large percentage of inferior melee (i.e. <1 ct stones) the overall value of the diamonds was low. Dixon (1979) reported that the largest stone ever recovered was an 86.5 carat stone in 1930.

6.6. Kaalvallei (Samada Mine)

6.6.1. Location and history

The Kaalvallei kimberlite pipe is located approximately 7.5 km from Welkom in the Free State Province (Fig. 1). The first diamond was discovered in 1890 by Hendrik de Bruyn, a labourer on the farm. A shaft was subsequently sunk and mining continued until the start of the Boer War in 1899. Wagner (1914) noted that it was also known as Robinson's mine at that time. Mining resumed after the war but the miners encountered a major aquifer at a depth of 259 m which resulted in large-scale flooding and the mine closed as a result. The mine remained closed for many years until it was re-opened by Samada Diamonds Pty Ltd. Open-pit mining was employed as well as mining of tailings. Water was still pumped out on a continuous basis until the mine closed again in the early 1990's (Lynn et al., 1998).

6.6.2. Geology

The small (1.9 ha), Group-1 pipe, was emplaced into Ecca shales of the Karoo Supergroup. It has been dated at ~85 Ma (Viljoen, 1994). Rare amygdaloidal basalt inclusions were present in addition to abundant baked Karoo shale inclusions, rare altered basement gneiss and dolerite (Stiefenhofer, 1989). Two main hypabyssal kimberlite phases as well as several post-emplacement dykes were identified through the use of petrographic, geochemical and groundmass mineral analysis (Stiefenhofer, 1989). A small blow comprising hypabyssal kimberlite breccia is present some 300 m from the main pipe.

6.6.3. Xenoliths

The Kaalvallei occurrence is known to contain a wide range of mantle-derived eclogite and pyroxenite xenoliths which were described in detail by Viljoen (1994) and Viljoen et al. (2005). Peridotites and megacrysts have also been recorded.

6.7. Monastery

6.7.1. Location and history

This mine is located in the eastern Free State Province (Fig. 1). It was discovered in early 1876 by a prospector (Whitelock, 1973) but was mined before this by local Bashoto tribesmen for ilmenite. Large-scale mining commenced in 1886 and continued until the outbreak of the Boer War in 1899. Since then it has operated and been re-evaluated only intermittently (Lynn et al., 1998).

6.7.2. Geology

Wagner (1914) described two bodies of kimberlite connected by a persistent dyke. Whitelock (1973) described the geology of the mine

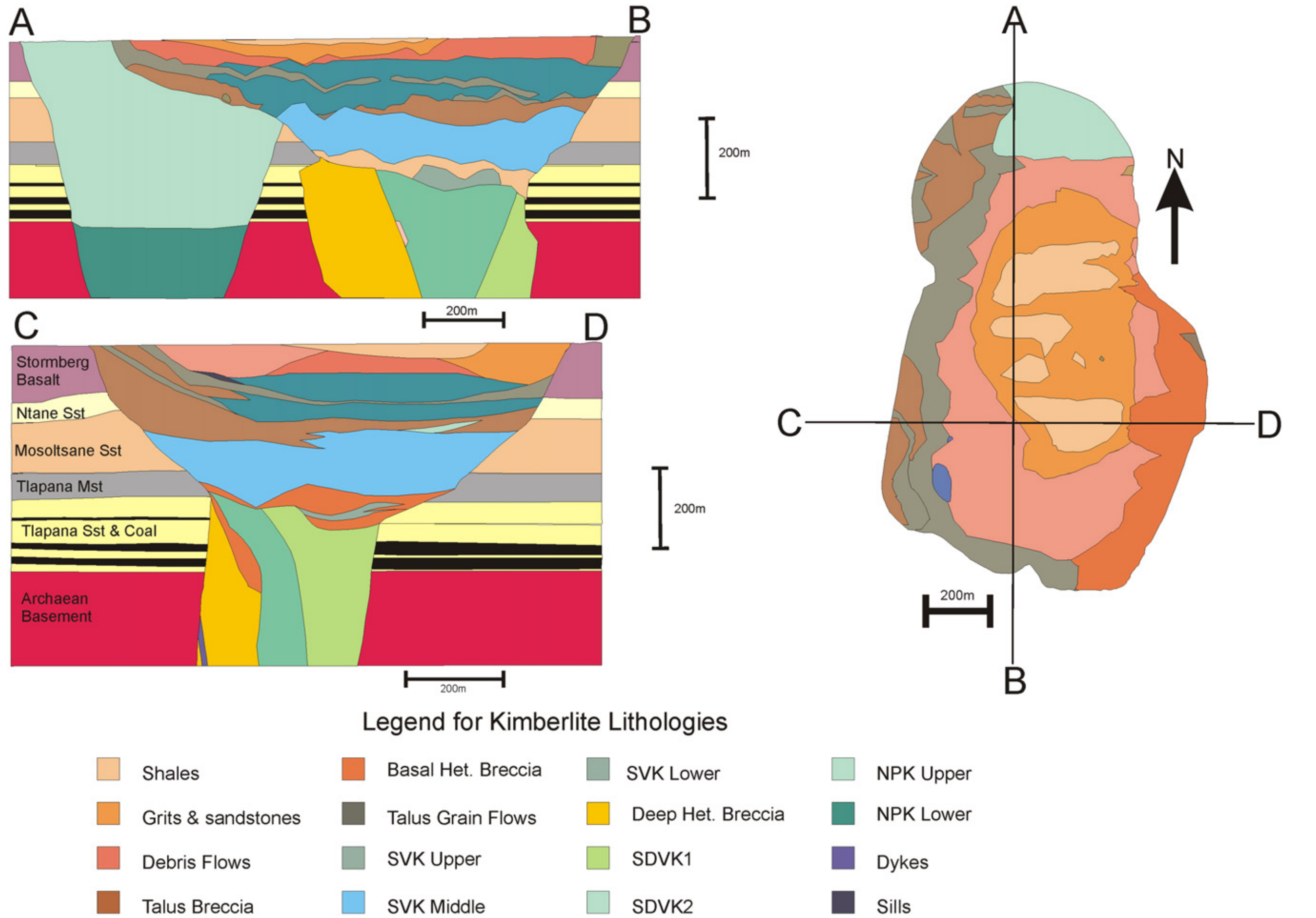


Fig. 12. A summary of the geology of Orapa A/K1, modified from Field et al. (1997). The right plan view shows a horizontal slice at the 945 m elevation (close to the original surface). The two vertical sections extend to a depth of 660 m below the current surface.

in more detail. It is an elongated diatreme located along a dyke of 1500 m length. The pipe contained five varieties of kimberlite which Whitelock named the Quarry, Breccia, Fine-grained, East-End, and South Vent types. The South Vent variety occurred as a blind intrusion which is overlain by up to 15 m of undisturbed Karoo sedimentary rocks (Clement, 1982). It is a Group-1 pipe of about 0.8 ha in surface area that intruded Karoo sedimentary rocks. It has been dated using several techniques, namely Rb–Sr on phlogopite (88±4 Ma — Allsopp and Barrett, 1975) U–Pb on perovskite (83±3 Ma — Kramers and Smith, 1983) K–Ar on phlogopite (~90 Ma — MacIntyre and Dawson, 1976) and U–Pb on zircon (~90.4 Ma — Davis, 1977).

6.7.3. Xenoliths

Monastery was noted by Wagner (1914) as a kimberlite that contained common mantle xenoliths (or “cognate xenoliths” as he called them). He noted ilmenite-diopside and ilmenite-enstatite intergrowths as being particularly common. Nixon and Boyd's notes in Whitelock (1973) provide a relative abundance table of mantle-derived xenocrysts and xenoliths present in coarse mine tailings. This analysis showed that ilmenite nodules and ilmenite-diopside intergrowth were the most common, but that garnet, ultrabasic and dunite nodules were also present, as well as garnet-diopside, diopside, bronzite and phlogopite megacrysts. Ultrabasic nodules were characterized by abundant phlogopite, and harzburgite and lherzolite were identified. The megacryst suite at Monastery has been extremely well-studied (e.g., Gurney et al., 1979b; Moore, 1986). These large mineral grains and intergrowths were interpreted to have crystallized at depth in the mantle from magmas that may have a genetic connection to kimberlites (Moore and Lock, 2001).

6.7.4. Diamond inclusions

A diamond-inclusion study of Monastery diamonds was undertaken by Moore and Gurney (1989). This showed that the majority of the inclusion-bearing diamonds where eclogitic (51%) and miscellaneous (42% — sulphides, oxides, plagioclase, zircon, phlogopite and moissanite), whilst peridotitic (6%) and websteritic (2%) varieties were rare. Monastery is also the locality where ultra-deep majoritic garnet inclusions in diamonds were first recognized (Moore, 1986).

6.7.5. Diamonds

Wagner (1914) described the diamonds from Monastery as being “inferior in quality to those of any other occurrence of kimberlite”. Whitelock (1973) provided a more detailed account of the diamonds. He recorded that there was a high proportion of rounded, silvery-grey, black-spotted formless aggregates. Even better quality stones were irregular to round and did not have any preserved crystal faces. Whitelock however noted that there are a few exceptional quality diamonds, most of which originated from the East-end kimberlite variety. The Quarry-type had the highest grades (up to 50 cpht) and it has also produced a few +100 carat stones. Moore and Gurney (1989) noted that the diamonds they examined for the inclusion study were also of poor quality, many showed chemical etching and high degrees of resorption. They also noted that the diamonds were mostly white and grey in colour.

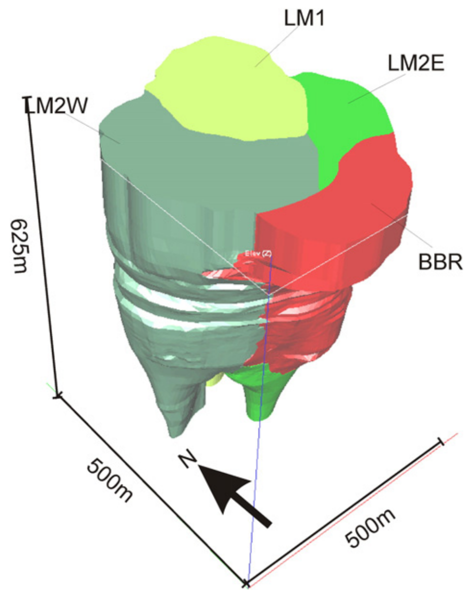


Fig. 13. Three-dimensional geological model for Letlhakane DK1. BBR is southern basalt-breccia; LM1, LM2W and LM2E are volcaniclastic kimberlite units. Unpublished geological model — Debswana — also see Kilham et al. (1998).

6.8. Letseng-la-terae

6.8.1. Location and history

This kimberlite, situated in the highlands of northern Lesotho (Fig. 1) was discovered in 1957 by P.H. Nixon, as a weathered outcrop in a stream (Bloomer and Nixon, 1973). In 1959 it was declared a "Government Digging" and hundreds of small- scale miners excavated the near-surface, weathered kimberlite. Rio Tinto acquired the kimberlite in 1968 and drilled and sampled it through a series of underground tunnels. The company abandoned the prospect in 1972. De Beers acquired the project and mined the Main Pipe from 1975–1982. Limited mining was undertaken in the Satellite Pipe. After its closure in 1982, no significant operational activity took place until the mining rights were obtained by Letseng Diamonds in 1999, the operating company of Letseng Holdings (Mining Review Africa, 2005). The latter was in partnership with the Lesotho government. Letseng Diamonds focused their efforts on the Satellite Pipe, and recovered a number of large flawless white diamonds during mining operations. This included stones of 76, 112, 106 and 72 carats within a single week (Mail and Guardian, 2006). In addition the recently discovered (22 August 2006) Lesotho Promise of 603 carats ranks as the world 15th largest diamond (Israeli Diamond Industry, 2006). The mine was recently acquired by African Gem Diamonds.

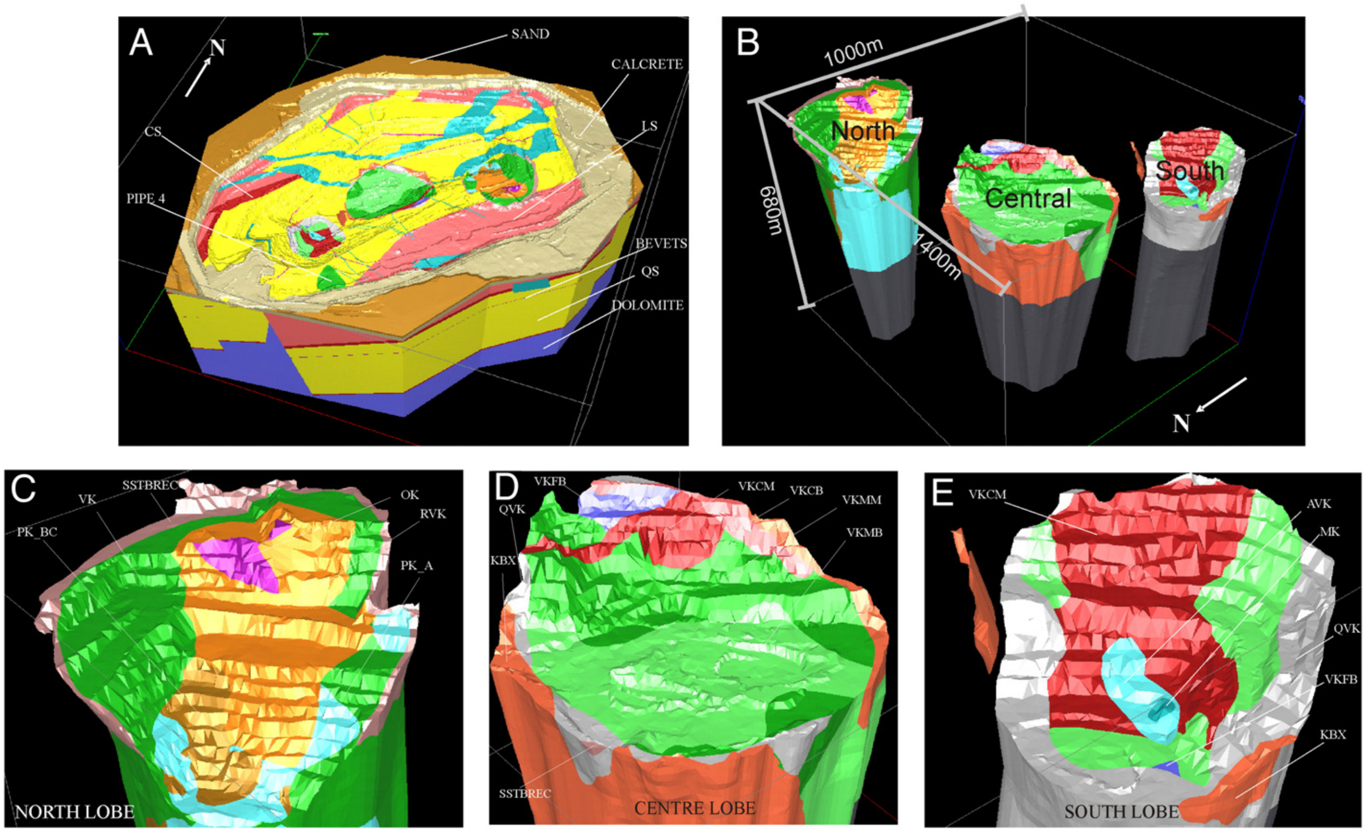


Fig. 14. Three-dimensional geological models of Jwaneng Mine after Farrow et al. (2004). A: The kimberlite pipes (green) placed within the country rock, where the blue is Transvaal dolomite, yellow (QS) is Transvaal quartzitic shales, including the Bevets conglomerate marker, pink is Transvaal laminated shale, red is Transvaal carbonaceous shale, cyan are diabase dykes and the light brown and brown are Kalahari-aged calcrete and aeolian sands. The approximate dimensions of the model are 2.5 km × 1.6 km × 1 km (deep). B: Models of the three pipes that comprise Jwaneng mine. The different colours represent different geological zones. The grey areas at the bottom are inferred. Details of the internal sub-divisions are given in C–E below. The approximate maximum radii of the three pipes are 360 m, 490 m and 325 m for the north, central and south pipes respectively. C: The northern pipe (or lobe) showing the identified geological units. PK_A, _BC refer to pyroclastic kimberlite, VK to volcaniclastic kimberlite, OK to oxidised kimberlite, RVK to re-sedimented volcaniclastic kimberlite and SSTBREC to sandstone breccia. D: The central pipe (or lobe). QVK refers to quartz-rich volcaniclastic kimberlite, KBX to kimberlite-shale breccia, VKFB to fine-grained bedded volcaniclastic kimberlite, VKCM to coarse-grained massive volcaniclastic kimberlite, VKMM to medium-grained massive volcaniclastic kimberlite, VKCB to coarse-grained bedded volcaniclastic kimberlite, VKMB to medium-grained bedded volcaniclastic kimberlite and SSTBREC to sandstone breccia. E: South pipe (or lobe). VKCM refers to coarse-grained massive volcaniclastic kimberlite, AVK to autolithic volcaniclastic kimberlite, MK to magmatic kimberlite, QVK to quartz-rich volcaniclastic kimberlite, KBX to kimberlite-shale breccia, VKFB to fine-grained bedded volcaniclastic kimberlite.

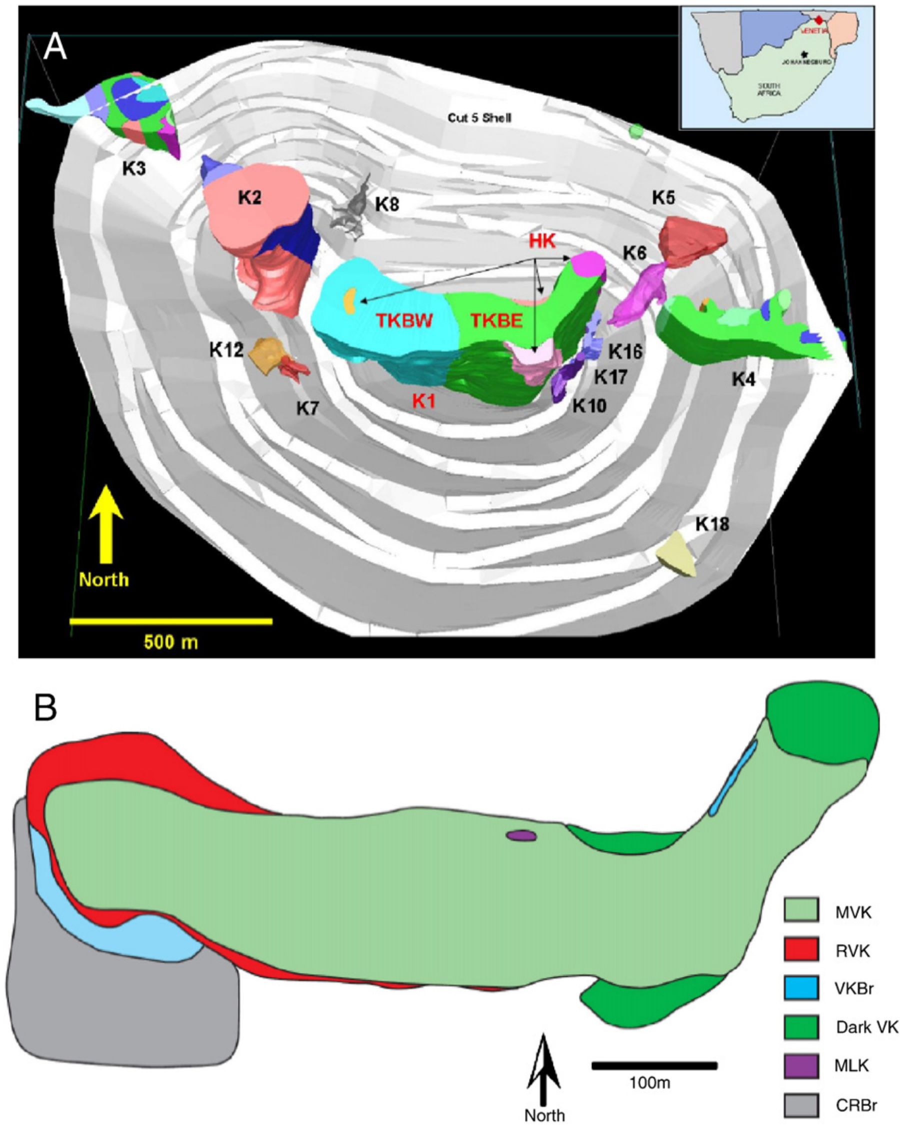


Fig. 15. A: Three-dimensional model of the Venetia kimberlite cluster with the old geological subdivisions shown for K1 and K2. B: Geological map of K1 for the 180 m level below surface with the new interpretation of Tait et al. (2006). The new interpretation for K2 by Brown et al. (2006) is displayed in the next figure.

6.8.2. Geology

There are two kimberlite pipes that are of economic interest, referred to as the Main and Satellite pipes respectively. These were emplaced through approximately 1500 m of Karoo (Stormberg) basalt. Letseng is a Group-1 kimberlite that has been dated at ~94.6 Ma by Davis (unpublished data quoted by Allsopp et al., 1989). Bloomer and Nixon (1973) recognized eight varieties of kimberlite in the Main pipe named K1–K8 (Fig. 18B) and nine varieties in the Satellite pipe (KA–KJ). In the Main pipe only K6 was of economic significance, and is described by Bloomer and Nixon (1973) as a late-stage diatreme that cuts through all of the other types with the exception of K5. This kimberlite had higher garnet xenocryst content than any of the other kimberlite types. Lock (1980) suggested that the geological subdivisions of Bloomer and Nixon reflected variations in lithic content and hydrothermal alteration features. Lock recommended the retention of the K4, K5 and K6 varieties, but that the others should be grouped into one, which he called the "autolithic kimberlite". Lock also noted the garnet-rich nature of the K6 kimberlite, and he called it the "garnetiferous kimberlite". Unlike Bloomer and Nixon (1973), Lock (1980) considered the boundary between the garnetiferous and autolithic varieties as gradational. Similarly, he reduced the variety of kimberlites in the satellite pipe to just one, which he noted was similar to the autolithic variety in the Main pipe. Lock also recognized sedimentary structures within the kimberlites, which pointed to a volcaniclastic origin for these rocks.

6.8.3. Xenoliths

Letseng contains a considerable array of mantle and lower crustal xenoliths. Bloomer and Nixon (1973) provided a list that included abundant garnet-bearing gneisses and granulites from the lower crust, but also eclogites, granular lherzolites and harburgites, dunites and megacrysts of olivine, enstatite, bronzite, diopside and garnet. Studies of these xenoliths pioneered the use of thermobarometry and an understanding of the sub-continental lithosphere (e.g., Boyd and Nixon, 1975) and the understanding that the textures of the xenoliths could be related to mantle temperatures (i.e. that coarse-granular textured rocks derived from shallower, cooler mantle and sheared rocks from deeper, hotter mantle).

6.8.4. Diamond inclusions

A study of inclusions was undertaken by McDade and Harris (1999). This showed that peridotitic, eclogitic, websteritic and sulphide and ferro-periclase assemblages are present within Letseng

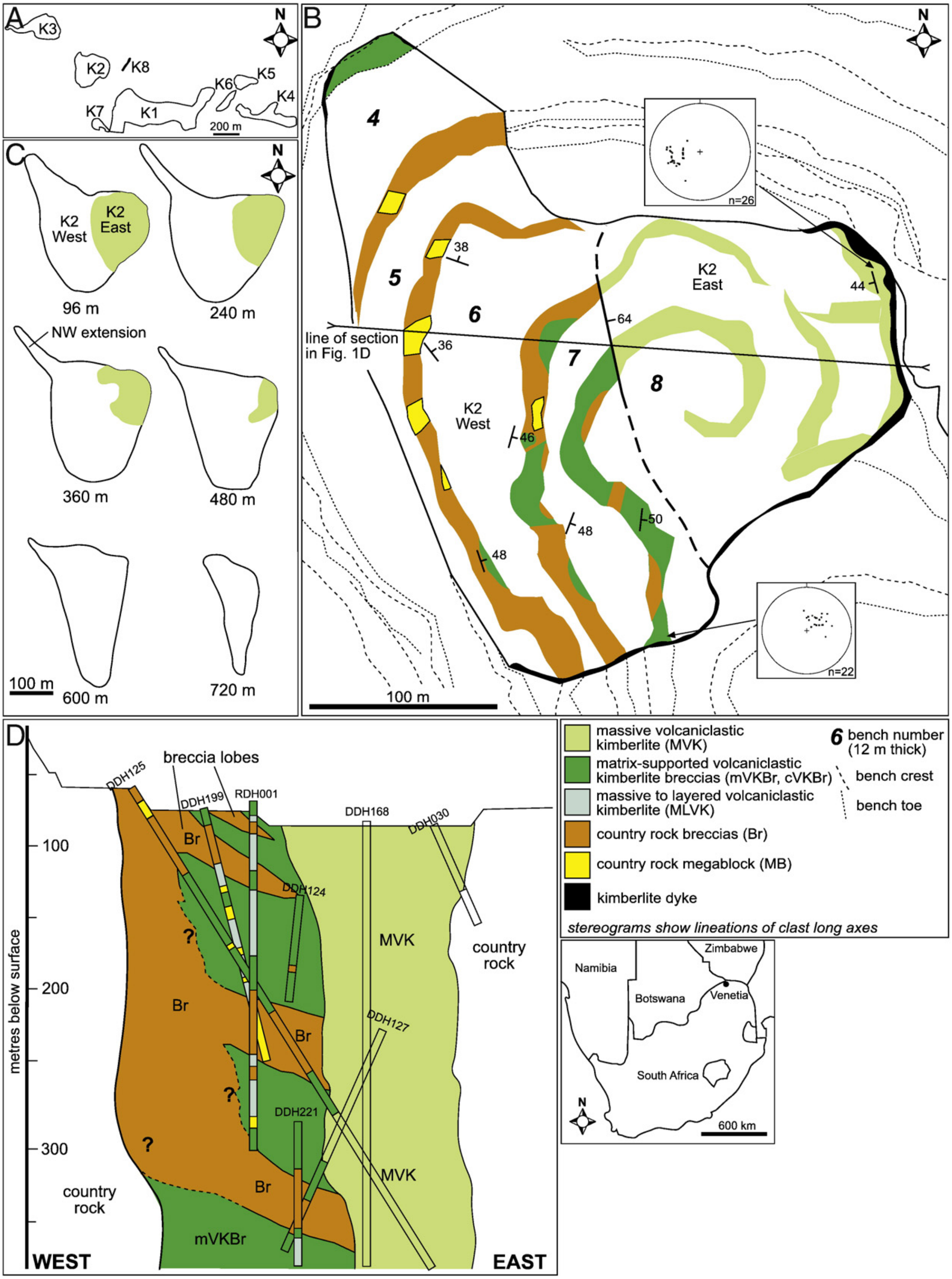


Fig. 16. A: Locality map showing the surface outlines of the Venetia kimberlites. B: Map of the K2 open-pit. C: Vertical cross-section through K2 showing drill hole information used to interpret the geology. D: Planview outlines showing the change in shape with depth. This figure is adapted from Brown et al. (2006).

diamonds. On the basis of carbon isotope and nitrogen aggregation studies, ten different growth episodes were identified. Similarity with other craton-edge localities, such as Monastery, Jagersfontein and Koffiefontein was demonstrated by these authors.

6.8.5. Diamonds

The diamonds recovered from the Letseng-la-terae kimberlites are described by Harris (1973) and Harris et al. (1979). The most notable feature of the diamonds is the almost complete absence of octahedral

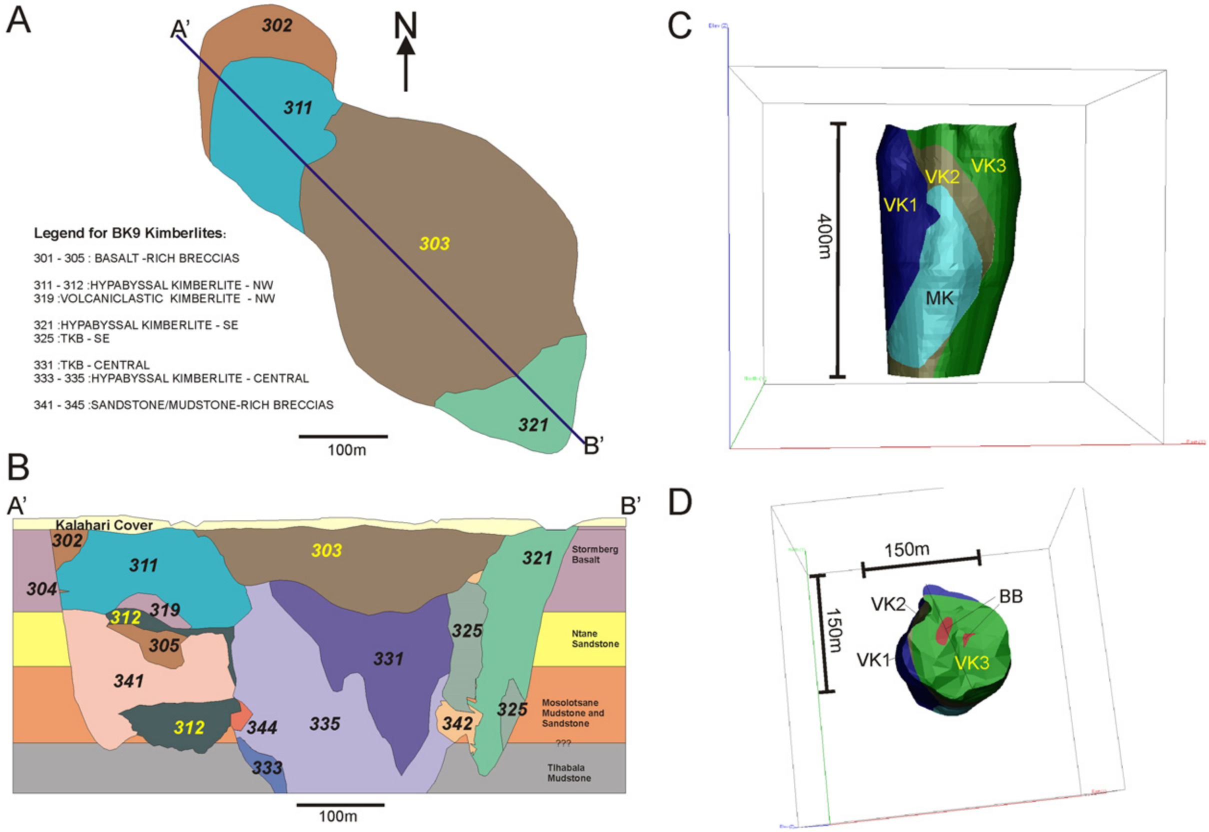


Fig. 17. Damtshaa Mine. A: Near-surface plan view of the BK9 kimberlite pipe (from Field and Selfe, 1996). B: Vertical cross-section of the BK9 pipe. C: Oblique view of the 3D geological model of the BK12 kimberlite pipe illustrating the distribution of the lithofacies. VK1-3 are volcaniclastic kimberlite varieties, MK is magmatic kimberlite. D: Top view of the BK12 geological model showing the location of basalt-breccia (BB) bodies in the central portion of the VK3 facies.

stones, and abundant stones that display transitional morphologies between octahedral and dodecahedral forms. This is interpreted by Harris et al. (1979) to be the consequence of extensive resorption of the diamonds, although whether this occurred in the growth environment, in the mantle, or en-route as a result of reaction with the kimberlite could not be determined with any certainty. Harris et al. (1979) noted further that there was no detectable difference in the diamonds between the different kimberlite varieties in the Main pipe, although subtle differences were noted between the Main and Satellite pipes. These differences had to be qualified due to the relatively small number of stones examined from the Satellite. The predominant colours of diamonds were light browns and pale yellows, although colourless, dark brown, bright yellow, dark greys and opaque stones were also present. It was also noted that large stones tended to be colourless.

6.9. The Oaks

6.9.1. Location and discovery

The Oaks kimberlite is located 20 km from Swartwater in the Limpopo Province of South Africa (Fig. 1) and forms part of the Marnitz kimberlite cluster. The kimberlite on the farm The Oaks was discovered in 1988 by De Beers and occurs in close proximity to the low-grade Mooikloof and barren Dartmouth kimberlites.

6.9.2. Geology

The Oaks is a small, Group-1 kimberlite pipe. It intruded rocks of the Limpopo Metamorphic Belt and has been dated by Phillips et al. (1999) using both Rb–Sr and $^{40}Ar/^{39}Ar$ techniques. The two methods produced overlapping ages of 509 Ma (Rb–Sr model age) and 503 ± 6.2 Ma ($^{40}Ar/^{39}Ar$). The kimberlite occurs as two separate and geologically distinct lobes which are separated by a neck area consisting of a mixture of country-rock breccias and kimberlite (Fig. 18A). The distinct geology of the two lobes was also reflected in the diamond population, with higher grade and higher values being mined from the North lobe compared to the South lobe.

No published information is available on mantle-xenoliths or diamond-inclusions from The Oaks.

6.9.3. Production

A feasibility study on the Oaks kimberlite was initiated in 1997 and production officially commenced in January 1999. The estimated mine life was only 8 years to a final pit depth of 200 m. The mine treated 250 000 tons of ore in 2005 and recovered 85 766 carats at an average grade of 34 cpht (Damarupurshad, 2006).

6.10. River Ranch

6.10.1. Location and discovery

The River Ranch kimberlite is situated some 12.5 km north-west of Beitbridge in Zimbabwe (Fig. 1), close to the border with South Africa. The Venetia kimberlite cluster is situated approximately 50 km to the south-west of River Ranch. This kimberlite was discovered by De Beers in 1974 during an exploration programme in Zimbabwe. Auridiam Zimbabwe (Pty) Ltd eventually took ownership of the project in 1991.

6.10.2. Geology

The kimberlite is a Group-1 kimberlite of probable Cambrian age. Dating of the River Ranch kimberlite was problematic (Muusha and Kopylova, 1999), and it was inferred to be of broadly similar age as the Venetia kimberlites. The River Ranch kimberlite was cut by 180 Ma

Karoo dolerite dykes. Muusha and Kopylova (1999) reported that strong structural control was evident during emplacement, similar to that described for the Venetia kimberlites. As a result, the River Ranch pipe shows a pronounced east-west elongation. Muusha and Kopylova (1999) identified seven different phases of kimberlite — a combination of "TKB" breccias and magmatic/hypabyssal kimberlite. The western and eastern TKB's represent the most significant units. Three other breccia units were present, in addition to a sandy/crystal tuff which occurred as isolated fragments and were interpreted as "floating rafts" in the TKB. The tuff-bearing breccia was regarded as being younger since it contained xenoliths of the older phases. Muusha and Kopylova (1999) interpreted the hypabyssal kimberlite as representing a late-stage intrusive phase.

6.10.3. Mantle xenoliths/xenocrysts

There are no reported occurrences of mantle xenoliths, but the mantle xenocryst suite is composed of garnet, chromite and clinopyroxene, whilst ilmenite is very rare. The garnets are mostly peridotitic (harzburgitic and lherzolitic) and Cr-poor megacrysts (Kopylova et al., 1997).

6.11. Diamond Inclusions

Kopylova et al. (1997) reported that more than 99% of diamond inclusions studied from a total of 72 stones was of harzburgitic paragenesis. The remainder was of eclogitic or unknown parageneses. From this study they showed that the palaeo-geothermal gradient in the Limpopo Belt at the time of kimberlite emplacement was slightly hotter (41–43 m Wm^{-2}) than that recorded for most diamondiferous kimberlites on the Kaapvaal Craton.

6.11.1. Production

Production at River Ranch commenced in 1992, and operations were gradually scaled up, but the mine was closed in 1998 due to low diamond prices (Mobbs, 2006).

6.12. Dokolwayo

6.12.1. Discovery and location

The Dokolwayo (or Dvokolwayo Mine in some literature) kimberlite diatreme was discovered by De Beers in north-eastern Swaziland in 1975 as a result of following up an earlier discovery of diamond-bearing grits and gravels within the Red Beds of the Karoo sequence (Hawthorne et al., 1979).

6.12.2. Geology

The diatreme had an elongate shape and a surface outcrop of 2.8 ha, but increased slightly to 3.4 ha at a depth of 50 m. The kimberlite intruded the Archaean Mliba granodiorite pluton. It consists of two main lithofacies, a central clastic zone that contained lithic clasts of basement as well as sandstone, siltstone and coal-bearing formations of the Beaufort Group of the Karoo sequence, and a peripheral zone of macrocrystic, hypabyssal-facies, phlogopite-rich kimberlite. The kimberlite is Group-2 type and has a preferred emplacement age of 203 ± 7 Ma (Allsopp and Roddick, 1984). This makes it the oldest Group-2 kimberlite in southern Africa. It is interpreted to be a highly eroded remnant of a kimberlite that was emplaced prior to the formation of the Karoo flood basalt province.

6.12.3. Xenoliths

No detailed studies have been undertaken, but analysis of garnet and chromite macrocrysts by Daniels and Gurney (1989) indicated the presence of peridotitic and eclogitic mantle lithologies. Megacrystic garnets and deformed high-temperature peridotites were also identified. These latter types were considered unusual for Group-2 kimberlites.

6.12.4. Diamond inclusions

The study by Daniels and Gurney (1989) demonstrated the presence of sulphides, eclogitic and peridotitic inclusions in diamonds from Dokolwayo. The peridotitic inclusions were mostly of lherzolitic type.

No additional information on the nature of the diamonds from Dokolwayo has been published.

6.12.5. Production

Production at Dokolwayo Mine ceased at the end of 1996, when it became uneconomic. Between 1990 and 1996 the mine had produced between 42,500 and 76,100 carats of diamonds per annum (Coakley, 1996).

6.13. Mines of the Boshof District

Three small mines occur in the Boshof district of the Free State Province of South Africa (Fig. 1).

6.14. Roberts Victor

6.14.1. Location

Roberts Victor Mine is located about 40 km east of the town of Boshof.

6.14.2. Geology

Roberts Victor Mine consists of two small pipes and blows located on a dyke and a second dyke (Fig. 19D) that has no associated blows or pipes (Gurney and Kirkley, 1996). The pipes contain large masses of Beaufort Sandstone as well as Karoo basalt xenoliths which were derived from above current erosion levels. By contrast, the dykes contained only lithic clasts derived from immediate wallrock and deeper lithologies. The pipe-dyke system contained several varieties of kimberlite (Wagner, 1914). Gurney and Kirkley (1996) noted that seven varieties of kimberlite have been recognized. Wagner noted the petrographic character as being "micaeous". Skinner (1989b) classified the occurrence as a Group-2 kimberlite. Two dates have been obtained by Rb–Sr methods on phlogopites, namely 127 ± 3 Ma (Allsopp and Barrett, 1975) and 128 ± 15 Ma (Smith et al., 1985).

6.14.3. Xenoliths

Wagner (1914) noted that Roberts Victor was a mantle-xenolith-rich locality, especially with regards to eclogites. He noted further that some of these xenoliths were diamond-bearing. The eclogites in particular have been subjected to considerable study (MacGregor and Carter, 1970; Harte and Gurney, 1975; Lappin and Dawson, 1975; Hatton, 1978; Hatton and Gurney, 1979; MacGregor and Manton, 1986; Ongley et al., 1987; Jacob and Jagoutz, 1994). MacGregor and Carter and Hatton recorded the overwhelming dominance of eclogitic xenoliths (~90%) versus peridotitic xenoliths at this locality. However, peridotites do occur in greater abundances than previously recognized, because of their altered state and some are diamondiferous (Viljoen et al., 1994). Gurney and Kirkley (1996) noted that the relative abundance of different types of garnets (peridotitic vs. eclogitic), chromites and diopsides varied significantly in the different kimberlite varieties.

6.14.4. Diamond inclusions

Gurney et al. (1984a) showed that 85% of the diamond inclusions in diamonds from Roberts Victor were of peridotitic origin, in complete contrast to the xenoliths that are predominantly eclogitic. Deines et al. (1987) conducted a carbon-isotope, nitrogen content and diamond-inclusion study of diamonds from Roberts Victor. They demonstrated that the eclogitic inclusions could be divided into two groups on the basis of carbon isotopes, but that peridotitic and eclogitic diamonds overlapped in terms of nitrogen content. They also

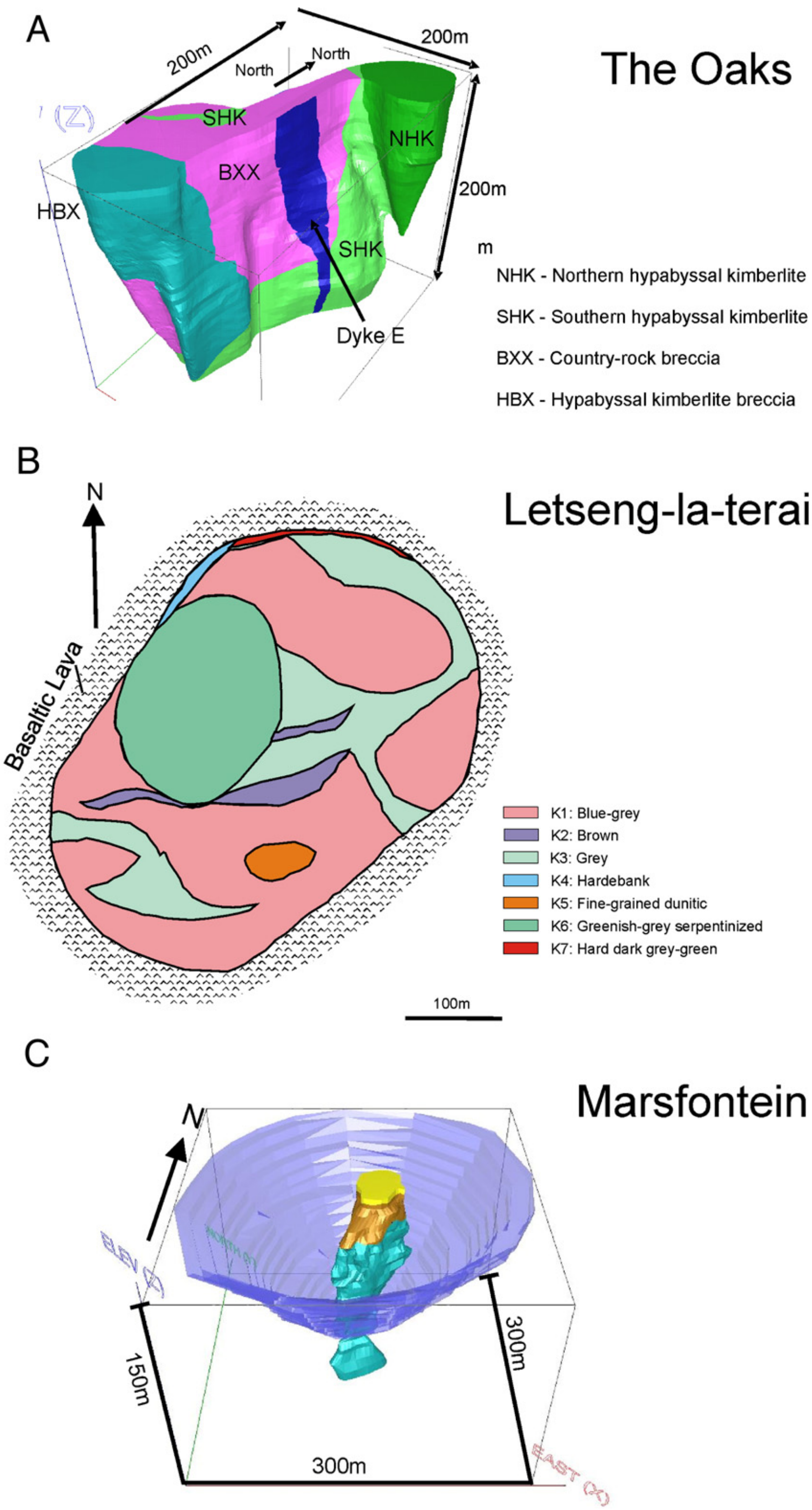


Fig. 18. Small mines: A: 3D geological model of The Oaks kimberlite (after Rowlands and Farrow, 2001 and Rowlands, 2002). B: Bloomer and Nixon's (1973) map of Letseng Main Pipe. C: 3D model of Marsfontein with the final open-pit and the M1 Pipe shown (after Compton, 2002).

demonstrated that there was no direct correlation between carbon-isotopic composition and nitrogen concentration, and that the diamonds from Roberts Victor are probably derived from multiple sources.

6.14.5. Diamonds

Wagner noted that although the diamonds from the various Boshof kimberlites had many similarities, there were also some diamonds from Roberts Victor that were unique. Further he noted that the diamonds from the pipes were generally of poorer quality than those from the dykes. Parts of the dykes, referred to as "the Jewel Box", contained high-quality diamonds.

6.14.6. Production

The diamond grades of the various kimberlites types varied considerably (Wagner, 1914; Gurney and Kirkley, 1996) from about

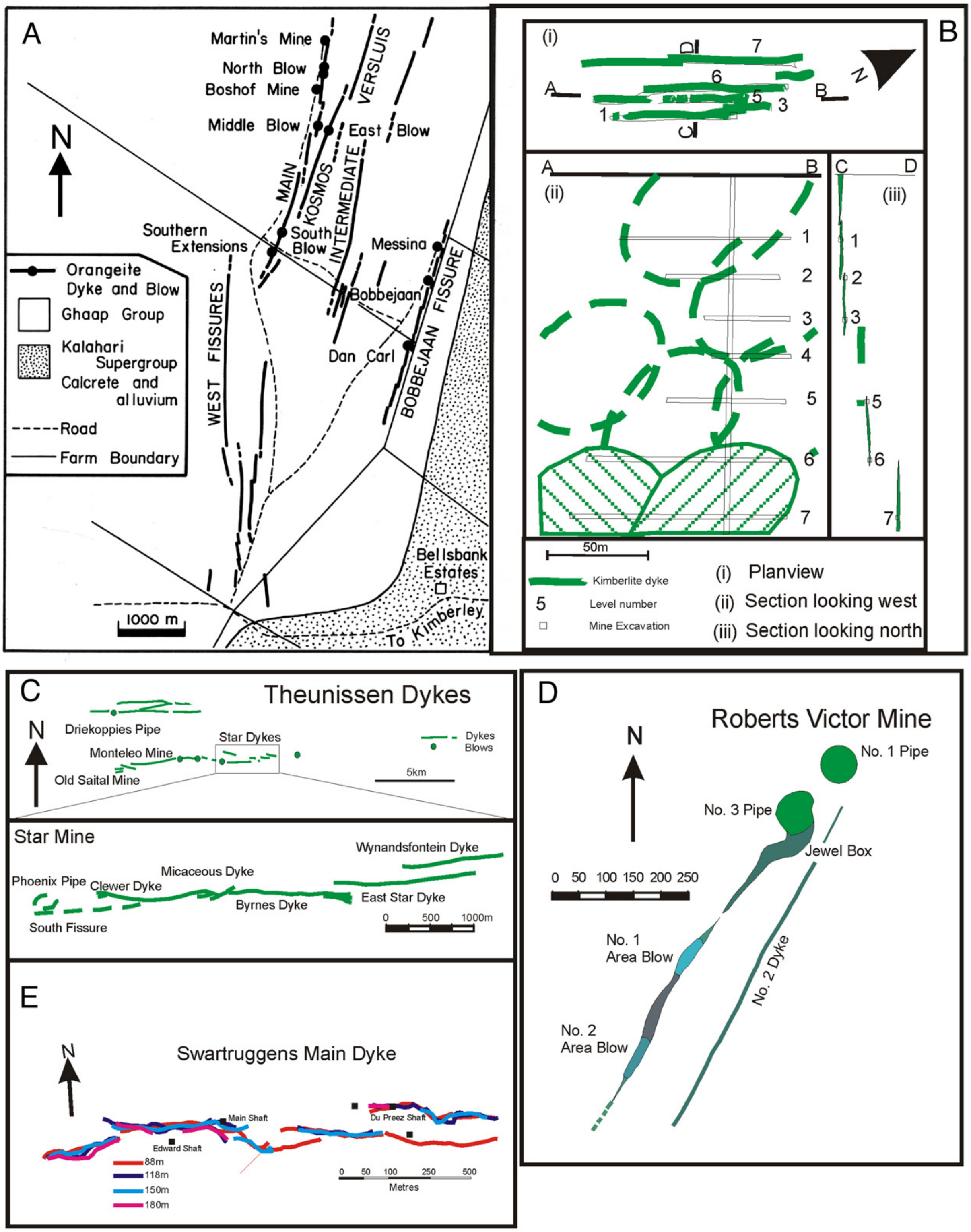


Fig. 19. Fissure mines. A: Map of the Bellsbank north of Kimberley showing the different Group-2 kimberlite dykes and blows (from Mitchell, 1995, after Bosch, 1971, Tainton, 1992). B: Plan and sections of the Bobbejaan dyke at Bellsbank (after Clement et al., 1973). C: Map of the Theunissen dyke with an inset of the Star Mine dykes (after Gurney and Kirkley, 1996). D: Map of the Roberts Victor dykes modified form Wagner (1914) and Gurney and Kirkley (1996). E: Plan view outlines of the mined-out portions of the Main Fissure at Helam Mine (courtesy De Beers).

30 to 60 cpht. The Jewel Box area had the highest grades. The mine was considered marginal (Gurney and Kirkley, 1996), and the underground portion was closed following a major underground mud-rush accident in the 1990's. In recent years some re-treatment of tailings dumps has taken place, but this has now also ceased.

6.15. New Elands

6.15.1. Geology

This pipe occurs at the intersection of two older dykes (Wagner, 1914). The pipe is then cut by a later internal dyke. The pre-pipe dykes were found to be much richer in mica than the pipe. The kimberlite has been classified as a Group-2 type, and dated at 127±5 Ma (Smith et al., 1985).

6.15.2. Diamonds

The diamonds, while possessing the overall characteristics of the district, were characterized by the presence of numerous octahadera of pure-white and blue-white colour, and the rarity of macles and cleavage fragments (Wagner, 1914). A relationship between diamonds and kimberlite type was also indicated within this mine. The larger dyke contained the highest grade and better quality diamonds described above. The diamonds recovered from the pipe were spotted and flawed, and a greater proportion of boart and cleavage was recovered from it.

6.15.3. Production

New Elands was purchased by Dwyka Diamonds Limited in 2005. Historically the mine recovered approximately 460,000 carats at an average grade of around 34 cpht (Dwyka Diamonds Limited, 2006).

6.16. Blaauwbosch

6.16.1. Geology

Blaauwbosch is a small Group-2 kimberlite that has been dated at 133±27 Ma by Smith et al. (1985).

6.16.2. Diamonds

According to Wagner (1914) larger diamonds were predominantly rounded octahedral stones having a greenish tint. There were also brown dodecahedral stones.

6.16.3. Production

The mine is wholly owned by Dwyka diamonds (Damarupurshad, 2006) and has been upgraded to enable it to treat approximately 15,000 tons of underground ore and 5000 tons of tailings per month. Production was due to recommence in the latter part of 2006.

6.17. Loxtondal cluster

6.17.1. Location

According to Lynn et al. (1998) the Loxtondal kimberlites were discovered in 1965 about 20 km north-east of Kimberley (Fig. 1). They consist of a small (approximately 1 ha) pipe and eight dykes located on the farms Loxtondal, Klein Leeuwkuil and Una.

6.17.2. Geology

Clement et al. (1973) and Clement (1982) showed that the pipe enlarged beneath a dolerite sill through which it intruded. Loxton is a Group-2 kimberlite. Subsequent work identified various kimberlite varieties, some of which had a much higher associated diamond grade (Lynn et al., 1998).

No information concerning mantle xenoliths or diamond inclusions could be found in a literature search on this locality.

6.17.3. Diamonds

Damarpurshad (2006) noted that the mine produced good quality diamonds.

6.17.4. Production

Loxton Mine (now also known as Don Diamonds) has been mined at a recovered grade of around 7 cpht (Lynn et al., 1998). A dyke extension has also been mined and has grades of around 30 cpht. The mine is currently owned by Good Hope Diamonds and according to Damarpurshad (2006) it was producing ore from underground workings in 2005 with a declared resource of 413,000 tons running at a grade of 85 cpht.

6.18. The Bellsbank group

6.18.1. Location and discovery

A series of sub-parallel Group-2 kimberlites dykes were discovered in 1952 on farms north of Kimberley (Fig. 1) by D. De Bruin and T. Mitchell. These dykes were to prove diamondiferous and have been mined almost continuously since then. The area has been sub-divided into various mines that have changed ownership and names with time.

6.18.2. Geology

The kimberlite dykes are intruded into Proterozoic-aged dolomites of the Ghaap Group. The dykes have been dated at 118±2.8 Ma by Smith et al. (1985) using the Rb–Sr method on phlogopites. A number of discrete dykes have been recognized that have been named the West, Main, Kosmos, Versluis, Intermediate and Bobbejaan fissures (Fig. 19A). One of the striking features of these kimberlite dykes is their structure. The Main dyke is approximately 4.2 km long but consists of a series of en-echelon segments that are generally less than a metre in width. At the extremities of each segment the dyke horse-tails into a few thin veinlets (Gurney and Kirkley, 1996). The main dyke also contains a number of "blows" which were interpreted by Bosch (1971) and Tainton (1992) to be remnants of a diatreme, whereas Mitchell (1995) regards these as hypabyssal-facies root zones. Mitchell presents the argument that the country-rock xenoliths contained within the blows are only derived from immediate and deeper lithologies, and therefore the kimberlite had to be from the root zone, rather than the diatreme. The Bobbejaan fissure is described by Clement et al. (1973) and Mitchell (1995) as a series of en-echelon lenses (Fig. 19B) which are more continuous than the Main Fissure.

6.18.3. Xenoliths

Smyth and Caporusico (1984) and Smyth et al. (1984) describe a suite of eclogites from the Bobbejaan fissure that include both Type-1 and Type-2 varieties (based on textural criteria), as well as kyanite and corundum-bearing varieties. Further work by Taylor and Neal (1989), and Neal et al. (1990) provided geochemical evidence that both crustal- and mantle-derived eclogites occur in these kimberlites. Viljoen et al. (2005) conducted a mineral chemistry and carbon isotope study of several graphite- and one diamond-bearing eclogite from Bellsbank. He found that graphite occurred in both Group-1 and Group-2 eclogites, but that the diamond-bearing eclogite is of Group-1 type, confirming observations made elsewhere on the Kaapvaal Craton. Shirey et al. (2001) have demonstrated that Group-1 eclogites from many Kaapvaal localities, including those from Bellsbank have an Re–Os isochron age of 2.9 Ga.

6.18.4. Diamond inclusions

Gurney (1989) stated that the Bellsbank/Bobbejaan mines have predominant eclogitic diamond-inclusion populations.

6.18.5. Production

The "Main" and "Bobbejaan" fissures are the most diamondiferous whereas the "Intermediate" and "Water" fissures have lower grades and are seldom mined (Mitchell, 1995; Gurney and Kirkley, 1996). The Main and Bobbejaan fissures produce high-quality diamonds, most of which are colourless and of gem-quality (Gurney and Kirkley, 1996; Lynn et al., 1998). Current ownership, the new names and the current state of the various mines are listed by Damarupurshad (2006) who also provides some mineral resource statistics.

6.19. The Doornkloof-Sover or Ardo group

6.19.1. Location

A set of Group-2 dykes occur approximately 20 km SSE of Bellsbank (Fig. 1). These are known as the Doornkloof-Sover dykes and they extend over a length of about 4 km (Bosch, 1971; Tainton, 1992; Mitchell, 1995; Gurney and Kirkley, 1996).

6.19.2. Geology

Bosch (1971) described two discontinuous dykes that occur as lenses intruded into Ventersdorp lavas and overlying Karoo shales. In addition to the dykes there is an elliptical intrusion located 1.5 km north of the Sover Mine. This intrusion was classified as a lamproite by Tainton (1992). This lamproite has not been mined. Mitchell (1995) prefers to refer to this occurrence as a differentiate of an orangeite (Group-2 kimberlite) magma. Gurney and Kirkley (1996) noted that two types of kimberlite occurred within the viable dykes, the “Red” and “Black” kimberlites. The Black occurs as lenses in the Red, which is also the dominant type. Higher diamond grades correlate with the Black.

6.19.3. Production

Only one of the dykes is of economic significance and it has been mined since the 1940's at a realized grade of around 20 cpht, although Gurney and Kirkley (1996) noted that in-situ grades are probably in the order of 50 cpht. Two mines exploit the dykes. Doornkloof Mine is owned by Rex Diamonds and is being operated by Afgem. Mining operations currently take place between 300 and 540 m depth (Damarupurshad, 2006). Nearby Sover Mine is currently only re-treating dump material, but is scheduled to recommence underground mining in 2007 (Damarupurshad, 2006). The latter is owned by Diamcor Inc.

6.20. The Swartruggens group

6.20.1. Location

A number of Group-2 kimberlite dykes occur approximately 130 km WNW of Johannesburg in the Northwest Province of South Africa, where they are mined at Helam Mine near the town of Swartruggens (Fig. 1). At least six dykes occur, namely the Main, Changehouse, Muil, John, North and South dykes each with differing diamond grades (McKenna et al., 2004). The Main dyke has a reported grade of over 200 cpht (Lynn et al., 1998), the Changehouse dyke has a much lower grade of around 20 cpht, whilst the Muil is barren.

6.20.2. Geology

The dykes are sub-parallel and discontinuous (Fig. 19) and are emplaced into lavas of the Pretoria Series of the Proterozoic Transvaal Supergroup. The dykes have been dated on three occasions. Smith et al. (1985) obtained an errorchron age of 156 ± 13 Ma from Rb–Sr isotopes on phlogopite, whereas Allsopp and Barrett (1975) obtained an age of 144 ± 4 Ma using the same technique, but as this age was determined by a two-point isochron, it is therefore unreliable (Mitchell, 1995). MacIntyre and Dawson (1976) obtained an age of 142 ± 4 Ma by using the Ar–Ar method on whole rocks. Mitchell (1995) observed that the dykes consist of multiple intrusions and that they display considerable lateral and vertical variation. Further, Mitchell (1995) noted that the diamond-bearing dykes are macrocryst-poor in texture and mineralogically standard orangeites (Group-2 kimberlites) whereas diamond-free dykes, such as the Muil, are best classified as lamprophyres that contain olivine set in a groundmass of clinopyroxene and sanidine. Mitchell believed that the orangeite and lamprophyric dykes are contemporaneous but not consanguineous and that the genetic relationships between them are not simple. Klump (1995), Coe et al. (2003) and McKenna et al. (2004) noted that the individual dykes can be distinguished on the basis of petrography and geochemistry, and that age relationships can be determined from field mapping. These indicated that the Muil is the oldest, followed by the Changehouse and then the Main dykes. Further, Coe et al. (2003) showed that the dykes are genetically linked, with the possible exception of the Muil.

6.20.3. Xenoliths

McKenna et al. (2004) noted that mantle xenoliths are very rare in these kimberlites and instead they investigated mantle-derived xenocrysts, diamonds and diamonds inclusions in these dykes. These showed that the Main dyke has harzburgitic, lherzolitic and eclogitic mantle components, whilst the Changehouse dyke has a predominantly lherzolitic component, with eclogite and harzburgite being very rare. The Muil dyke was found to be devoid of mantle components (Gurney and Kirkley, 1996). They suggested that the major difference in grade between these dykes was due to the enhanced eclogitic component of the Main dyke.

6.20.4. Diamonds

The diamonds from these dykes were first described by Harris et al. (1979). They identified unique characteristics including an almost complete absence of macles (<1%), a higher proportion of cubic diamonds (5–10%) and the presence of diamonds possessing distinct colours such as orange-amber and blue stones, as well as stones having multiple colours. Also a large proportion (>25%) had transparent green coats. Harris et al. found no difference between diamonds from different localities on the mine. The study by McKenna et al. (2004) provides further quantitative data on a small parcel of run-of-mine diamonds, which showed that the predominant diamond variety present was resorbed tetrahexahedra. They also showed that the diamonds had complex growth histories, with many stones having older cubic or octahedral cores surrounded by later overgrowths. They also demonstrated that the diamonds derived from at least three mantle parageneses, namely peridotite, eclogite and websterite. In addition possible ultra-deep majoritic garnet inclusions were also identified.

6.20.5. Production

Helam Mine is currently owned by Petra Diamonds, and in 2006 had a reserve of 1.67 million tons at a grade of 81 cpht and a diamond-value of US$271/carat. In addition it had a further inferred resource of 2.19 million tons at an average grade of 86 cpht (Damarupurshad, 2006). Current production has been maintained at about 80,000 carats per annum.

6.21. The Marsfontein–Klipspringer group

6.21.1. Location

The Marsfontein and Klipspringer Mines are located about 50 km east of the town of Mokopane (formerly Potgietersrus) in the Limpopo Province (Fig. 1).

6.21.2. Geology

Marsfontein consisted of a small kimberlite pipe, or blow (M1), located on or associated with a Group-2 kimberlite dyke (Compton, 2002). The kimberlite has been dated at 155.1 ± 0.8 Ma (Kiviets and Barton, 1999). The kimberlite intruded the Archaean Meinhardskraal granite and a dolerite dyke of unknown age. M1 formed the entire mining reserve, whilst the dyke (termed M8) proved to be sub-economic. The M1 pipe was sub-divided into four varieties by Machin (1999). Three of these were classified as hypabyssal-facies macrocrystic kimberlite, and the fourth as diatreme-facies TKB (Fig. 18C). The latter was found to be insignificant in size. The kimberlite is of the Group-2 variety.

Klipspringer Mine consists of Group-2 kimberlite dykes and blows, of which the Leopard and Kudu fissure (dykes) and Sugarbird and Kudu blows, are diamondiferous (Damarupurshad, 2006).

There is no published information on mantle-xenoliths, diamond-inclusions or the nature of the diamonds from these dykes and mines.

6.21.3. Production

Mining of M1 was carried-out by conventional open-pitting methods. It was operated as a joint-venture between De Beers Consolidated Mines Ltd and SouthernEra Resources Ltd. The mine was evaluated in 1997 and 1998, and mining commenced in August 1998, and was completed by November 2000. During that time 1.8 million carats were recovered from 1.03 million tons of ore, at an average grade of 177 cpht. At the same time 7.6 million tons of barren waste was also removed from the mine. A very high grade overburden was encountered over the pipe, which contributed greatly to the economic success of the mining venture. Klipspringer Mine is owned by SouthernEra Diamonds Inc, and according to that Company's 2005 resource statement, an indicated resource of 762,000 tons with a grade of 49 cpht exists (Damarupurshad, 2006).

6.22. The Theunissen group

6.22.1. Location

A series of dykes occur in the Theron area about 10 km north of the town of Theunissen in the Free State Province of South Africa (Fig. 1). There are two main dyke complexes, a north complex that is mostly uneconomic and consists of at least one pipe (Driekoppies), and three dykes that extend for approximately 3 km (these dykes will not be considered further here) and a south dyke complex that extends for 14 km and contains the economic deposits of Star Mine (Gurney and Kirkley, 1996), and at least another nine dykes or dyke sets (Erfbloem, Monteleo, Vergelegen, Leeuwkop, Stieniesrus (Rex Mine), Driehoek, Diamant, Mullersvlei and Magrietha) and five pipes (Fig. 19C) (Fullerton, 1968).

6.22.2. Geology

The kimberlites are all of Group-2 variety (Phillips et al., 1999) and intruded sedimentary rocks of the Karoo Beaufort Group. They are also closely associated with Karoo dolerite sills and dykes. MacIntyre and Dawson (1976) obtained a K–Ar age of ~124 Ma from phlogopites from Star Mine. Phillips et al. (1999) obtained an $^{40}Ar/^{39}Ar$ age spread of 130–140 Ma and a Rb–Sr age of 135±6 Ma for the Rex Mine. The Star Mine is a dyke complex that consists of four individual dykes named the Micaceous dyke, the Byrnes dyke, the East Star dyke and the Wynandsfontein dyke (Gurney and Kirkley, 1996). To the west of the Micaceous dyke the Clewer and South Fissure dykes continue into the Phoenix Mine property, where the Phoenix Pipe occurs. There is considerable variation in the nature of these dykes, which is reflected in variable diamond grades. Gurney and Kirkley (1996) suggested that the Micaceous dyke is a calcite-rich lamprophyre similar to the Muil dyke at Swartruggens. They also presented figures that show that diamond grade varies with dyke width.

6.22.3. Xenoliths, diamond-inclusions and diamonds

Gurney and Hatton (1989) examined and analysed diamond inclusions and diamond-associated minerals from Star Mine. They found that the diamond-inclusions were of harzburgitic, lherzolitic and eclogitic parageneses with about 80% being peridotitic. The mineral-diamond intergrowths were found to be mostly eclogitic, but of compositions not found in diamond inclusions elsewhere. They were however similar to diamond eclogites described from Roberts Victor. One lherzolitic diamond-garnet intergrowth was found. Gurney and Kirkley (1996) noted that diamonds from Star Mine are of high quality.

6.22.4. Production

Gurney and Kirkley (1996) provided information regarding grade variation at Star Mine. These data indicated that the East Star dyke has the highest grades of around 150 cpht whereas the Wynandsfontein dyke has grades of around 40 cpht. They also noted that high-grade pockets of 300 cpht occurred within the East Star dyke that have been interpreted as local accumulations of diamonds near the bottom of dyke lenses. Star Mine produced 16,000 carats during 2004 at an average grade of 47 cpht and an average value of US$179/carat (Damarupurshad, 2006).

7. Discussion

7.1. Origin and emplacement of primary diamond deposits

“Primary” diamond deposits are the end-product of an extremely complex set of geological processes that have permitted the growth and preservation of diamond in the earth's interior in the first place and then its subsequent extraction from its host environment and transport to the earth's surface where as a consequence of different geological processes it may be concentrated sufficiently to permit its economic extraction. From the extensive scientific investigations that have been conducted on southern African kimberlites and their mantle inclusions the following are seen as crucial factors in the development and preservation of such deposits:

1) Preservation of old Archaean crust and its associated thick relatively cool and chemically depleted sub-continental lithospheric mantle (Gurney, 1989; Harris, 1997).
2) Presence of primordial carbon, and the correct pressure, temperature and oxygen fugacity conditions for that carbon to crystallize as diamond during the Archaean (Kramers, 1979; Richardson et al., 1984, 1993; Richardson, 1989).
3) Periodic influxes of carbon introduced into or remobilized within the sub-continental lithosphere as a consequence of major tectono-thermal events. These events also produced crustal volcanic, metamorphic and sedimentary sequences and igneous intrusions. In the southern African geological record, examples such as the intrusion of the Early Proterozoic Bushveld Complex, Early Proterozoic Kheis Belt, Middle Proterozoic Namaqua–Natal Metamorphic Province and Late Proterozoic Damaran orogenies illustrate events whose ages can be correlated with the ages of diamond inclusions in various kimberlite mines. Such events appear to be important generators of eclogitic diamond populations that are important in mines such as Orapa, Jwaneng and Premier. It is possible that such events may also have resulted in major modification of the sub-continental lithosphere and have been detrimental to diamond preservation.
4) Periodic generation of low-degree partial melting events that spawn kimberlite magmas (Smith et al., 1985; Allsopp et al., 1989, 1995; Phillips et al., 1999). In southern Africa these have occurred in a number of discrete time-slices, i.e. ~1600 Ma (Kuruman — Shee et al., 1989), 1200 Ma (Premier), 500 Ma (Venetia), 250 Ma (Jwaneng), 200–110 Ma (Group-2's e.g., Finsch), and then the major Cretaceous group of 90–70 Ma (e.g., Orapa, Kimberley, Letseng). Only the 1600 Ma event has not produced mines to date, but this may be due to a lack of exposure. Such deposits may lie buried beneath younger sedimentary cover rocks. It is also evident that magmas of similar age were generated in “off-craton” settings, or in areas of thinner lithosphere within the cratons. Such magmas produced rocks that are superficially kimberlite-like, such as olivine melilitites of Bushmanland in South Africa (Cornelissen and Verwoerd, 1975). It should also be remembered that Premier Mine has a number of temporally and spatially associated alkaline complexes e.g., the Pienaars River Complex (Harmer, 1985). Perhaps the latter are examples of magmas generated in lithosphere that had been affected by the intrusion of the Bushveld Complex. In other instances potassic lamprophyres, which have little or no mantle minerals, are closely associated (in time and location) with highly diamondiferous Group-2 kimberlites, such as at Swartruggens, Star and Doornkloof-Sover. The exact origin and petrogenetic links between these rocks are still poorly understood (Mitchell, 1995).

In each case, dynamic and rapid emplacement of the most diamond-rich kimberlite batches through thick continental lithosphere and crust must occur. Slow rising magma may result in diamonds being lost either through physical separation or settling or through chemical resorption (Harris and Vance, 1974; Robinson et al., 1989; Fedortchouk and Canil, 2004). The mantle-sampling and transporting efficiency of the kimberlite is very important. This is best gauged by considering the proportion of mantle xenocrysts incorporated in the kimberlite (e.g., Gurney and Kirkley, 1996), as well as the depth of derivation of the grains. Traditionally the latter could only be determined by thermobarometric calculations done on mineral pairs found in mantle xenoliths, but with the development of Ni-garnet and Zn-spinel thermometers this can now be done on single grains (Ryan et al., 1996). This method does require some knowledge or assumption about the geothermal gradient at the time of kimberlite eruption. These minerals can also be used to re-construct the mantle profile at the time of kimberlite emplacement (Griffin et al., 2002, 2003a, 2003b).

In the intruded or erupted edifice that is preserved at or near the earth's surface it is important that the most diamond-bearing event is preserved. There are many examples cited in this review where only portions of dykes (e.g., Doornkloof-Sover and Star) or pipes (e.g., De Beers, Dutoitspan, Letseng-la-terae and others) are sufficiently diamondiferous to ensure economic exploitation. The magmatic model of Sparks et al. (2006) and the phreatomagmatic model of Lorenz (e.g., Lorenz, 1975) emphasize prolonged volcanic activity, and it is feasible that the materials that are preserved only represent the waning stages of the total event. Other, major diamond-bearing pyroclastic deposits may have been widely dispersed initially by volcanic processes and later by erosional and depositional agents. Evidence for early events may have been completely removed by subsequent events.

Another factor which influences the economic viability of such deposits is the quantity of barren country-rock materials that have been incorporated into the deposit as a consequence of volcanic or sedimentary processes. Examples of where country-rock dilution has negatively impacted the viability of mines are Koffiefontein and Voorspoed amongst others. In some cases, concentration of diamonds may also occur in specific parts of the volcanic edifice that is created. Orapa AK1 has modified grain-flow deposits that display very efficient sorting and concentration of gravel-sized particles. As is evident in the Star East dyke sorting can also occur in kimberlite dykes. At the other extreme, crater-lake lacustrine sediments, such as those at Orapa, will only contain very small diamonds as a consequence of hydraulic sorting. The very homogeneous character of typical diatreme-facies “TKB” or “MVK” may be the consequence of post-depositional fluidisation processes. These homogenized rocks make for much more simplified evaluation, whereas complex geological architecture leads to greater uncertainties. Clearly the geological characteristics of the preserved kimberlite are important for understanding the distribution of diamonds within kimberlites. The processes involved in the formation of these deposits are many and varied and span the traditional fields of igneous petrology, volcanology, sedimentology, hydrothermal alteration studies and geomorphology.

The size of the final volcanic edifice that is preserved also influences its economic viability and importantly the scale of potential mining operation that it may enable. In southern Africa the amount of post-emplacement erosion that has occurred is highly variable across the sub-continent. The work of Hawthorne (Hawthorne, 1975 and Fig. 2) indicated that up to 1400 m of erosion may have affected the Kimberley pipes. A recent compilation (Hanson et al., 2006) of country-rock xenoliths from across South Africa suggested that the depth of erosion may be considerably less than this, and was probably less than 850 m. At Premier good evidence has been presented that as little as 300 m has been removed from the top of the pipe (Bartlett, 1998). The sizes and shapes of kimberlite bodies are to some extent controlled by the depth of exposure, although there are local variants that may have other causes such as strong structural controls (e.g., Venetia; Kurszlaukis and Barnett, 2003).

Post-emplacement alteration and weathering can have many affects on the kimberlite deposit. These can include concentration of diamonds in lag deposits formed immediately over less weathered kimberlite, for example as recorded at the Marsfontein Mine. Secondly, where calcrete develops in kimberlite this can lead to restricted release of diamonds in the treatment of ore. Also, weathered oxidised kimberlite frequently contains diamonds that have green coatings that result from radiation damage in the weathered zone, as have been demonstrated at Finsch Mine for example (Harris et al., 1979).

7.2. Economic significance

The economic significance of the discovery of diamonds in South Africa in 1866, and especially the much richer kimberlite-hosted diamond deposits cannot be under-estimated. In South Africa it was the forerunner to the discovery of major gold deposits of the

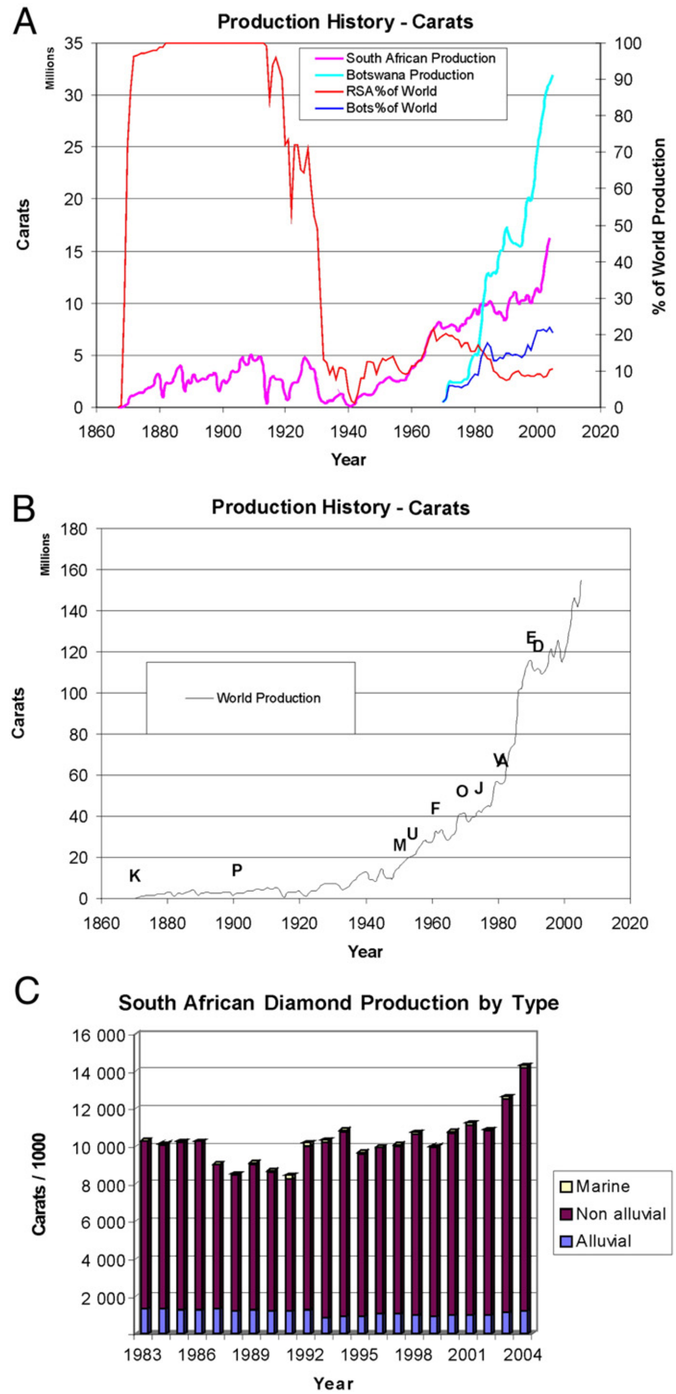


Fig. 20. Diamond production figures: A: Production histories for South Africa and Botswana, also showing the percentage of world production for both countries. (Data source: De Beers Group Services) B: World production in millions of carats since 1886, highlighting the discovery of major kimberlite and lamproite diamond mines. K = Kimberley, P = Premier (Cullinan), M = Mir, U = Udachnaya, F = Finsch, O = Orapa, J = Jwaneng, V = Venetia, A = Argyle, E = Ekati and D = Diavik. (source of data De Beers Group Services).C: Diamond production for South Africa by deposit type. Non-alluvial refers to kimberlite and kimberlite-derived tailings (data source: South African Department of Minerals and Energy).

Witwatersrand in the 1880's, and one could argue that had the kimberlites not been found there may have never developed a mineral prospecting culture in the country, or that this may have only occurred much later in the country's history. It was also largely due to the wealth generated by diamonds that the capital was available to commence gold mining operations. These discoveries of diamonds and then gold almost certainly led directly to the industrialization of South Africa, a factor which to this day makes South Africa the industrial leader of Africa. Fig. 20A shows that South Africa was the world's leading producer of diamonds during the period 1870–1935. It also illustrates the considerable contribution of Orapa and Jwaneng after 1969, which was one of the major factors for the large increase in world production relative to South African production after 1970. Fig. 20B illustrates the almost exponential increase in diamond production world-wide since 1940. The discoveries of Finsch, Orapa, Jwaneng and Venetia in southern Africa contributed considerably to this trend, although in pure carat terms, the contribution of the Argyle mine in Western Australia was also substantial.

Fig. 20C illustrates the importance of kimberlite producers to the South African production. All of the contribution labelled as "non-alluvial" in the diagram were derived directly from kimberlites or from the re-treatment of kimberlite tailings. A considerable proportion of these carats in fact derive from Venetia Mine. For example in 2004 Venetia produced 7.18 million carats (De Beers, 2004) of the total South African production of 13 million carats (Damarupurshad, 2006), or 55%. For the same period, De Beers kimberlite producers (viz. Cullinan, Finsch, Koffiefontein, Kimberley, The Oaks and Venetia) produced 12.83 million carats, or 98% of South Africa's production by carat weight.

The economic strength of Botswana is similarly linked directly to the presence of diamonds in kimberlites. Diamonds contribute over 60% of Botswana's GDP, and it has the highest GDP per capita in Africa. Lesotho is a country which is geologically impoverished, with over 80% of the country covered by Karoo flood basalts. The only mineral of significance is the presence of diamonds in kimberlites. Unfortunately for Lesotho these deposits are small in comparison to those in Botswana. It could be argued that the diamond rushes that occurred at the beginning of the 20th century in Namibia, where alluvial diamonds were found along the south-western coast, were also the consequence of the earlier discoveries in South Africa. These diamonds sparked the establishment of the first infrastructures in Namibia and are still a major factor in Namibia's present day GDP.

8. Conclusions

The kimberlite-hosted diamond deposits of southern Africa are highly variable in terms of their size, and the quantities and the qualities of diamonds they contain. These are the end-product of a considerable array of geological processes that span most of the geological history of the sub-continent. These deposits produced some of the richest mines on earth, as well as many sub-economic and uneconomic ventures. The presence of diamonds in kimberlites in southern Africa is undoubtedly linked to its ancient geological history. The distribution of the diamond mines show in Fig. 1 illustrates that they are restricted to areas underlain by the Archaean cratons and their associated sub-continental lithosphere (Griffin et al., 2003b). This relationship, referred to as Clifford's Rule (Janse, 1985) was first recognized in southern Africa and is now applied widely as a diamond exploration targeting philosophy.

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