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Kimberlite and lamproite diamond pipes

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EXPLORATION MODEL

Examples

Australia: Argyle (AK1), Ellendale, Merlin.
Overseas: Jwaneng, Orapa (Botswana), Finsch, Premier, Venetia (Republic of South Africa), Udachnaya, Mir, Aikhal (Russia), Ekati (Canada)

Target

- Volcanic pipes (diatremes) of kimberlite, less commonly lamproite, 100–1500 m across;
  - economic diamondiferous pipes have surface areas of ~1–150 ha or more (average size 12 ha);
  - dykes and root-zones to pipes have small surface area—less attractive to mine.
- Kimberlite pipes typically occur in clusters (~50 km across) with up to 100 individual intrusions; percentage of economic pipes is highly variable.
- Deposits 1–350 Mt; richest have estimated reserves of ~500 MCM* valued at many billions of dollars.
- Grades 20–100+ CM/100 t (Argyle 650 CM/100 t, Jwaneng 150 CM/100 t);
  - most economic deposits contain >30% gem quality diamonds, worth tens to hundreds of dollars/CM; industrials worth less than a few tens of dollars/CM.

Mining and treatment

- Mining mostly by open cut methods;
  - large open pits producing for 2–50 years;
  - about 30% of pipe mines continue production from underground operations below the pit, using bulk mining methods.
- Pipe size, shape and grade limit mining; pipe narrows with depth.
- Major mines typically process 3–6 Mt/yr to produce 2–10 MCM/yr (Argyle processes 10 Mt/yr);
  - Argyle produces >35 MCM/yr (39 MCM in 1998), mostly of industrial grade;
  - cut-off grades typically >10 CM/100 t, but strongly dependent on diamond quality and size;
  - cut-off size typically ~1 mm; mean diamond size typically 0.01–0.7 ct.
- Diamonds extracted by crushing, screening, heavy media separation (HMS), and X-ray fluorescence separation, followed by acid cleaning and hand sorting, according to established grading criteria;
  - HMS typically achieves reduction of 1000:1 ore to 'concentrate';
  - X-ray fluorescence supplemented by vibrating grease tables;
  - diamonds hand sorted on basis of size, shape, clarity, colour and cutability, according to the Central Selling Organisation (CSO) classification.

Regional geological criteria

- Economically important kimberlite and lamproite restricted to ancient cratons (typically >2.5 Ga) or cratonised provinces older than 1.8 Ga;
  - pipes in younger accreted cratonised mobile belts rarely carry economic diamond grades;
  - non-diamondiferous alkaline ultrabasic rocks at craton margin or off craton.

* CM = metric carat; 1CM = 0.2g; MCM = million metric carats; CM/100 t = metric carats per 100 tonnes; Mt = million tonnes

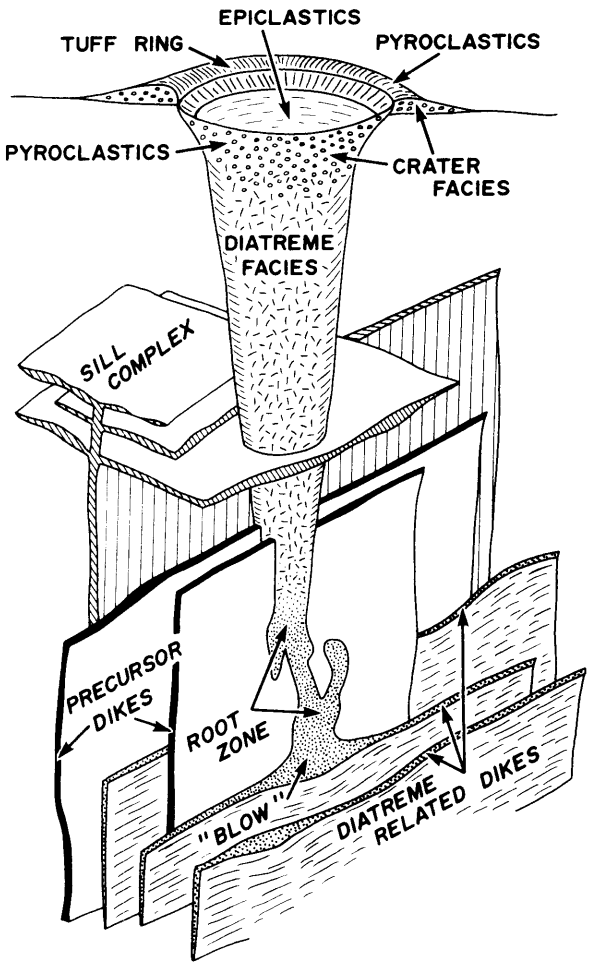

Figure 1. Model of idealised kimberlite magmatic system illustrating the relationships between crater, diatreme and hypabyssal facies rock (after Mitchell, 1986. Reproduced with permission of Plenum Press, New York).

- Structural controls on the distribution and emplacement of many kimberlites/lamproites;
  - association with major lineaments and fault zones suggests deep structural control.
- Multiple periods of kimberlite magmatism in some provinces.
- Kimberlite fields typically preserved on peneplains or plateaux.
- Preservation (and size) of intrusion related to uplift history and level of erosion;
  - presence of platform sediments overlying craton regarded as favourable indicator of preservation;
  - only dykes and root zones typically preserved in highly eroded basement terrains.

Local geological criteria

- Kimberlite distribution commonly associated with epeirogenic faulting.
- Faults and lineaments may locally control emplacement of kimberlite as pipes, dykes and blows.
- Pipes commonly exhibit circular features—depressions or mounds—and vegetation anomalies.

- Intrusions commonly highly weathered (clay) and recessive;
  - –oxidised clays (yellow ground) at surface underlain by unoxidised kimberlite 'blue ground'.
- Intrusions occur as
  - –crater facies: tuffs and other pyroclastic and epiclastic rocks common, some bedded;
  - –diatreme facies: steep-sided bodies containing breccias of kimberlite, mantle-derived material and wall rock;
  - –hypabyssal facies: hypabyssal intrusions and breccias.
- Multiple intrusions common in root zones of diatremes;
  - –mantle indicator and diamond content vary between intrusive phases.

Mineralisation features

- Diamonds disseminated in volcanic host (and rarely mantle xenoliths);
  - –alluvial redistribution from primary source common.
- Micro-diamond content can indicate macro-diamond grades, but is complicated by resorption/growth of multiple diamond populations.
- Grade varies in different phases of body.
- Crater-facies sequences can contain major amounts of country rock with minor juvenile material.

Deposit geochemical criteria

- Kimberlites and lamproites are ultrapotassic alkaline ultrabasic rocks with high MgO, Ni, Cr, K, Rb, Sr, Cs, Nb, Ta, LREE, Pb, Th, U, Ba, P;
  - –LREE abundances typically 200 ∞ normal ultramafic rocks;
  - –lamproites also enriched in Ti, Zr, Hf.
- High Ni, Cr, Nb and Ta levels in regional stream and soil geochemistry close to source.

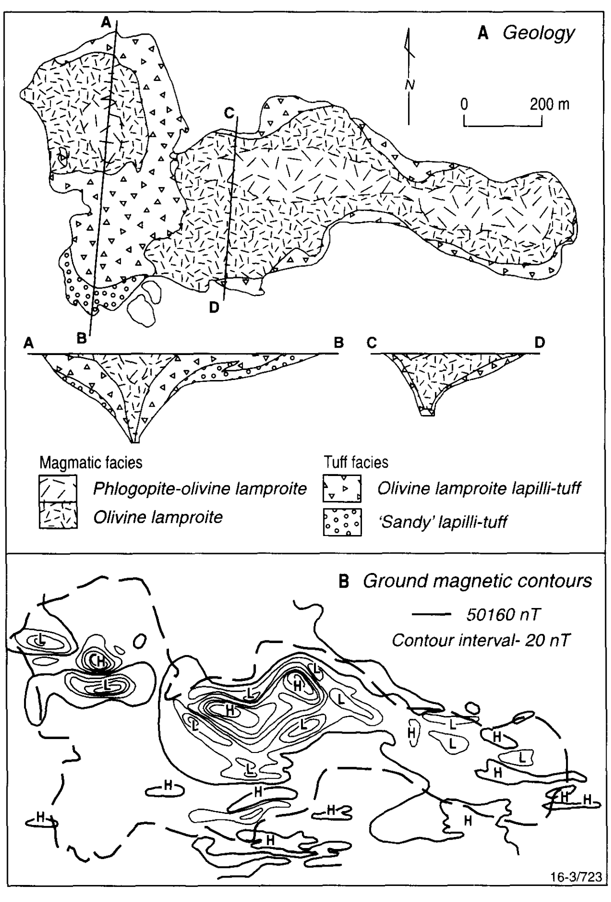

Figure 2. Geology and ground magnetic contours of olivine lamproite pipe Ellendale 9 (after Jaques et al. 1986).

Comments on genesis

- Diamond forms in peridotite and eclogite in the lithospheric keels to cratons (150–250 km depth at 950–1350°C).
- Diamonds carried to surface in deep-seated volcanics (mostly kimberlite, less commonly lamproite, rarely lamprophyre).
- Rare diamonds contain ultra-high-pressure mineral inclusions derived from deep mantle; origins in subducted lithospheric slab.
  - –inclusions dated by Sm–Nd, U–Pb and Ar–Ar: P-type >3Ga; E-type 600–2100 Ma, typically much older than host eruption age.

Diamond properties and composition

- Colour highly variable: white, yellow, brown, grey-black, depending on the deposit and history of diamond (Argyle diamonds mostly brown, but some highly prized pinks).
- Occur as single crystals, mostly octahedral, dodecahedral or cubic forms, as twinned crystals (macles) and, less commonly, as aggregates.
- Major impurity is N (up to 5000 ppm) in lattice defects;
  - –type 1a (N present as aggregates), 1b (N in single substituted atoms);
  - –type 11a (N absent), 11b (boron present).
- Type of N substitution is reflected by characteristics of the IR spectra.
- Diamonds contain primary (syngenetic) mineral inclusions (typically <100 µm) in two paragenesis:
  - –*peridotite—P-type*: olivine, Cr-pyrope, enstatite, chrome diopside, chromite, Ni sulphide;
  - –*eclogite—E-type*: omphacitic pyroxene, garnet, kyanite, corundum, coesite, rutile, sulphide.
- Diamond $\delta^{13}C$ ranges from +5‰ to –34‰;
  - –P-type diamonds from –2‰ to –9‰ (mostly –5‰ to –6‰).

Indicator minerals

- Diamond-facies chrome spinel extremely rich in Cr and Mg (≥61 wt% Cr_2O_3, 11 wt% MgO) and poor in TiO_2 (<0.5 wt%).
- Diamond-facies garnets belong to 2 parageneses:
  - –*peridotitic* with high Mg and Cr (typically ≥14 wt% MgO, ≥4 wt% Cr_2O_3) and commonly, but not exclusively, low Ca (<5 wt% CaO);
  - –*eclogitic* with >0.7 wt% Na_2O.
- Picroilmenite with high Mg (>4 wt% MgO), Cr (0.1–11 wt% Cr_2O_3 and low Fe^{3+}; typically rounded, with vitreous conchoidal fracture.
- Other kimberlite indicator minerals—chrome diopside, enstatite, olivine, phlogopite, rutile and zircon. Lamproite minerals—priderite, wadeite and potassic richterite.
- Morphology of indicator minerals indicates transport distance and history: increased abundance of fresh to worn grains close to source;
  - –highly susceptible to weathering in tropical terrains; zircon, ilmenite, chromite most resistant;
  - –depending on environment, indicators generally restricted to within few km of source.

Exploration methods

- Most pipes found by dispersal pattern of diamonds and indicator minerals around primary source, defined by heavy-mineral sampling of stream sediments and loams. Main indicator minerals: chrome pyrope, picroilmenite, chromite, chrome diopside, zircon, diamond;
  - –mineral compositions distinctive and indicate equilibration under high P and T;
  - –diamond grade may relate to relative abundance of mantle minerals.

- Airborne and ground magnetic and EM surveys useful in certain terrains, line spacing <400 m;
  - kimberlite and lamproite magnetic susceptibility typically 200–2000 ∞ 10^6 emu;
  - complicated by highly variable and complex responses (anomalies of 1–5 nT common);
  - weathered kimberlite is commonly conductive;
  - use of gradiometer surveys is increasing, <300 m line spacing.
- Micro-diamond dispersal pattern.
- Remote sensing—Landsat TM, aerial photography, multi-spectral scanning used to define structure (fractures and circular structures) and weathering products (clays).

Introduction

Diamonds have been prized as gems since antiquity. Before their discovery in kimberlite host rocks, in South Africa in 1869, all diamonds were produced from alluvial deposits, mostly in Brazil, India and Borneo. Today, more than 75% of the world's supply of natural diamonds is produced from primary sources—volcanic pipes (diatremes) of kimberlite[1] and, less commonly, lamproite[2]. More than 5000 world occurrences of kimberlite and lamproite are now known. However, fewer than 1000 contain diamond, less than 100 bodies are economic, about 50 have been mined and, of these, only half have produced significant quantities of diamond (Rombouts 1995). At present only 15 major mines are in production, but at least 5 new mines in the Canadian North West Territories are scheduled to begin production, the first of which (the Panda pipe at Ekati) commenced poduction in October 1998. Trial mining of four pipes in the Merlin field in the Batten Trough, Northern Territory (Australia) is due to begin in January 1999. New production is also likely from Russia in the next few years, including new discoveries north of Mirny and in the Arkhangelsk area, as well as the Jubilee pipe, which is currently under development.

Alluvial diamonds, from gravels and conglomerates eroded from primary kimberlite (or lamproite) sources by modern and palaeo-drainage systems, are being produced in several countries, notably Zaire, Angola and Sierra Leone. Such deposits are generally low grade, since grade typically decreases away from the primary sources, but the quality of the eventual diamond is typically higher (60% or more), because flawed diamonds get destroyed by mechanical transport.

Mining of marine diamonds is becoming increasingly important, especially off the west coast of southern Africa (Gurney et al. 1991). These diamonds are commonly of high value, as marine processes also destroy flawed diamonds. Production is from former beach deposits and, increasingly, from marine gravels in water up to 100 m deep.

Australia is the world's largest diamond producer (Table 1), with approximately 40 million metric carats (MCM) a year, equivalent to about 35% of the world's supply of natural diamonds. In terms of value, Australian production represents only about 5% of the world figure because the bulk of its production is low-value stones (less than US$10/CM) of industrial and cheap gem quality. Production is entirely from the major pipe mine and associated alluvial deposits at Argyle in the East Kimberley region of Western Australia. Future production from the new mines in the North West Territories of Canada will establish Canada in the top seven producing countries with an initial output of approximately 4% of world production.

Tectonic setting of pipes

Diamondiferous pipes are known from most Precambrian cratons. The most significant diamond-producing regions (in terms of value) are the Kaapvaal Craton of southern Africa and the Siberian Platform of eastern Russia, each containing more than 800 kimberlite occurrences. The economically important pipes are restricted to ancient cratons (typically >2.5 Ga) or cratonised provinces older than 1.8 Ga (e.g. Clifford 1966, Janse 1994). Although diamondiferous bodies have been found in younger accreted cratonised mobile belts, they typically do not carry economic diamond grades. The Argyle pipe is an exception, lying in a Palaeoproterozoic orogenic belt which became part of the North Australian craton at about 1800 Ma (Plumb 1979, Myers et al. 1996).

Apart from Argyle, virtually all primary diamond production is from *kimberlite* bodies. With the exception of Argyle, lamproites discovered to date—e.g. Ellendale (Western Australia), Prairie Creek (Arkansas), Majhgawan (India)—are either barren or have low diamond content (<30 CM/100t; Mitchell & Bergman 1991, Moore & Gurney 1989, Scott Smith 1992). Traces of diamond have also been found in olivine-rich lamprophyres (e.g. Jaques et al. 1986, 1989b, Hamilton & Rock 1990), but no economic deposits are known.

Kimberlite pipes typically occur in clusters, forming fields about 50 km across, with up to 100 individual kimberlite intrusions. Kimberlites are rarely found complete; the more eroded deeper pipe (>2 km) components, including dykes and root-zones, may also contain diamonds, but their small surface area generally makes them less attractive to mine. Typically, only 1 in 100 kimberlite bodies is economic, although this figure varies greatly—from as low as 1 in 200, to 1 in 10 in certain fields, such as the North West Territories, Canada.

Lamproites differ from kimberlite in their petrography, mineralogy and chemical composition. They commonly include pyroclastic rocks, contain glass, and a wide range of K, Ti, and/or Ba-rich minerals, such as leucite, titanian potassic richterite, priderite, and wadeite. In terms of chemistry, olivine lamproites are typically richer in SiO_2, TiO_2, K_2O, Ba, Zr, Rb, and LREE and poorer in Fe, MgO, CaO, CO_2 and Cr than kimberlites. At equivalent MgO contents, Al_2O_3 and Na_2O are lower than kimberlites. Significant differences exist in the mode of emplacement of kimberlites and lamproites. Most lamproite bodies are volcanic craters (Fig. 2) of up to 1500 m across, which are typically less than 300 m deep and commonly infilled by pyroclastic rocks and late crater-filling magma (e.g. Atkinson et al. 1984, Jaques et al. 1986, Smith & Lorenz 1989, Mitchell & Bergman 1991, Scott Smith 1992).

The economic grade of kimberlites varies greatly, depending on the quality (value) of the diamonds. Most economic deposits contain 30% or more gem-quality diamonds and grades of 20 CM/100 t or better. Tonnage ranges from 1 to 350 Mt; the richest deposits have reserves of ~500 MCM. Grade–tonnage models for kimberlite pipes (excluding kimberlite sills and dykes and lamproite) suggest a median resource of 26 Mt and a median diamond grade of 25 CM/100 t (Bliss 1992). With the exception of the Argyle pipe lamproite, diamond grades in lamproites are typically <30 CM/100 t (Scott Smith 1992).

Table 1. World diamond production 1996 (from the Diamond Registry, http://www.diamondregistry.com/world.htm—Oct. 1998).

Country	*Total production (million carats)*	*Gem*	*Industrial*	*Ranking (by production)*
Australia	41.99	18.90	23.10	1
Russia	18.50	9.25	9.25	2
Zaire	18.00	3.00	15.00	3
Botswana	16.00	11.00	5.00	4
South Africa	11.36	5.36	6.00	5
Angola	4.00	3.60	0.40	6
Brazil	1.30	0.70	0.60	7
Namibia	1.30	1.30	–	7
China	1.13	0.23	0.90	9
Other	3.42	2.06	1.35	
Total	117.00	55.40	61.60	

[1] *Modern definitions of kimberlite are given by Clement et al. (1984) and Mitchell (1986).*

[2] *Lamproite is a potash and magnesia-rich lamprophyre, i.e. rock of alkaline composition. The review of lamproites by Mitchell & Bergman (1991) gives a comprehensive definition and descriptions.*

Australian diamond deposits

Diamonds were first found in Australia near Bathurst in New South Wales, in 1851, and later as scattered alluvial occurrences, during alluvial gold and tin mining, in all States except the Northern Territory (reviews by Atkinson et al. 1990, Smith et al. 1990). Before mining began at Argyle (alluvials in 1983 and pipe in 1985), diamonds were produced only from the Copeton, Bingara and Cudgegong alluvial fields in New South Wales (MacNevin 1977). Exploration for primary sources of diamond began in the 1960s and 1970s in eastern Australia, where alluvial diamonds were known to be associated with the dominantly Tertiary alkaline basaltic rocks in the Tasman Fold Belt. This led to discovery of several alkali basalt breccia pipes of Jurassic to Tertiary age and, eventually, to kimberlite dykes and small pipes in South Australia, but no economic diamond deposits (Atkinson et al. 1990, Smith et al. 1990).

The Western Australian diamond fields were discovered following exploration in the Kimberley region by the Ashton Joint Venture. Diamondiferous lamproites were found in the west Kimberley region in 1976 and the world-class Argyle diamond pipe in the east Kimberley in 1979 (Atkinson et al. 1984, Jaques et al. 1986, Smith et al. 1990). Large-scale mining of the Argyle pipe began in 1985 and in the first year of mining (1986) more than 29 MCM were produced (Boxer & Jaques 1990).

The first generation of Australian diamond exploration, which relied heavily on stream-sediment sampling for heavy-mineral indicators,

- proved that kimberlites similar to those of southern Africa are present in Australia, although those in northern Australia are mica-rich compared to those in southern Africa and Siberia;
- demonstrated the diamond potential of Australia's extensive Precambrian terrains;
- resulted in the discovery of the Argyle deposit and established Australia as a major diamond producer;
- proved that lamproite, a previously ignored rock type, was a second primary source of economic diamonds;
- demonstrated that (traces of) diamonds could also be found in other alkaline ultrabasic rocks;
- indicated the presence of diamond-bearing alkaline ultrabasic rocks in at least nine separate provinces in Australia (Fig. 3); and
- demonstrated the usefulness of airborne geophysical surveys in diamond exploration in Australia.

Australian alkaline ultrabasic rocks, including both diamondiferous and barren types, have been reviewed by Atkinson et al. (1984, 1990), Jaques et al. (1984a,b, 1985, 1986) and Jaques (1994). Features of these suites are:

- ages of intrusion ranging from Precambrian (Palaeoproterozoic) to Tertiary (1.9 Ga–20 Ma);
- location in cratonised crust older than 1.6 Ga and at least 35 km thick; and
- common association of intrusions with major crustal structures, some of which can be directly linked with major worldwide extension events, such as the breakup of Rodinia (~800 Ma) and Gondwana (~160 Ma).

Distinct assemblages can be recognised amongst the alkaline ultrabasic suites prospected for diamonds in Australia on the basis of differences in species and composition of indicator minerals (Jaques 1994):

- a *kimberlite* assemblage, dominated by pyrope, chrome diopside, chrome spinel, ± picroilmenite and ± zircon, comparable to those from kimberlites elsewhere, notably southern Africa, Siberia and China;
- a *lamproite* assemblage, dominated by chromite with subordinate pyrope and sparse chrome diopside without picroilmenite. Ti- and K-rich minerals specific to lamproite such as priderite and potassic richterite may also be present;
- a *lamprophyre* suite, dominated mostly by chromite and pyrope, but which may contain abundant chrome diopside, ilmenite (mostly Mg-poor), and/or other minerals, such as Ti-rich garnet (melanite);
- an *alkali basalt indicator* suite, which commonly contains low-pressure minerals, such as megacrystal kaersutite and/or Al-rich augite, and has indicator minerals with significantly different chemistry to those of kimberlites.

A large body of compositional data exists for indicator minerals from Australian ultrabasic rocks (e.g. Ferguson & Sheraton 1979, O'Reilly et al. 1989, Jaques et al. 1984a,b, 1986, Lucas et al. 1989). Smith et al. (1994) reviewed the chemistry of indicator minerals from the Kimberley region and evaluated the effectiveness of predicting diamond grades using established schemes based on garnet, chromite and ilmenite composition. These authors concluded that the methods developed for determining the diamond potential of kimberlite—notably the presence of sub-calcic peridotitic garnet, high Na_2O in eclogitic garnet, and high-Cr, high-Mg chromites and ilmenites—failed to adequately predict the diamond grade of Australian lamproites. In addition to the above methods, trace-element analysis of indicator minerals is increasingly being used to evaluate the diamond potential of pipes, using the Ni and Cr content of garnet or the Zn content of chromite (Griffin et al. 1989, Griffin & Ryan 1995).

Recent exploration has been based on more detailed indicator surveys and bulk sampling, and airborne magnetic and electromagnetic methods. This phase of exploration has

- resulted in the discovery of the Merlin kimberlites in the Batten Trough, where trial mining is proceeding on four pipes;
- resulted in the discovery of new kimberlite dykes and pipes in the north Kimberley region, some of which are currently being evaluated;
- concentrated more detailed surveys in areas where diamonds had previously been found (e.g. the Kimberley region);
- indicated the presence of diamond-bearing kimberlitic rocks in the Yilgarn Block; and
- focused new exploration in the cratonic regions (notably the Yilgarn), although exploration has continued in the New England region in search of primary sources of alluvial diamonds.

A new development in the early 1990s was the search for alluvial diamonds, especially marine diamonds off the Kimberley coast. Exploration was based on the premise that erosion of diamondiferous pipes in the north Kimberley, as well as the Argyle pipe, had shed alluvial stones in palaeodrainage systems draining into the Joseph Bonaparte and Cambridge Gulfs and that these may have been concentrated in palaeochannels. Diamonds have been recovered from channel-fill sequences in an extensive alluvial braid plain, but these are commonly overlain by fine-grained marine sediments (Hamilton 1996).

To date, the only economic deposit is the Argyle lamproite pipe, but production is expected to begin in early 1999 from four small kimberlite pipes (Excalibur, Launfal, Palomides and Sacramore) in the Merlin field. The Bow River alluvial deposit near Argyle produced some 7.2 MCM in the period 1988–1995. Sub-economic deposits are hosted by lamproite pipes at Ellendale in the west Kimberley. Evaluation of the diamondiferous kimberlites in the Bulgurri and Forrest River region of the north Kimberley is continuing.

Argyle

The geology of the Argyle lamproite pipe has been described in detail by Atkinson et al. (1984), Jaques et al. (1986), Boxer et al. (1989) and Boxer & Jaques (1990), and summarised by Jaques (1994). The 1200 Ma Argyle pipe intrudes Palaeo–Mesoproterozoic sediments overlying the 1.8–1.9 Ga crystalline basement rocks of the Lamboo Complex of the Halls Creek Province. The pipe has a total surface of 47 ha and is highly elongated, extending some 1500 m in a north–south direction and tapering in width from 600 m in the north to less than 50 m in the south. The northern part of the pipe is bowl-shaped and roughly circular in plan, resembling a volcanic crater, in contrast to the remainder of the intrusion, which has a narrow dyke-like form with steep westerly dips.

The Argyle pipe is infilled by diamondiferous olivine lamproite pyroclastic and reworked pyroclastic rocks and intruded by rare dykes of olivine lamproite. Shales overlie the pyroclastic deposits in the northern part of the diatreme. Two basic types of volcaniclastics are recognised at the mine: polygenetic, quartz-rich pyroclastics with sparse juvenile fragments ('sandy tuffs' of Atkinson et al. 1984) and largely monogenetic, non-quartzose olivine lamproite tuff and breccia, including autobrecciated olivine lamproite ('non-sandy tuff'). The geology and volcanology are described by Boxer et al. (1989), who proposed that the Argyle pipe formed through the action of multiple phreatomagmatic eruptions when olivine lamproite magma encountered groundwater.

Detailed petrographic and mineralogical descriptions of the pipe are given by Atkinson et al. (1984), Jaques et al. (1986, 1989a) and Boxer et al. (1989), and the geochemistry by Jaques et al. (1989c). Heavy mineral concentrates from the Argyle pipe are dominated by hematite and diamond with trace amounts of magnesiochromite, garnet, chrome diopside, and orthopyroxene (Lucas et al. 1989). Diamondiferous peridotite xenoliths from Argyle have been described by Jaques et al. (1990).

Argyle diamond production is dominated by small (mean <0.1 CM/stone), brown, frosted, strongly resorbed dodecahedral stones of industrial and cheap gem quality (Hall & Smith 1984, Boxer & Jaques 1990). Only about 5% are gem quality, although these include rare highly prized pink diamonds. Original reserves were 61 Mt @ 6.8 CM/t proven with a further 14 Mt @ 6.1 CM/t probable (Boxer & Jaques 1990). Annual production increased to more than 40 MCM in the early 1990s; in 1997, 40.2 MCM were produced, made up of 38.6 MCM from the Argyle AK1 pipe and 1.6 MCM from alluvial operations. The alluvial deposits, comprising Miocene terrace gravels to Recent floodplain gravels, have been described by Boxer & Deakin (1990). A major underground mining operation, planned for after the current phase of open pit production, has been deferred in favour of deepening the pit to allow open-cut operations beyond 2003.

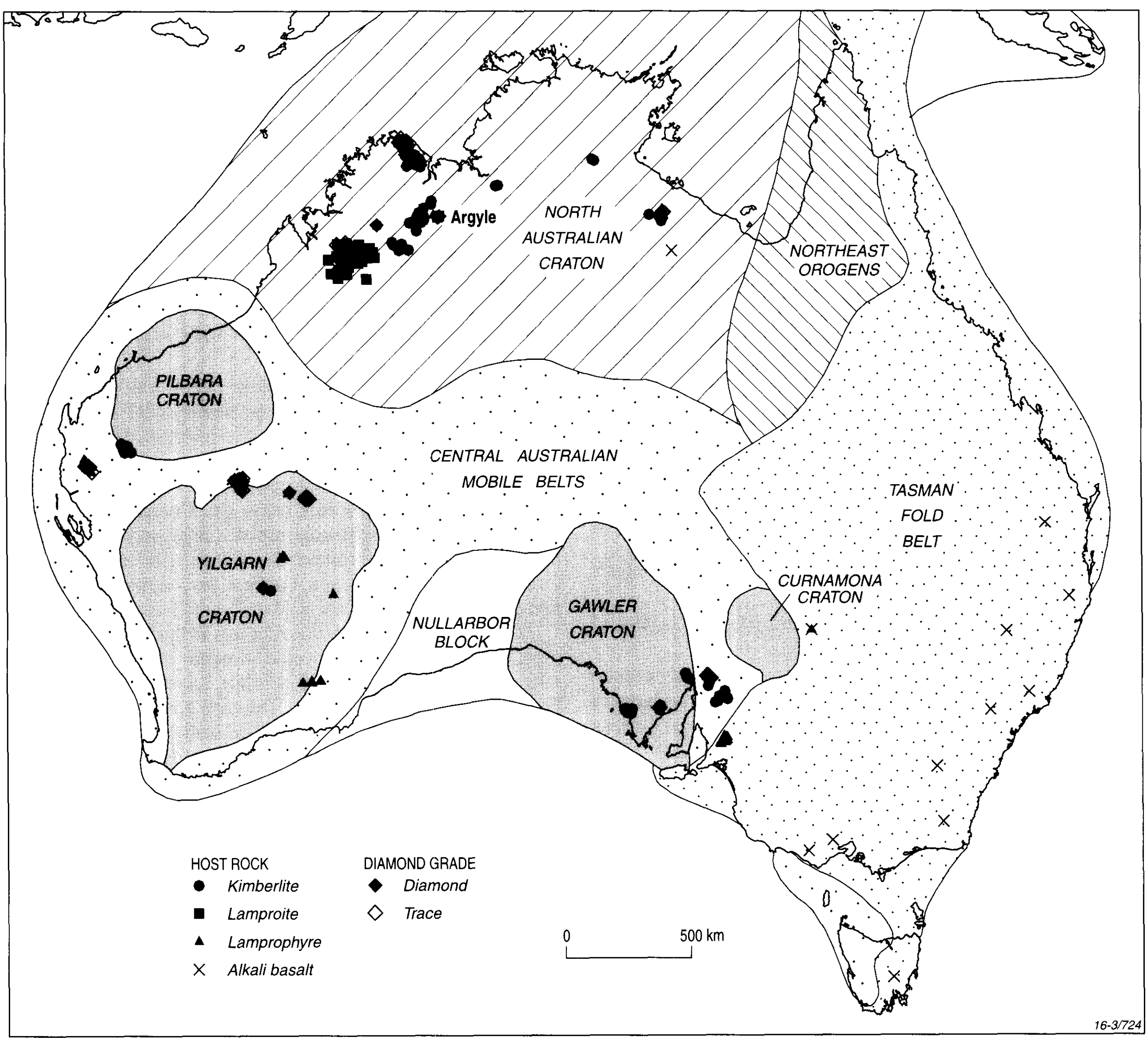

Figure 3. Distribution of kimberlites, lamproites, lamprophyres and diamonds in relation to major tectonic units (from Plumb 1979) .

Merlin

The diamondiferous Merlin kimberlite field in the Batten Trough includes the two Emu[1] pipes, discovered by CRAE in 1986, dated at 360 Ma (Atkinson et al. 1990), and the pipes discovered in 1992 by the Australian Diamond Expedition Joint Venture (ADEJV), managed and now wholly owned by Ashton Mining Ltd. Some thirteen small pipes occur in a 10 ∞ 5 km oblate field on the eastern side of the Batten Trough, about 6 km east of the Emu Fault and on the projected trace of the Calvert Fault (Lee et al. 1995, 1998). The pipes occur in clusters. Individual pipes have a constant diameter of between 100 and 125 m, and are infilled by up to 42 m of mudstone and sandstone.

The Merlin pipes are mainly diatreme-facies kimberlite, which is commonly micaceous. They intrude the flat-lying Cambrian Bukalara sandstone and underlying Proterozoic rocks, and have been dated by Rb–Sr as Devonian (367 Ma; Lee et al. 1998). Both chrome spinels (some very Cr-rich) and peridotitic garnets (mostly of lherzolite paragenesis) are present. Diamond grades are 8–129 CM/100 t and trial open pit mining on four of the pipes (Excalibur, Launfal, Palomides and Sacramore) is progressing, with first production scheduled for January 1999. Approximately 35% of the stones are gem quality, dominated by small clear and colourless white stones with an average valuation of ~US$70/CM (range US$41–140).

Other diamondiferous intrusions

Kimberley Block

The Kimberley Block contains the largest concentration of diamond-bearing intrusions in Australia. In addition to the Argyle lamproite pipe in the east Kimberley, two other diamondiferous suites occur—a suite of ~800 Ma kimberlite pipes, dykes and fissures in the north, on the eastern margin and in the southern central part of the Kimberley Block, and the ~20 Ma Ellendale lamproites in the west Kimberley.

Most kimberlites in the north and east Kimberley occur as deeply eroded dykes and a smaller number of pipes intruding Palaeo–Mesoproterozoic sediments of the Kimberley Basin. Pipes of up to 10 ha occur and, although most previously reported bodies are either barren of diamond or sub-economic, several recent discoveries (Bulgurri, Ashmore, Seppelt, de Lancourt) are diamondiferous and currently being evaluated. The 20 ha Aries kimberlite pipe in the Phillips Range, southern central Kimberley Basin, contains sub-economic diamond grades (Towie et al. 1994). A feature of the north Kimberley kimberlites is an abundance of indicator minerals with chemistry (e.g. G10 garnets) similar to that of diamondiferous kimberlites from southern Africa (Ramsay 1996).

The Ellendale lamproites are part of the Miocene (19–22 Ma) west Kimberley lamproite suite, which consists of more than 100 separate lamproite intrusions in a broad belt extending from the southern margin of the Kimberley Basin to the northern margin of the Canning Basin (Atkinson et al. 1984, Jaques et al. 1984a, 1986). The lamproites occur as pipes, plugs, sills and rare dykes in three main fields (Ellendale, Calwynyardah and Noonkanbah), but the diamondiferous olivine lamproites are largely restricted to the Ellendale field, where they occur as poorly exposed volcanic crater deposits, which were located mainly by detailed aeromagnetic surveys (Jaques et al. 1986, Hughes & Smith 1990). Details of the volcanic geology of the Ellendale pipes are given by Smith & Lorenz (1989), who inferred that pipe formation commenced with phreatomagmatic eruption and formation of maar-diatreme volcanoes and that the craters became progressively filled with base surge deposits and slumped country rocks. A late feature was the rise of magma into the craters to form lava lakes or domes (Fig. 2). Forty-five per cent of the west Kimberley lamproites carry traces of diamond, but only the more MgO-rich olivine lamproites of the Ellendale field contain potentially economic deposits. The highest grades (in Ellendale 4 and 9) are 14 and 5 CM/t, respectively, (Hughes & Smith 1990). Commercial diamonds from Ellendale are yellow, resorbed, rounded dodecahedra with lustrous smooth surfaces, and a high proportion (60–90%) are gem quality (Hall & Smith 1985).

Yilgarn Craton

A suite of alkaline ultramafic lamprophyre intrusions, some containing traces of diamond (Hamilton & Rock 1990), and, more recently, kimberlites have been reported at the northern and northeastern margin of the Yilgarn craton (e.g. Atkinson et al. 1990, Smith et al. 1990, Shee et al. 1996, Smith 1995). Most of the bodies are sills and dykes, but some are small pipes (typically 1 ha or less). Hamilton & Rock (1990) described four ultramafic lamprophyre, pipe or sill-like intrusions, of Carboniferous age (305±7 Ma), near Bulljah Pool. Heavy-mineral concentrates from loam samples over the bodies contain garnet, ilmenite, spinel, and chrome diopside. A further three fields of barren ultramafic lamprophyres have been reported from the Eastern Goldfields of the Archaean Yilgarn Block (Foster et al. 1991). More recently a suite of some 12 metamorphosed kimberlites, including four diamondiferous bodies of Precambrian age (~2 Ga), has been reported from the Nabberu region (Shee et al. 1996). Exploration is continuing in Nabberu, the Eastern Goldfields, central Yilgarn, and the Narryer region of the southern Yilgarn.

A suite of some 22 alkaline lamprophyre pipes, dykes and sills, of Jurassic age (160 Ma), intrudes the Phanerozoic Carnarvon Basin at Wandagee, on the western margin of the Yilgarn craton. The Wandagee bodies contain chromite, garnet, picroilmenite, chrome diopside, zircon, and enstatite, and are either barren or contain only traces of diamond (Jaques et al. 1986, 1989b).

The Yilgarn craton is a classic Archaean granite–greenstone terrain with a crustal thickness of >40 km and major crustal structures, some of which extend to the mantle. It has been tectonically stable since its last tectonism at ~800 Ma, and contains kimberlite/lamprophyre intrusions with ages of ~2 Ga, 850 Ma, 300 Ma and 160 Ma; some of these have traces of diamond. The potential of the Yilgarn craton is concealed by a complex ancient regolith, with elements as old as Permian, which was partly stripped and overprinted by extensive weathering and redistribution during the Tertiary (e.g. Clarke 1994).

North Australian Craton (excluding Kimberley Block)

The North Australian Craton is inferred, from airborne magnetic and gravity data (Shaw et al. 1996), U–Pb zircon geochronology, and Nd isotope data, to consist of Archaean basement fragments with Proterozoic sedimentary cover (Myers et al. 1996). The full extent of the Archaean basement is not known and the overall crustal structure is unclear. The Kimberley Block was joined to the Granites-Tanami region to form the North Australia Craton by continental collision at ~1830 Ma (Myers et al. 1996).

The existence of older (Archaean) terrains within the North Australia Craton and the presence of major crustal structures and diamondiferous kimberlite indicate a potential for further discoveries in this craton. Exploration is complicated by the tropical–arid weathering regime, regolith cover and the apparently widespread distribution of micro-diamonds of uncertain provenance (Smith et al. 1990).

Gawler Craton

Kimberlites are known from the Stuart Shelf (Augusta), Eyre Peninsula (Cleve) and the Adelaide Fold Belt (Orroroo). All are Jurassic (160–180 Ma) and occur as dykes, sills and highly eroded small pipes associated with major structures (Stracke et al. 1979, Scott Smith et al. 1984, Wyatt et al. 1994). Those found in the Adelaide Fold Belt and the Gawler Craton seem to

footnote—[1]Emu is the correct name; the spelling 'E.Mu' in Atkinson et al. (1990) is an error.

correlate with the earliest stages of the breakup of the Gondwana continent. Traces of diamond have been recovered in the Orroroo kimberlites (Scott Smith et al. 1984), some of which contain enstatite and magnesiowustite mineral inclusions, indicating an origin in the lower mantle.

The extensive thick (>40 km) Precambrian crust and major crustal structures suggest that the extensive, but largely concealed, Gawler Craton has potential for further kimberlite discoveries. Exploration by mineral geochemical methods (loam and stream-sediment sampling) is impeded by an extensive cover of wind-blown sand and lack of drainage over much of the craton. Airborne magnetic surveys, combined with stream-sediment indicator surveys, have proved useful in detecting kimberlites in the Eyre Peninsula (Wyatt et al. 1994).

Pilbara Craton

Alluvial diamonds were discovered at Nullagine in 1895, but the primary source has yet to be found. Until the recent report of a kimberlite dyke, no kimberlites or lamproites were known from the Pilbara Craton—the only recorded alkaline rocks were Precambrian calc-alkaline lamprophyres (Jaques et al. 1985, Rock & Barley 1988). Marked similarities in the tectonostratigraphic components of the Pilbara and Kaapvaal cratons (Trendall 1994) suggest a similar crustal evolution and, by analogy, a high diamond potential in the Pilbara lithosphere. Major structures in the north and west Pilbara may provide favourable locations for potential diamond host rocks, but exploration there is impeded by widespread ironstone. Recent airborne magnetic surveys in the Pilbara indicate major NNE and E-trending structures transecting the granite–greenstone terrain.

Tasman Fold Belt

Despite extensive exploration the primary source, or sources, of alluvial diamonds in eastern Australia remains unresolved. A number of historical accounts report the presence of diamonds (mostly micro-diamonds and single stones <0.3 CM, but including stones up to 1 CM) in alkali basalt breccia pipes and dykes ranging in age from Permian (~200 Ma) to Quaternary (0.4 Ma; summarised by Sutherland 1996). Detailed sampling by company exploration programs since the 1960s has failed to substantiate the existence of diamond-bearing source rocks (at least of commercial interest). Individual diamonds found in alkali basalt volcanics have been widely interpreted as accidental inclusions from underlying diamondiferous Tertiary deep-leads, which are particularly common in the New England province. The composition of megacrysts and xenoliths from both the Tertiary and Mesozoic alkali basalt suites indicates derivation predominantly from the spinel and rarely from garnet–spinel peridotite facies in the mantle under a high geothermal gradient (e.g. Ferguson & Sheraton 1979, O'Reilly & Griffin 1985, O'Reilly et al. 1989, Sutherland et al. 1994), well above the diamond stability field. The New England (Copeton, Bingara) diamonds exhibit some unusual characteristics—they are highly resorbed, commonly strongly macled (therefore, difficult to cut), isotopically heavier than other Australian diamonds, and contain an unusual coesite–diopside/omphacite–high-Ca garnet inclusion suite (Sobolev et al. 1984, Taylor et al 1990, Meyer et al. 1995).

Barron et al. (1994) proposed a model for the formation of eastern Australian diamonds, involving formation under relatively lower pressure in thick cold subducting lithosphere in the Palaeozoic and late transport to the surface in erupting alkali basalts. An alternative model proposes that the Copeton diamonds are derived from older decoupled lithospheric mantle sources by now largely eroded and/or buried pre-Mesozoic diamond pipes (Taylor et al. 1990). More recent exploration programs, involving reconstruction of palaeodrainage systems and further bulk sampling of the breccia pipes at Bingara and Copeton, have so far failed to identify potential diamond sources of commercial interest.

Conclusions

Exploration in the 1960s and 1970s resulted in discovery of the Argyle pipe and established Australia as a major producer of diamond. Exploration since then has discovered more than 400 occurrences of kimberlite, lamproite and lamprophyre, most of which are barren, but at least 5 provinces (Kimberley Block, McArthur Basin, Nabberu Basin, Yilgarn Craton, Gawler Craton) containing primary (mostly trace) diamond sources have been identified (Smith 1995). The most significant of the more recent discoveries are the Merlin deposits in the Batten Trough, where a suite of 12 diamondiferous pipes is undergoing trial mining and testing. Several new diamondiferous kimberlite pipes and dykes in the north Kimberley, with classic diamondiferous kimberlite indicator assemblages of diamond, are also being evaluated. These newer discoveries have emphasised the importance of detailed heavy mineral indicator surveys using refinements of traditional techniques developed during regional exploration in the 1970s and 80s (Hamilton 1996). Airborne magnetic surveys have been shown to be useful in defining kimberlite bodies in many provinces, particularly in areas of cover, such as the Yilgarn Block and Gawler Craton, and combined airborne magnetic and electromagnetic surveys are being used increasingly.

Despite the exploration to date, large areas of the Australian Shield remain relatively under-explored, notably the Archaean Pilbara, Gawler and Yilgarn Cratons. Much of the North Australian Craton, where the age of the basement is in many areas uncertain, but known to be mostly Palaeoproterozoic (though it includes Archaean remnants), is also relatively poorly explored. At the time of writing, there was increased exploration interest in the Kimberley, Yilgarn and Pilbara. Exploration for marine diamonds, especially in the waters off the Kimberley coast, is at a much reduced level. Future exploration will benefit from improved targeting of areas of potential through new insights into the crustal structure gained from continent-scale geophysical datasets and tomographic studies, such as the SKIPPY project (Zielhuis & van der Hilst 1996), and a better understanding of the regolith over much of the Australian Shield.

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