Geology and resources of diamonds

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Abstract: A brief review of diamond mining covers the succession of dominating resources, from India to South Africa, to elsewhere in Africa and then to Russia and Canada. Kimberlite pipes have come to be recognised as the explosive transporters of diamonds upwards from their high-pressure sources in the deep crust and upper mantle of Archaean cratons.

With the East Midlands Geological Society into its 60th Anniversary year, it seemed appropriate that the Presidential Address should concern diamonds. There has been massive evolution of the diamond industry during the last 40 years. The once-dominant centre of production, Kimberley in South Africa, is now in decline, while major resources have been developed elsewhere, notably after epics of exploration in Botswana and northern Canada. At the same time geologists have gained a reasonable understanding of the deep crustal sources of diamonds followed by their upward transport in kimberlite volcanoes to bring them within reach of economic mining. This review can be only a superficial summary, picking out some of the significant or more interesting parts of a great story. In similar vein, the bibliography cites only a few accessible sources from a vast literature.

Diamonds at Kimberley

Erasmus Jacobs was 15 years old when he found the first recorded African diamond, weighing 21 carats, on the bank of the Orange River in 1866. A subsequent discovery triggered a rush to diggings on the tributary Vaal River in 1869, but more significant were the discoveries during the next few years, of diamonds in weathered kimberlite at outcrop on the pipes that are the primary sources of the diamonds. A huge open-pit mine on one pipe became known as the Big Hole (Fig. 1), and the new town of Kimberley became the centre of the world's diamond industry under the careful direction of Cecil Rhodes and then the De Beers company. Between 1889 and 1959, Africa produced 98% of the world's diamonds, and Kimberley reigned supreme until the 1970s. The early story of Kimberley's diamonds has already been told by the author (1997).

During the last 25 years, huge changes in the world's diamond industry have included the approach to exhaustion of Kimberley's older mines. De Beers Consolidated Mines closed its deep mines at Kimberley in 2015 and sold the sites to Petra Diamonds and Ekapa Mining. Ekapa then re-opened the Wesselton Mine (now more than 1000 metres deep) and also the Joint Shaft that provides deep access to the Bultfontein and Du Toitspan pipes. This company is also re-working and reclaiming the mine dumps beside each of the big pipes, which is proving profitable by using new and improved processing. The new tailings have then been used to backfill and reclaim the old open pit on the De Beers pipe, though historical significance will prevent any filling of the Big Hole on the Kimberley pipe. It is symbolic that Harry Oppenheimer House, almost overlooking the Big Hole, was closed at the end of 2022. Since 1973, most of the world's gem diamonds were sorted within it, under daylight provided by its huge windows that face away from the sun. Sorting has now moved to Johannesburg, which is more accessible from the newer mines.

***Figure 1**. The Big Hole, in the centre of Kimberley; dug by hand into the Kimberley pipe, it was later undermined by block caving, and then flooded to water table.*

Alluvial diamonds in Namibia

Millions of years of erosion of the exposed kimberlite pipes, both at Kimberley and across most of uplifted southern Africa, has seen vast numbers of diamonds transported down the Orange River and its ancestors, to be dumped in terminal placer deposits along the west coast of the continent. They are therefore part of the story of Kimberley, and joined that story when Zacharias Lewala noticed a diamond stuck to grease on his shovel while working on the railway near Luderitz in 1908.

These coastal diamonds occur in fluvial, marine and aeolian terraces that date from late Cretaceous to modern times, forming low terraces that rise inland, along with beach deposits and off-shore marine sediments. They lie north and south of the mouth of the Orange River, mostly in a belt 150 km long within the Skeleton Coast of Namibia and the Namaqualand coast of South Africa.

Inland from Luderitz, alluvial mining grew rapidly, and annual diamond yields reached a million carats by 1912. As resources became depleted, mining moved south along the coast during the 1920s, and the original diamond town of Kolmanskop was abandoned to the desert in 1956. A huge chunk of Namibia was designated as ‘prohibited land’ (Sperrgebiet) to allow unconstrained mining, and included the closed company town of Oranjemund. Since the De Beers lease ended in 2010, most of this area has become the Tsau Klaeb National Park, which includes Kolmanskop and Oranjemund but excludes the narrow coastal strip of current mining activity. Total diamond production has surpassed 110M carats from Namibia and 50M carats from Namaqualand, with the latter becoming dominant on land after 1980. Offshore mining from Namibia expanded in the 1990s, with crawler dredges working the seabed at depths down to 120 metres and pumping sediment up to the ships that house separation plants. Marine production has now exceeded 25M carats of diamonds.

Vast resources of these alluvial diamonds, onshore and offshore, have placed Namibia among the world’s top producers without the nation having a single kimberlite pipe.

Kimberlite pipes

Diamonds occur in kimberlite and, less commonly, in lamproite. The former is a variation on peridotite, composed dominantly of olivine, with lesser diopside, phlogopite and calcite; the latter is similar but richer in potassium and mica. Both are formed within the Earth’s mantle, with their differences probably related to mantle variations.

Figure 2. *Kimberlite, an uninspiring rock to look at, even more so when weathered.*

These rocks also contain recognisable minor minerals that become valuable indicators in searches for diamonds based on sediment sampling. The important indicators are green chrome-diopside (which is soft, so grains do not travel far from their source pipes), ilmenite (which would not survive in oxidising conditions that would also burn up diamonds), and pyrope garnets. The critical garnet is the type known as G10, which is low in calcium and high in chromium. This was identified as a key indicator by John Gurney at the Smithsonian Institute, after microprobe analyses of hundreds of samples from African kimberlites; it then became famously crucial in tracking down the kimberlite pipes of northern Canada.

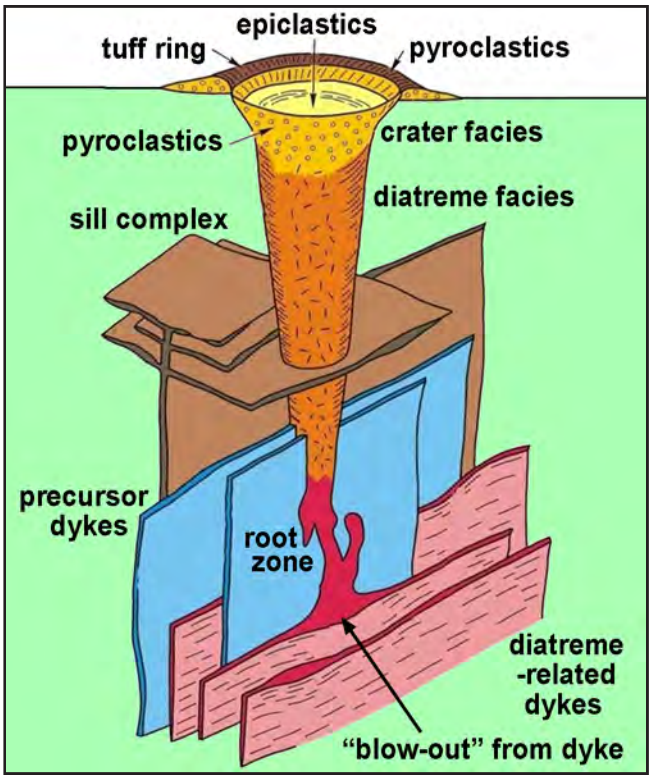

Figure 3. *Typical structure of a kimberlite pipe, from root zone to diatreme crater (after Kjarsgaard, 2022).*

Diamonds are not native to kimberlite (or lamproite); they are merely xenocrysts picked from the wallrocks as the host magmas rise through the upper mantle and crust, along with fragments of eclogite and other deep-seated rock types. Kimberlites are just the transporters of diamonds, carrying them up from their deep sources to the ground surface in what ultimately become violent, explosive volcanic eruptions.

The first kimberlite pipes to be found and recognised as diamond sources were at Kimberley, but all of those are only the lower parts of the structures, the upper parts having been eroded away to depths of around 800 metres. Subsequently, pipes were found, notably at Mwadui in Tanzania, with the larger, flared, upper parts largely intact; the pipes were then recognised as feeders to gas-rich, explosive volcanic vents known as diatremes. Within these, kimberlite ranges from hypabyssal intrusions to various types of pyroclastic breccias (Fig. 2). Later still, deep mining revealed the pipes' size reductions at depth, and also the feeder dykes from which the pipes broke out where overburden pressures were declining into shallower ground (Fig. 3).

A critical feature of a kimberlite volcano is the rapid ascent of its magma, which incidentally determines its violent style of eruption. The explosive rise of kimberlite magma is essential for the survival of its diamonds. A slow ascent of magma, as within a normal dyke system, would give it extended time at high temperature and reduced pressure, which would cause any diamonds to transition to graphite. That did happen in the huge peridotite intrusion south of Ronda, in Span, parts of which have abundant octahedral graphite pseudomorphs after diamond; the carbon converted during the millions of years of its slow tectonic rise from depth. There is still debate over why and how diamond-bearing kimberlites rose through the crust so rapidly, but it is likely that their ascent from depth was driven largely by volatiles, notably carbon dioxide, water and fluorine, exsolved from silicates. Around 7000 kimberlite pipes are known, but only a thousand contain diamonds larger than a millimetre, and fewer than a hundred have supported significant mines.

Formation of diamonds

It is now widely recognised how thick, ancient cratons have been critical to the formation of diamonds (Fig. 4). Of the two allotropes of carbon, diamond forms at higher pressures than graphite, but the transition pressure increases with temperature. Consequently, diamond is stable at depths greater than about 300 km within most of the Earth's crust, with graphite stable above it. But most of the carbon lies within the upper mantle and lower crust at depths of less than 100 km. However, the situation is different in Archaean cratons where parts of the crust can be around 200 km thick. These were formed prior to about 1600 Ma when the processes of plate tectonics were rather different due to mantle temperatures being around 200°C higher than they are today. Instead of the complete subduction and melting of modern oceanic plate, a zone of convergence was marked by partial subduction, with one plate of the more ductile lithospheric sliding beneath another to form a thickened lithosphere. Consisting of both upper mantle and crustal material, this is known as the keel of an ancient craton.

Formed of the lighter silicates, a cratonic keel has lower thermal conductivity, with the result that its temperature profile is depressed when compared with those of non-cratonic sites. And the depressed

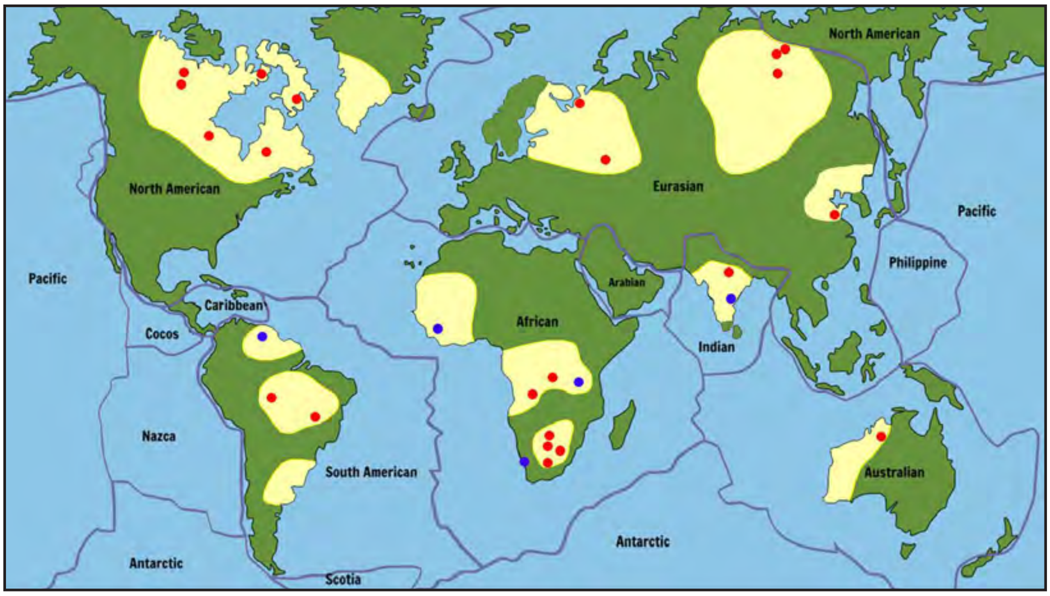

***Figure 4**. A generalised map of the world's major cratons, shown in yellow; some of the more significant areas with diamond-bearing kimberlite pipes are shown by red circles, and those with mainly alluvial diamonds by blue circles.*

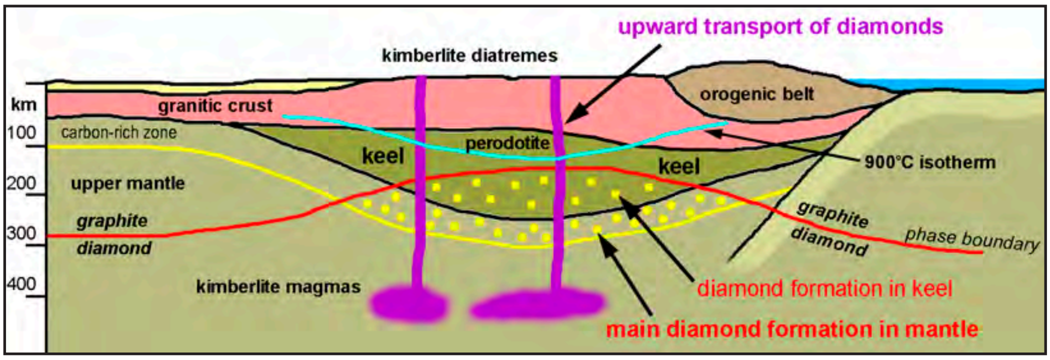

***Figure 5**. A conceptual diagram of the features of diamond formation in the keel of a craton.*

temperature profile means that the graphite-diamond transition rises into zones of lower pressure (Fig. 5). The result is that carbon in the keel and the underlying upper mantle is stable as diamond instead of graphite. Taking millions of years to form, these diamonds can grow to significant sizes at depths of around 200 km below ground, in magmas with the broad composition of peridotite.

Kimberlite magmas form by differentiation at even greater depths, but when they explode upwards they pick up diamonds (among all sorts of other wallrock debris) and blast them into pipes and diatremes before they can transition back to graphite. The triggers for kimberlite eruptions remain unknown, whether by hot-spot, subduction or tectonic stress. Also still open to debate is whether all the carbon is primary within the mantle or if some may be organic material re-cycled from the surface by subduction. But the end result is ancient diamonds being blasted through thick cratons by younger kimberlites to come within reach of the mining fraternity.

Impact diamonds

The high temperatures and pressures required to create diamonds can also be generated where meteorites impact our planet. The Nordliger Ries site in Germany is one of nine impact craters known to contain diamonds in their explosion breccias. These are however 'hexagonal diamonds', also known as lonsdaleite, with their shapes copying the flakes of graphite from which they were formed by the impact; the graphite, originally organic, occurs in gneisses that were melted during the impacts.

The Popigai crater in northern Siberia was formed by a meteorite probably 8 km in diameter arriving about 35 million year ago; it formed a crater 100 km across and maybe 10 km deep, reaching down into graphite-garnet-gneisses. Impact diamonds were formed where temperatures and pressures were just right between 12.0 and 13.6 km out from ground zero. The resultant annulus of breccia contains huge amounts of diamond, but stones are less than a millimetre across and of industrial quality only.

Diamonds have also been found within meteorites. Graphite nodules within the Canyon Diablo meteorite appear to have converted to tiny diamonds during the instant of impact that formed Arizona's Meteor Crater. A few smaller meteorites contain micron-size diamonds, strictly hexagonal lonsdaleites, that were probably formed by impacts and collisions in space before fragments headed for Earth; space collisions could also account for the carbonado black diamonds, known from sites that are remote from known pipes.

Diamonds in India

Until 1870, the world's supply of diamonds came almost entirely from India. The 105-carat Koh-i-Noor, now in the British crown jewels, and the even larger Darya-e Nur, in the Iranian crown jewels, are just two of the fabulous diamonds found in the Golconda mines around the year 1500. Those diamond mines had already been producing for 2000 years, when during the 1600s there were 60,000 people working the alluvial gravels along the valleys of the Krishna River. The centre of activity was Kollur, but no trace of the ancient diggings is recognisable today (Fig. 6). Golconda held political power over the mines, and its fort still stands in the western suburbs of Hyderabad. All the diamonds were taken from the river gravels, and their bedrock source has never been identified. There has to be the possibility that diamond-bearing kimberlite pipes lie buried beneath the expanse of Deccan basalts.

In northern India the open-pit mine at Panna has worked into the Majhgawan lamproite dykes for a hundred years. Production has reached an annual 10,000 carats, but the site is currently closed because it lies within a tiger reserve.

Diamonds have also been found in the Proterozoic Banganapalle conglomerates within the Vindhayan basin, partly covered by Deccan basalt. These were probably derived from nearby lamproite dykes, and could be the source of diamonds in Quaternary gravels in northern India, but their stones are distinctly different from those at Kollur.

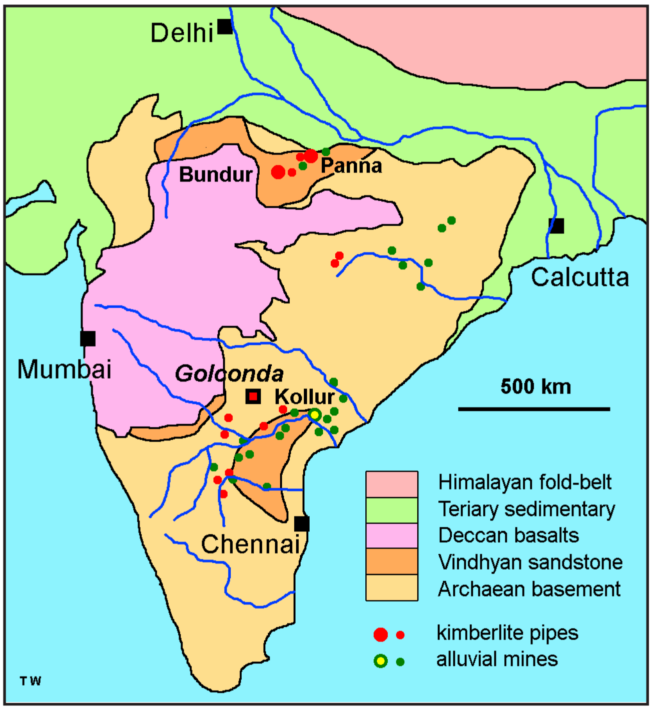

Figure 6. *Diamond locations in India.*

Diamonds across Africa

Following discovery of diamonds at Kimberley, diamondiferous kimberlite pipes and derived alluvial deposits have been found all across the great cratons of southern Africa (Fig. 7).

Figure 7. Diamond mine locations in southern Africa.

Further mines in South Africa

In 1898, Thomas Cullinan found a mine on the surface of farmland north of Johannesburg, and this led to the 1902 opening of the Premier mine (now known as the Cullinan mine) on a kimberlite pipe that is larger than any known at Kimberley. In January 1905, with the evening sun low in the sky, a miner saw a blaze of light in a wall of the open-pit mine that was then 10 m deep. He called the mine manager, who used his penknife to prize out a huge diamond; it weighed in at 3106 carats, or 621 grams. Known as the Cullinan Diamond, it is still the largest ever found. Bought by the Transvaal government, it was given to Edward VII, then cut into 105 stones, including the 530-carat Great Star that is now set into the royal sceptre among the Crown Jewels. The Cullinan mine is still operating, though its 32-hectare open pit ceased production in 1990 where a sill 60 m thick cuts through the pipe beneath the -350 m level. Underground workings were started beneath the sill in 1940, and have now reached to 1000 m deep.

Since its discovery in 1980 in the far northeast of South Africa, the Venetia pipe supported a highly productive open-pit mine for 30 years; it then converted to underground workings that aim for depths around 1000 m and an annual extraction of four million carats of gem-quality diamonds

East of the Cullinan mine, Marsfontein was a smaller operation that started with a classic case of exploration and discovery. Targeting an assumed trend of kimberlite dykes, a road survey sampled stream sediments and found two sites with high levels of indicator garnets. Soil sampling followed on a kilometre grid, and then on anomalies with a 200 m grid, followed by a 50 m grid. A gravity low indicated a pipe, and a magnetic survey identified dykes at depth. Drilling through 30 m of cover, the third hole hit the pipe, which proved to be 90 by 40 metres in plan, tapering into a dyke 10 m wide at a depth of 140 m. A single large-diameter hole drilled to 90 m deep confirmed viability without further bulk sampling. The open-pit mine was established just five years after exploration started, and recovered diamonds that recouped the capital outlay from the first four days of production. Ore grades reached 509 cpht (carats per 100 tonnes) in the weathered kimberlite, and were still in the hundreds at depth in unweathered blue ground. Mining lasted for three years, to yield nearly two million carats of diamonds with a value close to £200M. Marsfontein showed that there are still pipes to be found, that high-risk exploration can pay off, and that small pipes can be lucrative.

Diamonds from Lesotho

Now an independent nation as an enclave inside South Africa, northern Lesotho has one of the highest number of kimberlite pipes per unit area in the world, supporting a cluster of mines in the Maluti Mountains, all at altitudes around 3000 m. The nation's diamonds are notable for their highest quality, creating huge value from a modest total production.

The Letseng mine has been a major producer since the 1970s, now with a huge open pit on the fourth largest pipe in southern Africa, along with a satellite pipe; these have been explored to depths greater than 500 m. Ore grade is low at <2 cpht (less than 1% of the grade at Marsfontein), but economic viability derives from the few very large stones.

The nearby Kao mine opened in 2007. It also works a pair of adjacent pipes with low diamond yields, but again the mine is profitable due to its many excellent coloured stones, including rare blues, purples and pinks. Since 2010, two more mines, Liqhoborg and Mothae, have also gone into production with large open-pit developments.

Diamond bonanza in Botswana

Starting in the 1960s, exploration followed the main craton into the Kalahari Desert, until the Orapa pipes were the first to be discovered among a host of diamond sites that transformed the economy of Botswana. Eventually, the country was to become the world leader, not in tonnage, but in value of its gem-quality diamond production (Table 1).

Alexander du Toit was a South African geologist noted for his support of Alfred Wegener's theory of Continental Drift. In 1938, while working in Bechuanaland (as Botswana was then known), he believed that kimberlite pipes were there to be found beneath the sand, so took thousands of gravel samples, eventually finding three small diamonds, but he could not identify their source.

In July 1966, Gavin Lamont, working for the local Geological Survey, initiated a huge programme of soil

	2021		2022		
country	**M ct**	**M $**	**M ct**	**M $**	**$/ct**
Russia	39.1	2643	41.9	3553	76
Botswana	22.9	4657	24.8	4975	202
Canada	17.6	1512	16.2	1877	101
D. R. Congo	14.1	168	9.9	65	10
South Africa	9.7	959	9.6	1538	129
Angola	8.7	1017	8.8	1965	170
Zimbabwe	4.2	153	4.5	424	66
Namibia	1.8	720	2.1	1234	501
Lesotho	0.3	261	0.7	314	575
Sierra Leone	0.8	119	0.7	143	175
Tanzania	0.05	24	0.4	110	298

Table 1*. The world's main sources of diamonds, with figures for 2021 and 2022, by weight (in millions of carats) and by value (in millions of US dollars); the last column of average dollars per carat shows that Russia, Congo and Zimbabwe produce mainly industrial diamonds of lower value.*

sampling on a mile-interval grid across the same area. This was followed by De Beers sampling the soil anomalies, to find garnet and ilmenite indictors in areas that also showed up as magnetic anomalies. In April 1967 a pit sample on the strongest ilmenite anomaly produced four cubic metres of grey-green, weathered kimberlite that yielded 3000 ilmenites, 1000 garnets and 50 chrome-diopsides. The Orapa pipe had been found.

After also working for the Survey, Chris Jennings left to pursue diamond exploration with Falconbridge, where from 1971 he developed improvements in geophysical surveys. Soil sampling evolved from large-scale walking to rapid helicopter access, and magnetic surveys evolved from ground-based to airborne. In some areas of deep sand cover, termite mounds were found to be useful indicators where the termites had carried to the surface G10 garnets and even a few microdiamonds. The number of anomalies, and then kimberlite pipes, thereby discovered, not just by the termites, reached a hundred, and eventually a dozen of these became the sites of major diamond mines.

Orapa was Botswana's first mine into production, in 1971. A large open pit still works a pipe that yields up to 10M carats of diamonds per year, though most are of industrial grade. Within the same cluster of pipes, the Lethakane open-pit mine achieved ore grades of 26 cpth when it was worked from 1977 until closure in 2017. Also within the Orapa cluster, the Damtshaa was started in 2004 with an open pit in four adjacent pipes.

In southern Botswana, 350 km south of Orapa, the Jwaneng mine was opened in 1982, and may prove to be the world's richest diamond mine (Fig. 8). Its huge open pit works three adjacent kimberlite pipes that originally lay beneath 50 m of Kalahari sand. Annual yields exceed 11M carats of diamonds from 9M tonnes of ore and 37M tonnes of waste, to make it already the world's largest diamond mine. Jwaneng is a huge operation, its diamonds are of high quality and value, and reserves are proven until after 2040.

Again close to Orapa, a preliminary survey in 1970 estimated a kimberlite pipe to extend over about three hectares with a diamond grade of about 3 cpht. Then a detailed re-survey in 2003 identified nearly ten hectares of pipe with a grade of 25 cpht. This became the Karowe mine that opened in 2012. Karowe has since achieved fame for yielding five top-quality diamonds of greater than 1000 carats, including one of 2492 carats that is second only to the Cullinan in size. The open-pit mine is expected to reach a depth of 320 m by the late 2020s, to be followed by underground mining to a depth of 600 m; and more very large diamonds are likely to emerge.

The latest chapter in Botswana's diamond story was the opening in 2014 of the Gaghoo site, which was developed solely as an underground mine beneath a deep cover. However, despite ore grades that reached 19 cpht, costs were excessive, and the mine has been dormant since 2017.

Figure 8*. The open pit at the Jwaneng diamond mine in Botswana (photo: De Beers).*

Sizes of rough diamonds: in carats (5 carats = 1 gram): 1 digit = size of a match-head; 2 digits = size of a marble; 3 digits = size of a hen's egg.

Diamonds from central Africa

North of Botswana, central Africa contains another great craton with kimberlite pipes and widespread placer diamonds. Yet the geological story is almost lost in the cloud of nightmare politics, corruption, illegal mining and smuggling. These are the lands of the 'blood diamonds' and 'conflict diamonds' that have fuelled civil wars, death and destruction. No more than a brief review is appropriate for a complex situation.

In northeastern Angola, the kimberlite pipe at Catoca is worked as one of the largest diamond mines in the world, yielding around 7M carats per year; its huge reserves of gem-quality diamonds could see mining reaching a depth of 600 m. In the same area, the Luaxe kimberlite has reserves of 600M carats of diamonds in a pipe extending to 104 hectares, but development of its mine has been subject to repeated delays. There is also extensive alluvial mining in Angola, in deposits derived from more than a dozen kimberlite pipes.

Alluvial mining in the Democratic Republic of Congo (DRC, previously Zaire) started in 1903, and has provided a large share of the world's industrial-grade diamonds, with more than 10,000 miners working the diggings. Ten high-grade kimberlite pipes at Mbuji Mayi yield huge quantities of industrial diamonds, with just some of gem-quality; notable was a flawless white stone of 777 carats.

The Central African Republic (CAR) has rich deposits of alluvial diamonds. Mined since at least 1929, small-scale, hand-operated workings on two river systems employ around 70,000 miners; annual production is claimed to be around 500,000 carats, but is likely to be much greater when smuggled stones are taken into account.

On a separate craton underlying western Africa, the kimberlites of Koidu were found in Sierra Leone in 1948. Two pipes and their feeder dykes have been worked in small open-pit mines, but most mining is in alluvial gravels of the Woyle River basin (Fig. 9). These have yielded three stones each larger than 500 carats, but all were flawed. Some 300,000 miners work the gravels, but are poorly paid when profits go to the illicit dealers in a region devastated by corruption and civil war. This alluvial mining also extends into adjacent areas of Liberia and Guinea.

Zimbabwe, originally Southern Rhodesia, lies on Africa's southern craton, with its diamond geology allied to the adjacent Botswana, whereas its modern politics and its 'black' diamonds relate it more closely to the turbulent nations of central Africa. In the east of Zimbabwe, the alluvial diamonds of the Marange area have been reworked from Proterozoic marine conglomerates in which the rounded diamonds would appear to be far from their kimberlite source, which remains unknown. Reserves at Marange are huge, and annual production has reached 17M carats, though of low value stones; these mines, long riddled with corruption, saw the massacre of 200 miners when Mugabe's troops attempted a takeover in 2008. Away to the west, the Murowa diamond mine produces large, high-quality, coloured diamonds from three kimberlite pipes worked in individual open pits since 2004.

***Figure 9**. Miners in the diamond diggings of Koidu, in Sierra Leone (photo: Josef Skrdlik).*

The Mwadui pipe, Tanzania

A beacon of light within the murk of central Africa's diamond fields is provided by the great Williamson mine on the giant Mwadui pipe, in the north of Tanzania. A Canadian geologist, John Williamson, tracked red soils, then followed old ilmenite mines on kimberlite dykes. He stopped at Mwadui for lunch one day in 1940, stumbled on a diamond in the dust of a low hill and realised that a pipe lay under the adjacent plain. He staked the ground and exposed a kimberlite pipe of 146 hectares, which remains the largest in the world because the flared top of its pipe had not been lost by subsequent surface lowering.

An open-pit mine was developed, and Williamson retained total ownership. His management of the mine was renowned for its efficiency and technological innovation, and with ore grades of 60 cpht of high-value stones, he became for a time the richest man in the world. Despite having been in operation since 1940, the pit is still only 120 m deep due to the large size of the pipe. Ore grades have declined with depth, but the high-volume bulk mining methods maintained profits, notably from so many large stones.

In his later years Williamson became a rather eccentric, unmarried recluse, while still managing his mine. When he died in 1958, his brother, still in Canada, inherited the mine, but had no interest in it, so sold out to De Beers and the Tanzania government. Though not before a large marmalade jar had been found under the geologist's bed; this contained, beside remnants of marmalade, a small fortune in large coloured diamonds that Williamson had squirrelled away.

In subsequent years, the mine has been poorly managed due to government interference, and also has seen the diamond grade decline to 6 cpht as greater depths are worked. A tailings dam failure in 2022 caused one of a number of temporary closures, but the mine has since returned to production. Total yield from this remarkable pipe has reached close to 20M carats, or four tonnes.

Diamonds around the world

Beyond India and Africa, diamonds have been found in a few scattered regions, all on ancient cratons. In addition to the countries noted below, both Venezuela and China have produced limited quantities of diamonds from alluvial deposits, and in 1975 China opened its Changma mine on a kimberlite pipe in Shandong.

Ancient mines in Borneo

Diamond mining was recorded in Borneo in 1518 and had probably been producing for many centuries previously, thereby ranking it second only to India. The stones occur in Cretaceous conglomerates and Quaternary alluvium, but the location of their primary igneous source remains enigmatic. Most of the surface gravels are now worked out, so local miners sink shafts to buried horizons; the centre of activity is Martapura in southern Kalimantan. Found in a traditional mine 15 m deep during 1965, the Tri Sakti diamond weighed in at 167 carats, less than half the size of the Matan diamond, which remains uncut since its discovery in the same area back in 1787.

Diamonds from Brazil

After their initial discovery in 1725, diamonds from Brazil dominated the world market in the years between the supremacies of Golconda and Kimberley. Production has all been from alluvial deposits; though many kimberlite pipes have since been discovered, none has proved capable of supporting a deep mine. Workings are scattered all across Brazil, but the main sites are along the Jequitinhonha River in Minas Gerais (around the town named Diamantina) and on the rivers of Mato Grosso around the town of Diamantino. Both towns grew up when diamonds were discovered and thousands of garimpeiros (wildcat miners) gathered in illegal diggings; manual workings continue to dominate, though dredgers have been built at some sites, and Brazil remains as a minor producer.

Short-lived mining in Australia

It is hardly surprising that a few alluvial diamonds were found in 1851 on the ancient cratons of Western Australia, but it was 1978 when finds at Ellendale, on the edge of the Kimberley Plateau, led to a mine that worked between 2002 and 2015. This was noted for its yellow diamonds that were extracted from open pits on a cluster of small lamproite pipes.

On a much larger scale, the Argyle mine was worked from 1983 until 2020 (Fig. 10). It lies 400 km east of Ellendale. Argyle has a huge open pit that reached a depth of around 300 m, below which underground mining continued for a further 300 m; it achieved a peak production of 42M carats in 1994. Most of its diamonds were small, but it was famous for its beautiful pink stones of the highest quality. The source was an elongate lamproite diatreme that extends across 47 hectares at outcrop, but narrows at depth in the normal style.

***Figure 10**. The open pit of the Argyle diamond mine, in Western Australia, which had evolved into underground working in 2013.*

Vast diamond resources in Russia

In the 1950s Stalin wanted his own industrial diamonds, so geologists were sent to the frozen north of Siberia where an Archaean craton in Yakutia had been identified back in 1941 as a potential source. They ran a huge programme of alluvial sampling to trace garnet, chrome-diopside and ilmenite indicators; because Siberian river transport is reduced by freezing, the indicator plumes from pipes are smaller than those in warmer climes. The 'official' story is that the first kimberlite and the first diamonds were found by a geologist named Larissa, in 1954. Though her pipe proved uneconomic, 120 pipes were found in the next four years, of which four were rich in diamonds.

Figure 11*. The open pit of the Mir diamond mine in Siberia (photo: Alrosa).*

The Mir diamond mine was opened on a large kimberlite pipe in 1957 and supports the new town of Mirny (Fig. 11). Annual production has averaged 10M carats, but most diamonds are small and only fit for industrial use. The circular open pit is 1250 m across and 525 m deep, where surface working ceased in 2001. Its underground mine started in 1999, but was halted by flooding in 2017 due to a shaft failure beneath the open pit. It is intended that the mine will restart during the late 2020s. Mines have also been opened on six other pipes in Yakutia. During the prolonged freezes of Siberia, the mines' separation plants could not use grease table washed with water, so they pioneered the technique of air-jets blowing out diamonds identified by their X-ray fluorescence.

Huge tonnages of diamonds have been proven within the Popigai impact crater (see above), but there is little realistic potential for mining them, especially at such a remote location.

Diamonds were found in 1829 in the Ural Mountains near Perm, but mining was not developed until after the Siberian pipes had been found. The Perm region has many of Russia's twenty or more alluvial mines, and also has hard-rock mines in Devonian conglomerates. Production has remained tiny within Russia's huge output, but Perm's high proportion of good gem-quality diamonds makes it of significant value.

The Lomonosov diamond mine is the larger of two mines working within a cluster of six kimberlite pipes northeast of Arkhangelsk in northern Russia. After discovery in 1980, the mine was opened in 2005, and has estimated reserves of 73M carats of diamonds, mainly of gem-quality but with few large stones. The open-pit mine is expected to reach 320 m deep in the late 2020s, after which underground mining is planned to continue to greater depths.

Minimal diamonds in USA

Isolated diamonds have been found at nearly a dozen sites across the USA, but most are close to the limits of the Quaternary ice sheets and have likely been carried south from sources in the Laurentian Shield. Hundreds of tiny diamonds were found by gold miners in California; their sources are unknown and their abundance is largely due to the vast amount of panning that was primarily in search of gold.

A cluster of small kimberlite pipes at Sloan Ranch, in Colorado, have been shown to contain limited grades of small diamonds. The only mine to work a pipe was at Kelsey Lake, started in 1976 but closed down in 2001.

An exposed kimberlite pipe in Arkansas was mined sporadically between 1906 and 1932, always on a small scale, and with marginal profitability. It is now known as the Crater of Diamonds State Park, where amateurs can pay a small fee, pan for diamonds and keep what they find (Fig. 12). Thousands of diamonds have been found by visitors, the largest of which was the flawless Uncle Sam at 42 carats in the rough. This pipe remains as the only diamond source within the USA

Figure 12*. Family day out, sifting through the weathered kimberlite at Crater of Diamonds in Arkansas, USA.*

Diamond bonanza in Canada

A different story has unfolded in Canada, which has become one of the world's major diamond producers. Numerous pipes have been found in the barren lands and tundra of the far north, all after extensive, expensive, regional soil sampling in search of the indicator minerals; these searches required care because so much sediment, and diamonds, had been moved across drainage basins by Quaternary ice. Access and transport remain as key factors, by air in summer, and by ice-roads on the frozen lakes and rivers out of Yellowknife during winter.

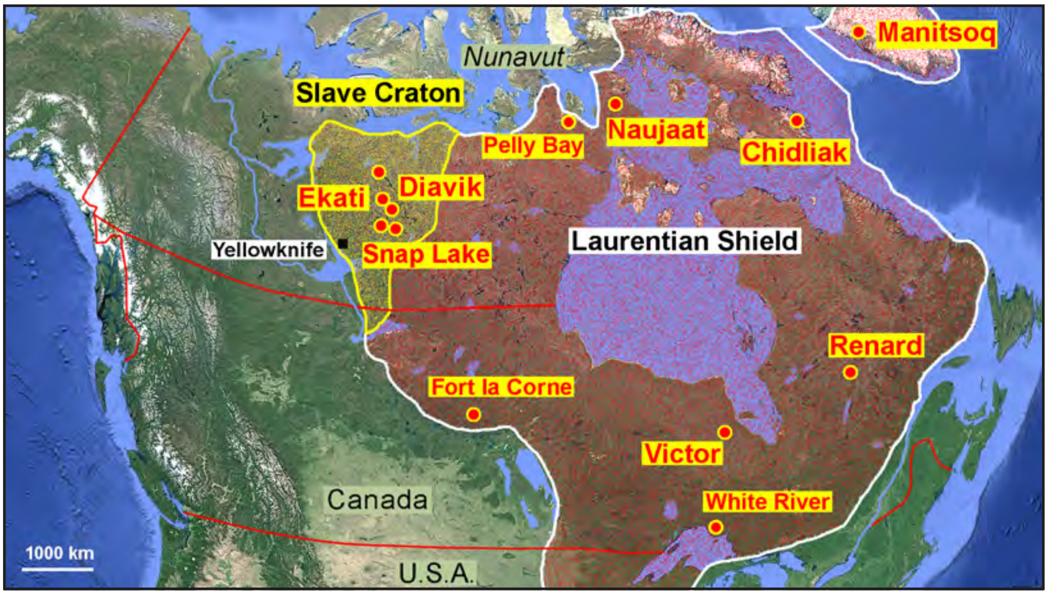

***Figure 13**. Notable diamond locations in northern Canada; the Fort la Corne, White River and Pelly Bay sites are still only in the project stage; for others, see text.*

Kimberlites of the Slave Craton

Formed of the four-billion-years-old Acasta Gneiss, the westernmost corner of the Laurentian Shield is known as the Slave Craton, and is ideal diamond terrain (Fig. 13). In 1984 Charles Fipke and Stuart Blossom formed their own Dia Met company to start exploration of the craton, using float-planes to fly to grab soil samples; these they then searched for the G10 garnets, chrome-diopsides and ilmenites that were the indicators for diamond-bearing kimberlite pipes. They traced the indicators in the up-ice direction, and homed in on an area north of Lac de Gras, where they found lots of the critical garnets.

Then on a sampling flight Fipke spotted a round lake of just 15 hectares with cliffs of schist dropping into deep water, and realised it was on a pipe. Given a false name of Point Lake, it had a small beach with pea-size chrome-diopsides. Dia Met could not afford to drill on its own, so brought in a deal with the larger Broken Hill mining company. Late in 1991 they flew in a drill rig, and drilled the lake floor through sediments and black iron pan into 300 m of kimberlite. The core sample of 59 kg contained 81 small diamonds. They rushed to stake and claim the good ground while others were prospecting nearby; they even encircled the lake with a wire loop to stop others reading the airborne electromagnetic signature of a pipe.

By 1992 they had drilled into nine pipes, all under lakes, and all containing diamonds. They now have 156 known kimberlite pipes within their block of claims, among more than 300 pipes that have been found within the Slave Craton, most lying beneath lakes (Fig. 14). Their kimberlites date to 45–62 Ma. The first mine to open, in 1998 was Ekati, with an open pit that will probably become worked out during the late 2020s. Other pipes, including Point Lake, have followed, some with underground workings. Annual production is around 7.5M carats of diamonds.

After the Point Lake discovery was announced, Aber was formed as another junior company to stake

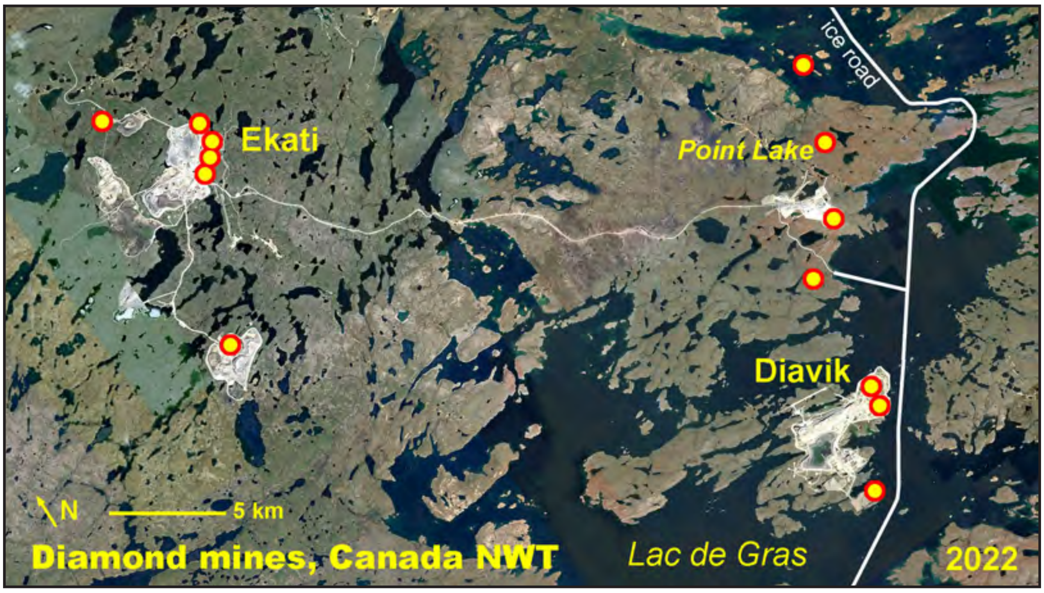

***Figure 14**. Kimberlite pipes in the heart of the Slave Craton, northeast of Yellowknife, Canada; Point Lake and some other pipes were yet to be developed in 2022.*

***Figure 15**. The open-pits and infrastructure of the Diavik diamond mine on the shores of Lac de Gras, Canada (photo: Rio Tinto).*

claims in adjacent areas around Lac de Gras. They flew electromagnetic surveys, then soil-sampled the best anomalies, and found the indicator minerals. After signing a deal with the Rio Tinto mining company to expand funding, the best site was drilled from the ice that covered its lake. Two holes went into kimberlite, and when the core was broken for sampling, an octahedral two-carat diamond stood clear from a break. The cluster of pipes now known as Diavik had been found. Four pipes have since been mined, each with a large open-pit followed by underground working to depth; all are contained inside barriers that isolate them from the lake (Fig. 15). Production started in 2003, with annual diamond yield of around 7M carats, but the mines are likely to be exhausted by 2029.

De Beers spent many years prospecting in northern Canada, but success only came later when they operated the Snap Lake mine between 2008 and 2016. This was followed by their Gahcho Kue mine that is still producing from four adjacent pipes. Both sites lie 100 km south of Lac de Gras. At the northern end of the ice road, and just over the border into Nunavut, the Jericho mine has proved to be too small and remote to be profitable for various junior companies, so is currently dormant.

Across the Laurentian Shield

South of Hudson Bay, the Victor mine worked on a cluster of 16 diamond-bearing kimberlite pipes. Between 2008 and 2019 its open pit yielded 8M carats of diamonds, but the site has now been cleared and reclaimed. Further east, in Quebec, the Renard diamond mine opened in 2014 on a cluster of a dozen kimberlite pipes, with an open pit evolving into underground mining in 2018. However, it struggled to achieve annual production targets of up to 2M carats, and in 2023 it closed down ‘temporarily’ but probably permanently.

Currently the most exciting prospects are in the far north. On Baffin Island, 71 kimberlite pipes have been discovered on the Chidliak claim, which is now in the hands of De Beers. Two pipes have been sampled to indicate reserves of 15M carats of diamonds within depths to 250 m. An open-pit has been proposed, but this faces huge environmental and budget challenges, including the need for an all-weather road reaching 160 km from the coast.

Further west, on the mainland Melville Peninsula, the Naujaat Diamond Project has eight kimberlite pipes, including one with an outcrop of 12.5 hectares in an area where diamonds were first found in 2003. Evaluation has reached the stage of bulk sampling, of 1800 tonnes of ore. Grades reach to 35 cpht, but significantly include many high-value stones of ‘fancy-colours’. The site lies only 7 km from tidewater that is ice-free for at least three months per year, so transport costs should be half those of the Lac de Gras mines. Plans for mine development were still being assessed early in 2024.

The Shield extends across to Greenland where a few kimberlite dykes and microdiamonds have been found, notably around Manitsoq on the west coast. It remains to be seen what might lie beneath the island’s Inland Ice. The same can be said for Antarctica where Archaean cratons are exposed beyond some margins of the ice sheet; kimberlites have been found, but no diamonds as yet.

Who could have known the future of diamond mining in 1865 or 1990, and who can predict the prospects in 2024?

Acknowledgements

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Further Reading

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