Diamond Sources and Production: Past, Present, and Future

By Alfred A. Levinson, John J. Gurney, and Melissa B. Kirkley

Africa was the major source of diamonds for most of the 20th century, but Australia and Sakha (of the Russian Federation) now produce about half of the world's supply. Also, most of the production today comes from primary sources (kimberlites and lamproite), whereas secondary (alluvial) sources dominated as recently as the early 1970s. Although the annual production of rough more than doubled in the 1980s, the production of rough yielding good-quality polished gems has not increased appreciably. The economic potential of a kimberlite or lamproite occurrence depends on the tonnage and grade of the ore, as well as on the quality of the diamonds it contains. The authors predict that the early 21st century will see the Russian Federation as an even more important source of diamonds and Canada as a major producer.

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As it has over the last 100 years, the demand for fine-quality diamonds will inevitably increase in the long term. Today, as markets in Europe, the United States, and Japan mature, the industry can look toward the prospect of new markets in emerging nations in Eastern Europe and Asia (Rothschild, 1992). Yet the remaining life expectancy of a number of important primary producers is thought to be less than 25 years (e.g., Mir in Sakha/Yakutia, of the Russian Federation; Koffiefontein and the three mines still operating in Kimberley, South Africa; the Mwadui mine in Tanzania), and the significant secondary alluvial deposits on shore in South Africa and Namibia approach depletion. Thus, to ensure an adequate supply of fine-quality diamonds from the mine to the marketplace (figure 1), it is necessary to locate new diamond deposits as older ones become exhausted.

This article addresses future diamond sources by first reviewing past and present localities, and examining production figures and trends. Next, we summarize the geologic constraints on the occurrence of diamonds and the various economic factors that must be considered in determining whether a newly discovered pipe could become a viable mine. On the basis of these critical factors, we predict what the major sources of diamonds are likely to be well into the next century, including the Russian Federation, Canada, and possibly even Antarctica.

DIAMOND PRODUCTION: PAST AND PRESENT

A review of historic diamond sources shows that whereas there were only two significant localities before the first South African discoveries in 1867, about 20 additional producing countries have been identified since then (table 1). The impact on world production of these additional sources is phenomenal: from only about 300,000 ct in 1870 to 3,000,000 ct in 1920, to 42,000,000 ct in 1970, and over 100,000,000 ct in 1990 (figure 2). If the impact of unreported, illicit mining is fac-

Figure 1. Although production of rough diamonds is at its highest level ever, the deposits at many major localities will be depleted within the next few decades. In addition, good-quality gems represent a very small portion of the diamonds mined at most of the new localities. Thus, there is a continuing need to identify and evaluate potential deposits to maintain the production of fine "colorless" and colored diamonds such as those shown here. Photo courtesy of Christie's New York; © Tino Hammid.

tored in, figures since 1940 could actually be as much as 20% higher for some countries in Africa and South America (G. T. Austin, pers. comm., 1992).* Johnson et al. (1989) estimate that the production of diamonds in the year 2000 will be about 113,000,000 ct.

Of particular interest for the purposes of this article is the fact that as recently as 1960 more than 80% of diamonds by weight were from secondary alluvial deposits; by 1990, only about 25% were secondary. This is another trend that is expected to continue with improvements in the technology used to identify and mine new primary deposits.

Total Diamond Production (Antiquity–1990). By combining all the production of all the diamond-producing countries listed in table 1, we estimated that the total production of diamonds, both gem and industrial, from antiquity through 1990 is 2,213,875,000 ct (table 2), which is conservatively rounded up (in recognition of the unreported illicit production) to 2,250,000,000 ct. This is the equivalent of 450 metric tons (mt; 1 mt = 1.1 U.S. ton).

*For more on illicit diamond mining, see Green (1981), Greenhalgh (1985), Miller (1987), and Johnson et al. (1989). In the cases of China and Russia (now the Russian Federation), precise production data have not been released because diamonds are considered strategic commodities (Miller, 1987), so the U.S. Bureau of Mines figures for these countries are only estimates. It is also recognized that other tabulations may vary, sometimes considerably, from those in table 1.

TABLE 1. Estimated world rough diamond production in carats, by country, for the first year in each decade, 1870–1990[a], plus other historical data (year diamonds discovered, year significant production began, production from secondary deposits).

Country (older names in parentheses)	Year diamonds discovered[b]	Year significant production began[c]	% of total production from secondary deposits[d]	1870	1880	1890	1900	1910	1920	1930	1940
INDIA	Antiquity	Antiquity	100	2,000	nr	nr	nr	147	nr	nr	nr
BRAZIL	1725	1730	100	200,000	nr	nr	nr	nr	nr	115,000	325,000
SOUTH AFRICA	1867	1870	10-20	102,500	3,140,000	2,504,726	2,113,000	4,807,056	2,533,896	3,163,590	543,474
NAMIBIA (German Southwest Africa)	1908	1909	100					891,307	295,831	415,047	30,017
GUYANA (British Guiana)	1890	1921	100					3,808	39,362	110,042	26,764
ZAIRE (Belgian Congo)	1907	1917	90						315,000	2,519,300	9,603,000
ANGOLA	1912	1921	100							329,823	784,270
GHANA (Gold Coast)	1919	1925	100							861,119	825,000
TANZANIA (Tanganyika)	1910	1945	0							13,107	6,222
CENTRAL AFRICAN REPUBLIC (French Equatorial Africa)	1914	1947	100								16,000
GUINEA (French West Africa)	1932	1950	100								75,000
SIERRA LEONE	1930	1935	100								750,000
VENEZUELA	1901	1955	100								14,525
IVORY COAST	1929	1960	100								
LIBERIA	1930	1958	100								
BOTSWANA	1966	1970	0								
LESOTHO	1958	—	0								
RUSSIA (USSR)	1829	1960	0								
INDONESIA (Borneo)	Antiquity	—	100								
AUSTRALIA[e]	1851	1981	5								
CHINA[f]	1955	?	?								
SWAZILAND	1973	—	0								
OTHERS										3,000	17,225
YEAR'S TOTAL				304,500	3,140,000	2,504,726	2,113,000	5,702,318	3,184,089	7,530,028	13,016,497

[a] *Data for 1870–1900: Bauer (1904, pp. 179, 204), Lenzen (1970, pp. 122, 159). Data for 1910: U.S. Geological Survey (1911) for India, South Africa, and Guyana; Lenzen (1970, p. 160) for Namibia. Data for 1920: Roush (1922). Data for 1930–1990: U.S. Bureau of Mines (1930–1991). Yearly production figures are constantly being revised as new data are received, so the final revised yearly production figures may be many years in coming. The following years (in parentheses) are the publication years in U.S. Bureau of Mines (1930-1991) in which the final revised publication figures presented in this table may be found: 1930 (1935); 1940 (1944); 1950 (1953); 1960 (1961); 1970 (1972); 1980 (1984); and 1990 (1991). These are official figures only, and in most cases do not include illicit production, which has historically been a problem in Zaire and Angola (as well as elsewhere in Africa and in South America). Note that most of the reported production for Liberia consists of illicit diamonds smuggled from other parts of West Africa. In this table, "nr" indicates production not reported in the above references.*

[b] *"Year diamonds discovered" sources: Bauer (1904) for India, Brazil, South Africa, Guyana, Russia, Indonesia, and Australia; Lenzen (1970) for Namibia; Webster (1983) for Ghana, Tanzania, Sierra Leone, Lesotho, and China; Maillard (1980) for Zaire, Angola, Central African Republic, and Guinea; Wilson (1982) for Venezuela, Liberia, Ivory Coast, Botswana, and Swaziland. Other dates reported: Keller and Guo-dong (1986, p. 16) and Miller (1987, p. 74) both report "the late 1940s" for China; Webster (1983) for Guyana 1987, Zaire 1910, Guinea 1933, and Botswana 1955; Wilson (1982) for Angola 1916, Guinea 1936, and Botswana 1967; Miller (1987) for Angola 1917; Strnad (1991) for Russia 1735 and a reference dating back to 1375.*

[c] *"Year significant production began" refers to the first year in which 100,000 ct were mined, except for Brazil which produced 20,000 ct in 1730—a significant figure for that time. A dash indicates that 100,000 ct were never produced in any one year. Sources: Bauer (1904) for India, Brazil, and South Africa; Lenzen (1970) for Namibia; Lee (1981) for Guyana; Roush (1922) for Zaire; Imperial Mineral Resources Bureau (1924) for Angola; Kesse (1985) for Ghana; U.S. Bureau of Mines (1930–1991) for all other countries.*

[d] *"% of total production from secondary deposits" is approximate in the case of:*

About 22% of this *total* was produced in the five-year period 1986–1990, largely as a result of the Argyle mine in Australia, which by the end of 1990 was responsible for about 8% of all diamonds ever produced and one-third of those mined for that year. The present annual production from the Argyle mine is essentially identical to the total world production from India and Brazil from antiquity to 1869, that is, about 35,000,000 ct.

In fact, about 94% of the world's total production of natural diamonds in 1990 originated from only five countries (in decreasing order): Australia, Zaire, Botswana, Russia, and South Africa.

Notwithstanding the number of carats produced, when the *value* of the rough is considered, the sequence changes significantly ("World diamond mining," 1991). In decreasing order, the ranking of the same five countries for 1990 based on estimated (U.S.) dollar value is: Russia ($1.6 billion), Botswana ($1.4 billion), South Africa ($550–$650 million), Australia ($320 million), and Zaire ($225 million). The value of the 1990 production from Namibia and Angola,

1950	1960	1970	1980	1990	Country
nr	nr	20,000	14,000	15,000	INDIA
200,000	350,000	300,000	667,000	1,500,000	BRAZIL
1,747,868	3,146,000	8,112,000	8,520,000	8,708,000	SOUTH AFRICA
488,422	935,000	1,865,000	1,560,000	761,000	NAMIBIA
37,462	101,000	61,000	10,000	8,000	GUYANA
10,147,471	13,453,000	14,087,000	10,235,000	19,427,000	ZAIRE
538,867	1,058,000	2,396,000	1,480,000	1,300,000	ANGOLA
950,000	3,273,000	2,550,000	1,258,000	637,000	GHANA
164,996	537,000	708,000	274,000	85,000	TANZANIA
111,407	80,000	482,000	342,000	381,000	CENTRAL AFRICAN REPUBLIC
126,346	1,117,000	74,000	38,000	135,000	GUINEA
655,474	1,962,000	1,955,000	592,000	78,000	SIERRA LEONE
60,389	71,000	509,000	721,000	333,000	VENEZUELA
	200,000	213,000	nr	12,000	IVORY COAST
	977,000	812,000	298,000	100,000	LIBERIA
		464,000	5,101,000	17,352,000	BOTSWANA
		17,000	54,000	nr	LESOTHO
		7,850,000	10,850,000	15,000,000	RUSSIA
		20,000	15,000	30,000	INDONESIA
			48,000	34,662,000	AUSTRALIA
			900,000	1,000,000	CHINA
				42,000	SWAZILAND
3,000	420,000[g]	nr	nr	nr	OTHERS
15,231,702	27,680,000	42,495,000	42,977,000	101,566,000	YEAR'S TOTAL

India (some production, e.g., about 15,000–18,000 ct per year since the 1970s, has come from pipes—Maillard, 1980; Bliss, 1992); South Africa (where during certain unusual periods, e.g., 1933 and 1941–1942, most or all production was from alluvials); Zaire (where alluvials or eluvials are close to, and overlie, kimberlite sources, and perhaps 10% of current production is from kimberlites); Angola (where minor production in the past was from kimberlites); and Russia (where significant alluvial mining has been noted, particularly from the Vilyui River, but no figures are given—see Miller, 1987; Johnson et al., 1989; Meyer, 1990; "World diamond mining," 1991).

[c] *Australia had a recorded production of about 202,000 ct between 1852 and 1922 from several alluvial deposits in New South Wales, but in no one year did production exceed 100,000 ct (MacNevin, 1977); this production is not shown in this table.*

[f] *Miller (1987) and Johnson et al. (1989) estimated the annual production for the late 1980s at 200,000–250,000 ct and 200,000–300,000 ct, respectively.*

[g] *Most of this production is probably from Russia and predates reporting of official figures.*

both about $250 million, exceeded that of Zaire, yet each produced less than one-tenth as many carats of diamonds as did Zaire (see table 1).

The Changing Concept of Diamond Value. The lower value of the Australian and Zairean production results from their high proportion (>90%) of industrial or near-gem material. In recent years, industrial diamonds have represented only about 10%–15% of the total value of all the diamonds mined annually (Johnson et al., 1989).

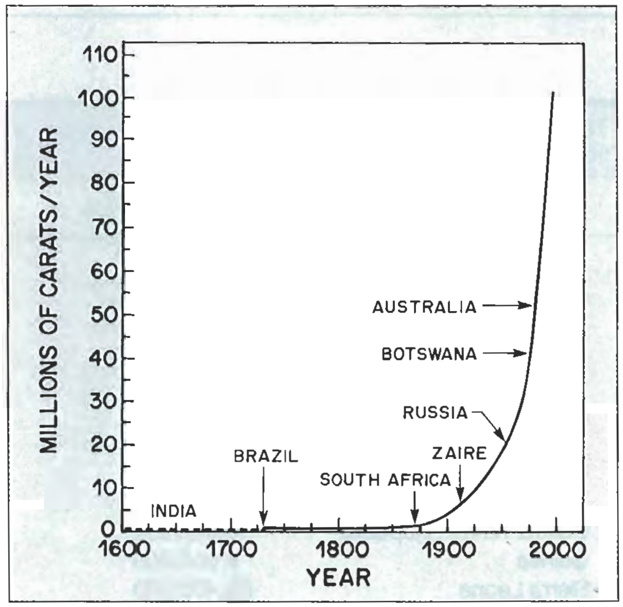


Figure 2. Using the data provided in table 1, this generalized graph shows the increase in total annual world production of rough diamonds (gem and industrial) from 1600 through 1990. The arrows mark the approximate years when each of the major sources noted began significant production.

Whereas historically the percentage of diamonds that are gem quality has been estimated at 20%–30% (e.g., Maillard, 1980; Atkinson, 1989), during 1985–1990 the percentage of diamonds classified by the U.S. Bureau of Mines as gem quality rose to an average of 46%. This is because, starting in 1983, the figures for "gem" included qualities of lower color, clarity, and shape that are commonly referred to as "near gem." Johnson et al. (1989) estimated that, on a worldwide basis, gem diamonds have a per-carat value that is roughly 10 times near gems, and near gems have a per-carat value roughly 10 times that of industrial diamonds. One source classified mine output for 1990 as 15% gem, 39% near gem, and 46% industrial ("World market trends," 1991).

Several factors are responsible for this change in the traditional classification of diamonds over the last decade, including: (1) the growth of the manufacturing industry in India, and its ability to fashion small diamonds economically from rough previously classified as industrial; (2) competition from synthetic diamonds that has kept prices for natural industrial diamonds low, enhancing the value of those industrial diamonds that could be reclassified as near gem; and (3) increased consumer demand for more affordable jewelry.

Today, it is no longer appropriate to consider diamonds in terms of "gem" and "industrial," but rather

TABLE 2. Estimated total production of rough diamonds from antiquity through 1990, by country.[a]

Country	Total production (ct)
India[b]	21,000,000
Brazil[c]	47,101,000
South Africa[d]	446,856,000
Namibia[e]	63,288,000
Guyana[f]	4,131,000
Zaire[g]	718,117,000
Angola[h]	59,800,000
Ghana[i]	100,785,000
Tanzania	18,590,000
Central African Republic	13,829,000
Guinea	8,865,000
Sierra Leone	52,405,000
Venezuela[j]	13,834,000
Ivory Coast[k]	5,743,000
Liberia	18,117,000
Botswana	151,747,000
Lesotho	412,000
Russia	271,850,000
Indonesia[l]	1,000,000
Australia[m]	184,061,000
China	10,850,000
Swaziland	327,000
Others	1,167,000
WORLD TOTAL	2,213,875,000

[a] *All production figures are based on data in U.S. Bureau of Mines (1930–1991) for both gem and industrial diamonds for the years 1930-1990, except as noted below. Where data for isolated years are missing, production has been estimated based on reported production for the preceding and following years.*

[b] *India: The figure of 21,000,000 ct is an average of the estimates of 12,000,000 ct and 30,000,000 ct, given by Blakey (1977, p. 72) and Maillard (1980, p. 26), respectively.*

[c] *Brazil: For 1725–1850, Bauer (1904, p. 179); for 1851–1869, Lenzen (1970, p. 122); for 1870–1929, an average annual production of 200,000 ct was assumed based on estimates of Lenzen (1970, p. 122) and Rich (1990, p. 34).*

[d] *South Africa: For 1867–1912, Wagner (1914, pp. 338–339); for 1913–1921, Roush (1922, p. 587); for 1922–1923, estimated at 2,000,000 ct per year based on average production of previous and following years; for 1924–1929, Lenzen (1970, p. 177).*

[e] *Namibia: For 1909–1929, Williams (1932, Vol. 2, p. 562).*

[f] *Guyana: For 1902–1929, Lee (1981).*

[g] *Zaire: For 1913–1929, U.S. Bureau of Mines (1955, p. 489).*

[h] *Angola: For 1919–1921, Imperial Mineral Resources Bureau (1924); for 1922–1929, estimated at 200,000 ct per year based on production before and after this period.*

[i] *Ghana: For 1920–1946, Kesse (1985, Appendix 3A).*

[j] *Venezuela: For 1913–1939, Themelis (1987).*

[k] *Ivory Coast: For 1945–1959, Greenhalgh (1985, p. 4).*

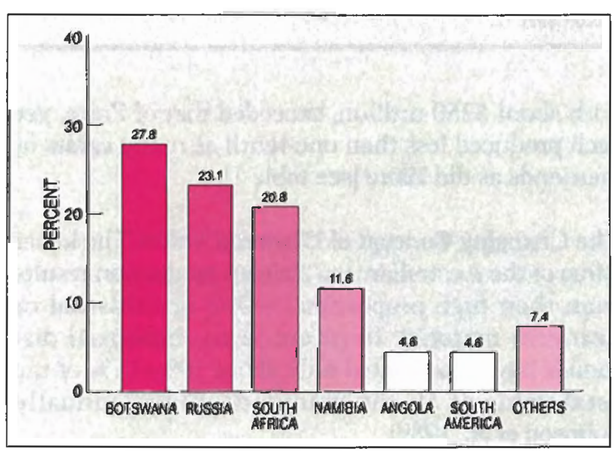
[l] *Indonesia: In the period 1966–1990, 489,000 ct were produced. Earlier production figures are intermittent and unreliable (Spencer et al., 1988). The figure of 1,000,000 ct given in this table as the total production since antiquity is an estimate, and it is in relative proportion to the significant historical production from India.*

[m] *Australia: For 1852–1922, 202,000 ct of alluvial production reported by MacNevin (1977) is included.*

in terms of "cuttable" and "industrial." *Cuttable* describes any natural diamond, regardless of quality, where all or part of the rough is suitable for manufacturing into jewelry. According to the Central Selling Organisation in London, about 50% of the world's diamond production today is considered cuttable, but only about 12% (by weight) of the diamonds mined in 1990 will eventually be set into jewelry as faceted stones. This is because near-gem material has a yield of only about 15%–25%, compared to about 45% for material traditionally classified as gems (Johnson et al., 1989).

Gemological Rarity. Even though 50% of the world's rough diamonds are now classified as cuttable, and the annual supply of rough more than doubled in the period 1980–1990, the total amount of available rough yielding good-quality polished stones (D–H color and Fl–SI_2 clarity) of 0.5 ct or larger has not changed appreciably in the last decade and, in fact, may have decreased (Moyersoen, 1989). The Argyle mine, which is responsible for much of the recent increase in world diamond production, for the most part produces small stones, of which only about 5% are gem quality (Boyajian, 1988); many of these are browns and most are difficult to cut. Near gems account for 40%–45% of the production. The estimated current annual supply of rough diamonds worldwide that yield polished

Figure 3. Although the current annual production of rough diamonds exceeds 100,000,000 ct, only about 2,000,000–2,500,000 ct yield good-quality (D–H color, Fl–SI_2 clarity) stones 1 ct or larger. Five countries, as noted here, are responsible for almost 90% of this production. Based on data in Moyersoen (1989).



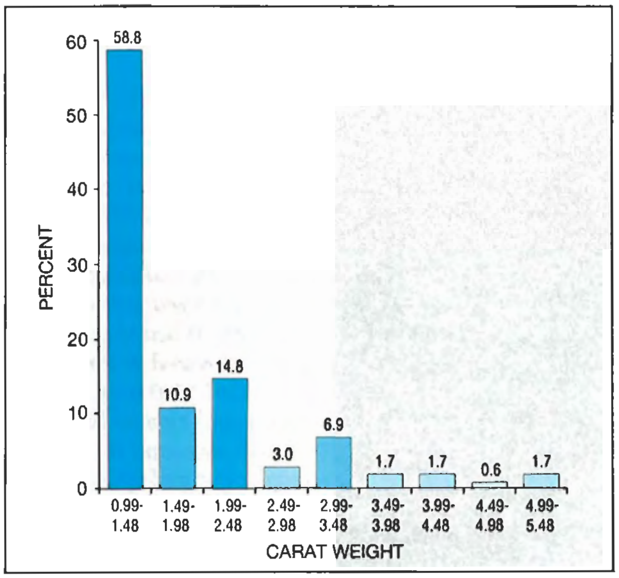


Figure 4. The relatively small proportion of cut stones 1.49 ct and above in the total population of gem diamonds is evident in this chart of the distribution, by carat weight, of a random sample of 9,000 good-quality (D–M color; Fl–SI$_2$ clarity) polished diamonds submitted to the GIA Gem Trade Laboratory, Inc., for grade analysis (1,000 each from the years 1982–1990). Data provided by D. V. Manson; courtesy of the GIA Gem Trade Laboratory, Inc.

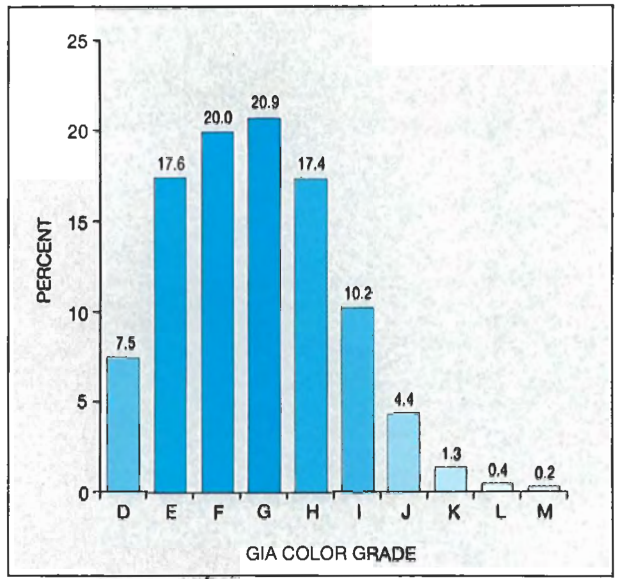


Figure 5. Of the random sample of 9,000 cut diamonds (D–M color, Fl–SI$_2$ clarity) described in figure 4, only 7.5% in the size range 0.99–1.98 ct were graded D-color. The decreasing proportion of stones graded H–M reflects the fact that stones of lower quality are less likely to be submitted for grade analysis. Data provided by D. V. Manson; courtesy of the GIA Gem Trade Laboratory, Inc.

gems of 1 ct or more amounts to about 2.0–2.5 million carats (Moyersoen, 1989). Assuming an average 55% weight loss during cutting for good-quality stones, the annual supply of polished gems in this category is about 900,000–1,100,000 ct.

The main countries that produce rough good-quality stones of 1 ct or larger are shown in figure 3. Both Australia and Zaire have had only a minor effect on the availability of such stones. Both countries are included in "Others" in figure 3.

The current annual production of polished stones 0.5 ct or larger with D–H color and Fl–VS$_2$ (not to be confused with the broader, to SI$_2$, range given above) clarity is only about 300,000 (± 50,000 ct). No more than three 1 to 2 ct polished D-flawless stones are produced each day. Further, fewer than 5,000 cut stones of D-color, 0.5 ct or larger, in all clarity grades are produced annually (Moyersoen, 1989).

Similar conclusions can be drawn for diamonds examined at the Gemological Institute of America. Figure 4 presents the size distribution, by carat weight, of a random sample of 9,000 diamonds (1,000 from each year, 1982–1990) from all diamonds submitted to the GIA Gem Trade Laboratory, Inc., during that period. Represented are stones ranging from D to M in color (which differs from the D–H color range given above) and Fl–SI$_2$ clarity. This figure clearly shows the significantly lower proportion of stones 1.49 ct and above. The desirability of certain weights (i.e., 2.0 and 3.0 ct), and cutting to those weights, is apparent in the fact that there are larger proportions of stones in the 1.99–2.48 ct and 2.99–3.48 ct categories than in the categories that immediately precede them.

Figure 5 shows the distribution of D–M color stones in the 0.99–1.98 ct range within these same 9,000 diamonds, which confirms the rarity of D-color stones. The decreasing proportion of stones graded H–M is a reflection of the fact that stones of lower quality are less likely to be sent for grade analysis.

From the above discussion, it can be seen that rough diamonds that yield good-quality polished gems, especially 0.5 ct or larger, are not common, and that stones over 1.48 ct are particularly rare. Depending on the characteristics of the mine, on the order of 100,000 tons of kimberlite or secondary material may have to be processed to produce a single piece of rough from which a 1-ct D-flawless diamond can be cut.

GEOLOGIC FACTORS

In the last decade, vast amounts of new information have become available on the origin of diamonds,

Figure 6. Presently, the Finsch mine is the largest producer of diamonds in South Africa, with production in 1990 of 4,177,572 ct (De Beers Consolidated Mines, 1992), although the rough averaged only 0.03 ct per stone. When the pipe was discovered in 1960, an estimated 1400 m of kimberlite had already been eroded away and the outcrop at the surface was 44.2 acres (17.9 ha). This photo, taken in September 1990, reflects the cone shape characteristic of kimberlite pipes and that the mine is pinching out at depth (present depth approximately 600 m). Note that the area shown here is larger than the original pipe because of the requirements of open-pit mining.

such as when they were formed and how and where they reached the earth's surface. General reviews of these topics may be found in Gurney (1989), Atkinson (1989), Kirkley et al. (1991), and Mitchell (1991).

Secondary deposits historically have been the easiest to find because they often cover large areas; for example, the alluvial diamond deposits in Zaire are spread over about 150,000 km^2 (Johnson et al., 1989), although only certain sections are economically viable. By comparison, economic primary deposits (kimberlite or lamproite pipes) are small; they have a median surface (outcrop) area of only about 30 acres (12 hectares [ha]) and only rarely exceed 250 acres (Bliss, 1992). This is one explanation for the fact that alluvial diamonds have been known for at least 2,000 years, but the first primary source was not discovered until approximately 1869, in the Kimberley region of South Africa (Janse, 1984). As mentioned above, after 1960, with the discovery of the major primary deposits in Russia, Botswana, and Australia added to the South African deposits, production from primary deposits grew until it accounted for about 75% of the total world production in 1990.

Primary Deposits. Most diamonds form deep within the earth, usually at depths of 150–200 km, in peridotite or eclogite source rocks. The diamonds are transported to the surface by kimberlite or lamproite. Although as many as 1,000 kimberlites occurrences are known to contain diamonds (Kirkley et al., 1991), as well as seven lamproites, only 50–60 kimberlites and one lamproite (Argyle) worldwide have ever been economic.

An uneroded kimberlite pipe consists of three zones: root, diatreme, and crater. The root zone, at the bottom of the pipe, has a vertical extent of about 0.5 km and is found about 2–3 km below the surface. The diatreme zone usually contains the bulk of the kimberlite ore and, therefore, most of the diamonds. Its vertical extent in a medium to large kimberlite pipe is 1–2 km. The crater zone occupies the upper parts of the pipe and is represented on the surface by an eruptive (volcanic) crater. Kimberlite pipes are rarely found complete; rather, most are partly eroded (figure 6). With increasing depth, the root zones narrow and merge into feeder dikes, usually about 60 cm (2 ft.) wide, which will contain diamonds if the pipe itself does. However, these may not be economic because of the high cost of mining such narrow zones.

Economic kimberlites are concentrated in those portions of cratons that are of Archean age (older than 2,500 My [million years]—for example, Kirkley et al., 1991; Janse, 1992). Cratons are parts of the earth's crust that have attained stability and have been little deformed for a very long period of time, generally more than 1,500 My.

Janse (1984, 1992) defined the following three major portions of cratons, each representing a different age of formation, to facilitate their comparison and the preliminary evaluation of their economic potential: (1) *archons*—Archean, older than 2,500 My; (2) *protons*—early to middle Proterozoic, 2,500–1,600 My; and (3) *tectons*—late Proterozoic, 1,600–800 My (figure 7).

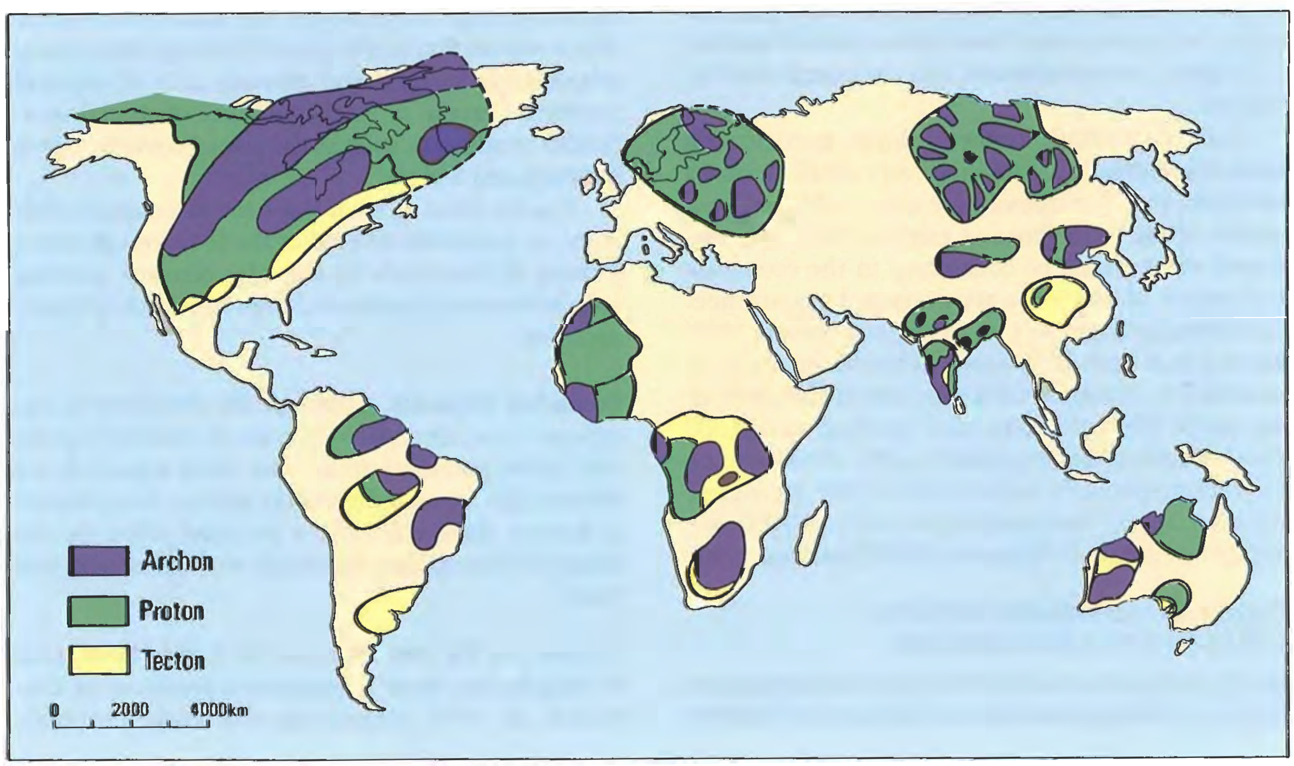
Although at this time, all economic *kimberlite* pipes (and dikes) worldwide occur on archons, some noneconomic kimberlites (e.g., the State Line Group, Colorado-Wyoming) and lamproites (e.g., the Prairie Creek lamproite pipe, Arkansas), as well as the highly productive Argyle lamproite pipe, occur on protons. Thus, protons may have considerable economic potential for diamonds, particularly in lamproites. No economic primary diamond deposit has yet been found on a tecton (or in any younger primary environment).

Numerous other geologic and geophysical factors (e.g., geothermal gradient, thickness of the craton) are also taken into account during modern exploration programs for primary diamond deposits. The reader is referred to Atkinson (1989) and Helmstaedt and Gurney (1992) for further information on these subjects, which are beyond the scope of this article.

Some cratons have been actively explored for over 100 years with ever-increasing sophistication, but with an ever-decreasing success rate; the Kaapvaal craton in South Africa is a case in point. In the 90 years since the Premier deposit was discovered in 1903, the only large and significant finds in South Africa have been those now worked as the Finsch and Venetia mines. Although the latter is scheduled for full production in 1993, with a projected annual output of 5,900,000 ct (Anglo American Corp., 1992), this craton is now considered at the mature stage (i.e., approaching its ultimate potential), from the point of view of diamond exploration.

Secondary Deposits. The moment a kimberlite pipe reaches the surface, it is subjected to weathering and erosion. Given a worldwide average erosion rate of 1 m every 30,000 years, a typical kimberlite pipe 2.3 km deep could be completely eroded away (except

Figure 7. This generalized world map shows known cratonic areas. The major portions of each craton (here referred to as archons, protons, and tectons) are indicated. To date, economic diamond-bearing kimberlites have been found only in archons, those portions of a craton that are older that 2,500 My. After Janse (1992).



for the root zone and feeder dikes) in 69 My (Kirkley et al., 1991).

Diamonds can be transported great distances and subsequently concentrated into a variety of secondary deposits amenable to mining. In close proximity to the primary diamondiferous kimberlite or lamproite deposits, diamonds may be found in economic eluvial or colluvial (i.e., those not involving stream transport) concentrations. With increasing distance, and where river transport and mechanical processes of concentration are involved, alluvial placers may form. If the diamond is carried to the marine environment either onshore (i.e., beach, beach terrace, dune) or offshore (i.e., marine shelf, sea-floor), marine processes such as wave action may form economic secondary deposits (Gurney et al., 1991). In general, alluvial deposits have a higher percentage of gem-quality diamonds than do primary deposits. However, there are exceptions, most notably Zaire, where only about 5% of the large alluvial production is fine-quality gems. The presence of alluvial deposits also implies the possible existence of kimberlite or lamproite pipes upstream in the drainage area.

ECONOMIC EVALUATION OF PRIMARY DEPOSITS

The major factors in determining whether a newly discovered kimberlite or lamproite pipe will be economically viable are its tonnage (size) and grade (concentration of diamonds), as well as the value (size and quality) of its diamonds. Other factors include location of the pipe, tax environment, and environmental legislation.

Even in economic kimberlite pipes, gem/cuttable diamonds typically are found in very small amounts and sizes, and in extremely variable qualities. These factors, along with those of gemological rarity discussed above, must be considered in the economic evaluation of any primary diamond occurrence. Consulting geologist A. J. A. Janse (pers. comm., 1992) states that at least 10,000 tons of kimberlite must be processed to obtain a valid estimate of the grade of any single kimberlite pipe, and as much as 100,000 tons for a complete feasibility study. To determine the average per-carat value of the stones recovered, at least 5,000 ct—and possibly as many as 10,000 ct—should be evaluated (Atkinson, 1989; Jennings, 1990).

MAJOR DIAMOND-PRODUCING AREAS IN THE 21ST CENTURY

The information presented in the preceding pages can help in predicting what diamond deposits are likely to be important in the future, as well as where new ones are likely to be discovered, what types they will be, and what factors should be considered in evaluating their economic potential.

Although many secondary deposits continue to be important and cannot be ignored, their overall role in diamond production is declining. Marine deposits would seem to have great potential, but first the technological difficulties of exploration and mining offshore must be overcome.

We predict that in the next century, most new major diamond deposits will be of the primary type, which are particularly attractive exploration targets. Such deposits, when economic, are likely to be long lived and amenable to large-scale mining, as well as to deterring illicit mining. For example, two-thirds (about 66,000,000 ct) of the total world production of diamonds in 1990 came from just eight primary mines (Argyle in Australia; Orapa, Letlhakane, and Jwaneng in Botswana; Mir and Udachnaya in Russia; and Finsch and Premier in South Africa [figure 8]). Most of these will have had a mine life of at least 30 years (some, like the Premier, possibly over 100 years) before they are exhausted of diamonds.

Given the current and projected decline in the discovery of new deposits on some cratons now commercially exploited for diamonds, the greatest potential for new, large, and economically important primary diamond deposits will be in those cratonic areas with large archons (and, less favorably, protons) where exploration to this point has been hampered by inhospitable location and climate, as in Siberia and northern Canada, or by the presence of special overburden conditions, such as the glacial cover in North America and Siberia.

On the basis of what has been discussed to this point, it is possible to predict the locations of major sources of diamonds for the 21st century, starting with secondary deposits and then turning to primary deposits.

Secondary Deposits. Although the discovery of significant new secondary deposits is unlikely, given that most potential areas have been explored, we believe that increased production from two presently known areas will have a profound effect on the supply of fine-quality diamonds within the next few years.

Angola. For the past 70 years, the Lunda Norte area of Angola has been a consistent producer of diamonds. In 1990, Angola was the world's seventh largest producer by weight, with most coming from the Cuango River Valley (figures 8 and 9). In marked contrast to the predominantly industrial production in nearby Zaire (East Kasai province), that in Angola is reportedly 70% gem quality, with an average value of about $185 per carat; 15% of these are stones of 2 ct or more ("World diamond mining," 1991; "World market trends," 1991). Illicit trade traditionally has been a major problem (e.g., Miller, 1987; Johnson et al., 1989), and it is widely believed that in 1992 the value of smuggled stones will have well surpassed Angola's official diamond exports of about $200,000,000 (Contreras, 1992).

Angola has significant reserves of both alluvial diamonds and, it appears, primary deposits. Alluvial production at Lucapa is estimated at 400,000 ct annually, with additional operations further northeast, in the Andrada region ("World diamond mining," 1991). In addition geologists have identified more than 300 kimberlite pipes. However, present political instability in this region makes it difficult to assess the long-term impact of these reserves.

Marine Deposits. Meyer (1991) and Gurney et al. (1991) reported on the vast resource of diamonds (estimated to be at least 1.5 billion ct) that may exist off the west coasts of South Africa and Namibia (again, see figure 8). It is estimated that 90%–95% of these are gem quality. These diamonds were released from weathered diamond-bearing kimberlites in the ancient and present Orange River (and probably other) drainage basins, and were then transported to the west coast where they were deposited in the marine environment. Raised marine deposits now on land have yielded almost 100,000,000 ct, but similar deposits still in the marine environment have yet to be fully prospected.

In 1990, about 75,000 ct of diamonds were recovered from the offshore Namibian waters, with another 128,000 ct offshore of South Africa (Gurney et al., 1991). Offshore Namibian production almost tripled in 1991, to about 212,000 ct, with 170,744 ct produced by De Beers Marine alone (De Beers Centenary AG, 1992; Namibia, 1992). Although production is difficult and expensive at present, the west coast off southern Africa should be an even more important source of fine-quality diamonds by the early 21st century. Possible future opportunities also include marine diamonds associated with the Argyle field (i.e., off the northwest coast of Australia), the Russian Federation deposits (in the Arctic Ocean, near the mouths of north-flowing rivers like the Lena), and even off the north coast of Canada (in Coronation Gulf).

Figure 8. For most of this century, Africa has supplied the vast majority of diamonds to the world market. The three Botswana mines and South Africa's Finsch and Premier mines are still among the most productive. However, all of the primary South African operations shown here—with the exception of the newly opened Venetia mine—are mature operations that will probably be depleted in the early 21st century. Although the proportion of diamonds produced from secondary deposits worldwide has decreased greatly over the last three decades, the secondary occurrences noted here—alluvial deposits in Angola and marine deposits offshore Namibia and South Africa—are likely to be of increasing importance in the future.

Primary Deposits. We believe that the cratons of the Russian Federation and North America have

Figure 9. Extensive alluvial deposits are being worked in Angola, with a significant production (1,300,000 ct reported in 1990) of rough that is reportedly 70% gem quality. Angola appears to have major reserves that could last well into the future once the problems of political instability and irregular production are resolved. Here, illegal miners work one of the many active areas in the country. Photo © Paul Lowe–Network/Matrix.

the greatest potential for producing major amounts of diamonds in the near and intermediate (i.e., 10–25 years) future. In the very distant future, perhaps in 100 years, Antarctica could be a major producer.

The Russian Federation. The eastern Siberian republic of Sakha (formerly known as Yakutia), in the Russian Federation, C.I.S., already is a major diamond-producing region. Mining activity has progressed rapidly since the discovery in 1953 of the first diamond in the Malaya Botuobiya River, a tributary to the Vilyui River, and the discovery of the first kimberlite (Zarnitsa) in 1954 (figure 10). The desirability of prospecting for diamonds in these Archean areas was first noted by Russian academician Vladimir S. Sobolev. In the late 1930s, he realized that similarities between the geologic structure of the central Siberian shield and the interior plateau area of southern Africa suggested the possibility of great diamond riches in Siberia. Prospecting on the basis of this relationship started in 1947.

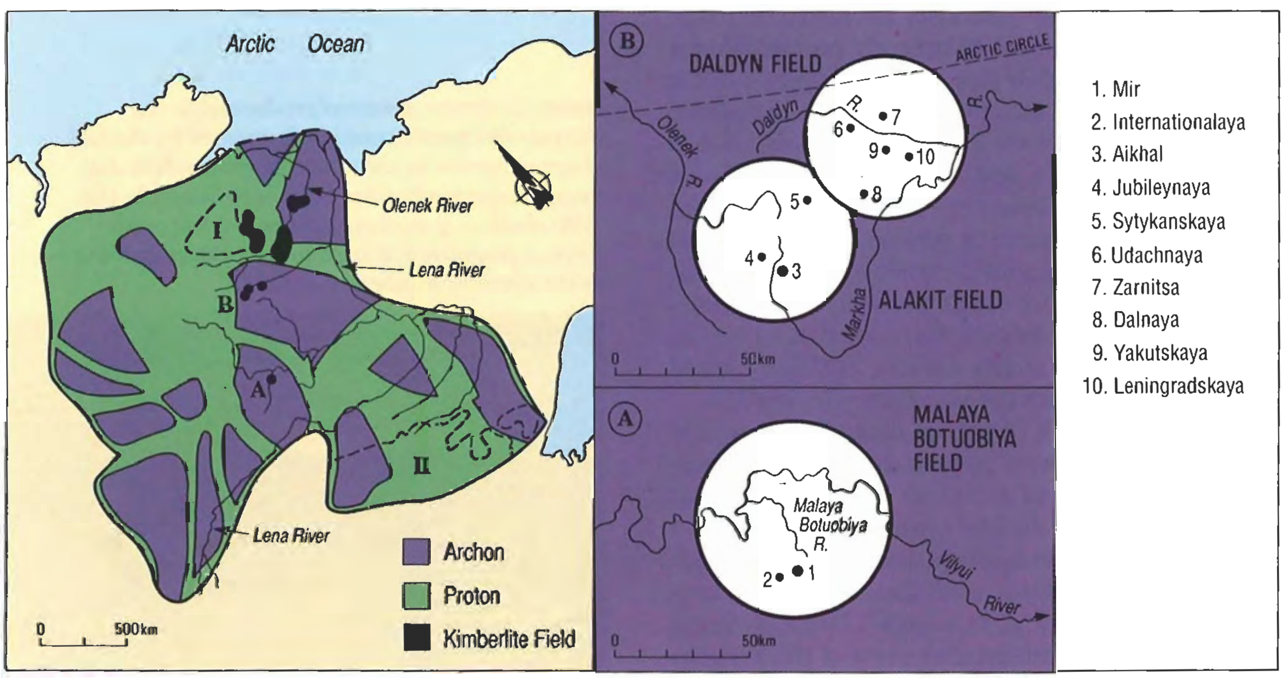
In 1955, the richly diamondiferous Mir pipe (17 acres [6.9 ha]) was located; only 10 days later, the Udachnaya pipe, 400 km to the north and about 20 km south of the Arctic Circle, was found (again, see figure 10). By 1956, the number of known pipes had risen to 40. To date, the Amakhinsky Exploration Team has found more than 500 kimberlite occurrences. These kimberlites lie in clusters that straddle the Arctic Circle to 400 km north. The diamond contents of the kimberlites range from zero to highly economic (e.g., Meyer, 1990). The first mining started, at Mir, in 1957. Augmented by the mining of alluvial deposits in the nearby Vilyui River, total annual production had risen to an estimated 5,200,000 ct by 1965. The smaller Internationalaya pipe was opened next, followed by Aikhal to the north, the larger Udachnaya pipe 60 km away (about 49 acres [20 ha]), and Sytykanskaya halfway between. (For more on diamond mining in this region, see Meyer, 1990.)

Internationalaya has now reached the end of its working life as an open-pit operation. Underground mining of the root zones of the pipe is hampered by the presence of saline water containing hydrogen sulfide and sometimes by the acid conditions in the Devonian sediments above the archon in which the pipe is emplaced. Currently, there is no active mining of kimberlite at Mir, though production from stockpiled ore continues. The main current mining activity is at the Udachnaya open pit. However, it is now a mature mine (figure 11). Production in this area is augmented by that from Aikhal and Sytykanskaya. A new major deposit, the Jubileynaya, is scheduled for full production in 1994/95. This very large pipe, nearly the size of Orapa (262 acres [106 ha]), was concealed by an overlying diabase sill that has been stripped away to allow open-pit mining (Meyer, 1990).

The five older kimberlite mines (Mir, Internationalaya, Aikhal, Udachnaya, and Sytykanskaya) and their associated alluvials have provided the more than 270,000,000 ct of diamonds estimated to have been produced from the Yakutia region since 1960.

Figure 11. The Udachnaya kimberlite is currently the most important diamond-mining operation in Sakha. It is about 49 acres (20 ha; Johnson et al., 1989) in surface area. Large dump trucks remove the kimberlite and waste rock at a rate of about 1,000 metric tons per hour. The mine operates 24 hours a day and throughout most of the year.

Figure 10. The Yakutian craton of eastern Siberia (again, see figure 7) is presently one of the most productive diamond-bearing cratons in the world. The mines shown here are located in the republic of Sakha (formerly Yakutia) in the Russian Federation (C.I.S.). The craton, on the left, has two exposed portions: the Anabar Shield in the north (I), and the Aldan Shield in the south (II). Note the elaborate pattern of archons surrounded by protons. The main producing kimberlite areas are shown in black and marked by A and B. The maps on the right show the important diamond-bearing kimberlite pipes in the Malaya Botuobiya field (A) and the Alakit and Daldyn fields (B).



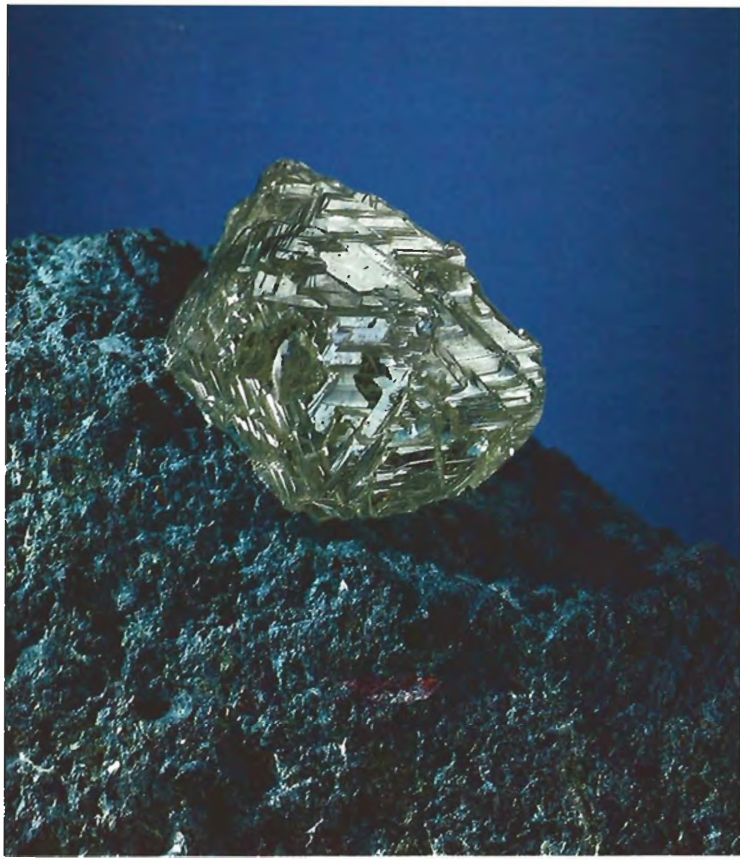


Figure 12. The diamonds of the Sakha region, in eastern Siberia, are noted for their excellent color, clarity, and shape. This 2-cm crystal in kimberlite is from the Mir mine. Courtesy of the Houston Museum of Natural Science; photo © Harold & Erica Van Pelt.

Unfortunately, official data for diamond grades and value, tonnage mined, total production, and future reserves—such as are routinely published by many mining companies—are completely unavailable for this region. At the Mir pipe, grades of up to 4 ct/mt have been reported, along with 2 ct/m^3 in high-grade gravels dredged from the Vilyui River. Aikhal is also extremely high grade, and some of the diamonds out of Udachnaya have been described as being of exceptional clarity and color. In general, diamonds from the two producing regions are noted for their excellent shape for cutting, since a high proportion are extremely regular, sharp-edged, flat-faced octahedra. Exceptionally large stones are rare, but well-formed crystals over 20 ct are not uncommon (figure 12).

Despite the lack of official data, the apparently high grade of kimberlite pipes in this region is important in attempting to assess its impact on the diamond industry into the 21st century. There are many known diamondiferous kimberlites, some of considerable size (e.g., Zarnitsa, at 53 acres [21.5 ha], is larger than the Finsch mine, 44.2 acres [17.9 ha], in South Africa), in Sakha and in other parts of the Russian Federation that are not currently exploited. In the past, Siberian kimberlites with less than 0.5 ct/mt of diamond were considered barren, and economic grade was greater than 2 ct/mt. Elsewhere in the world, the Argyle lamproite is the only primary deposit that consistently meets this criterion! Therefore, the possibility exists that kimberlites found but not previously worked will prove viable in the future.

The relatively recent discovery and sampling of diamondiferous kimberlites on the Baltic Shield near Arkhangelsk (on the White Sea, in the province of Oblast, near the border with Finland) gives added potential to the future supply of diamonds from the Russian Federation. It has been speculated that mines could be established on at least one kimberlite, the Lomonosovskaya, and perhaps on as many as five kimberlites. Like those in Sakha and other localities, this new kimberlite province lies close to the Arctic Circle.

One concern regarding future production is that the superb quality of many of the diamonds from Sakha is not matched by diamonds from kimberlites elsewhere in the region; in these latter kimberlites, resorbed diamonds and those that are colored, including yellows and browns, are more abundant. This may translate into a lower average value per carat for the diamonds. In addition, the fact that many deposits lie well within the Arctic Circle, some in low-lying, waterlogged ground, and in regions where there is absolutely no infrastructure (figure 13), signifies logistical problems that will take time to overcome.

Figure 13. Future diamond production in the Russian Federation could be hampered by the lack of infrastructure in the remote regions where diamondiferous kimberlites have been found. In this 1990 photo, a special exploration vehicle (with tracked propulsion) is used to ford a river en route to the Zarnitsa kimberlite in Sakha.

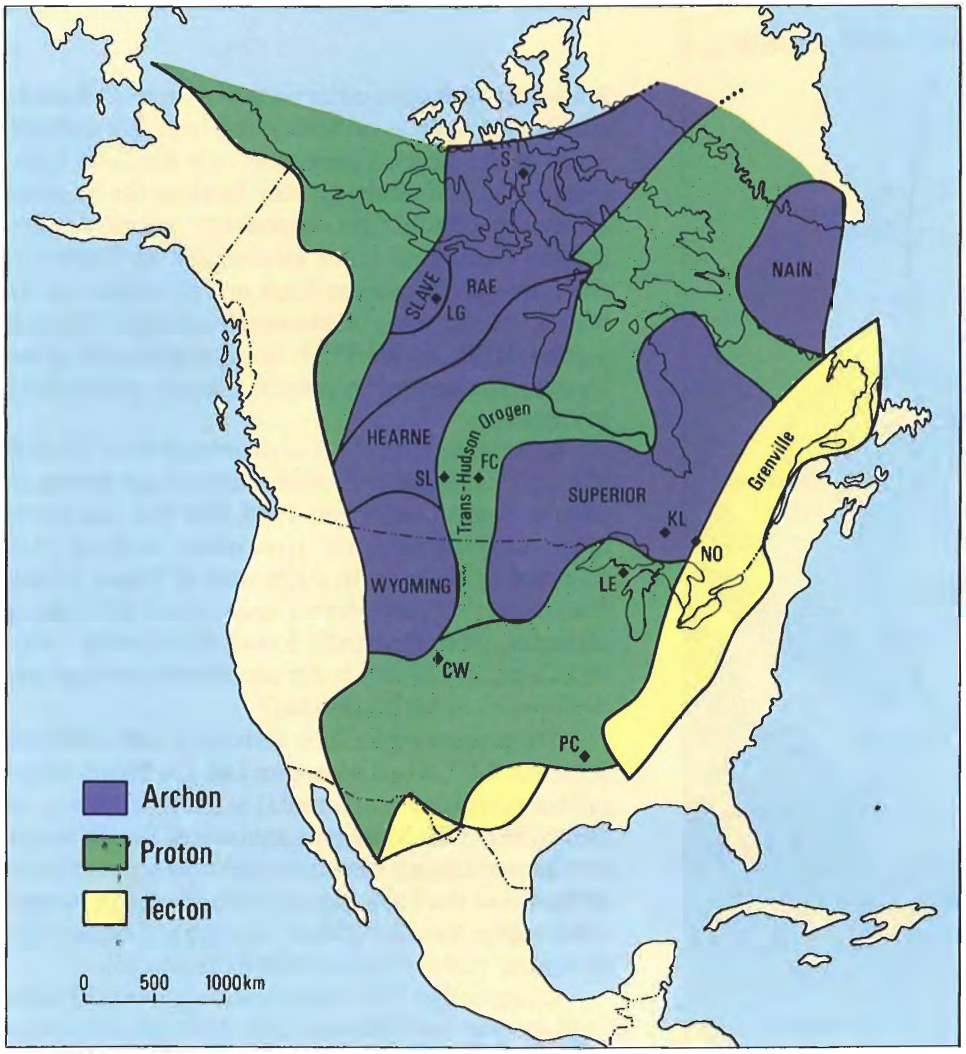


Figure 14. North America contains the largest known craton in the world (again, see figure 7), shown here with the three age-based divisions identified (after Hoffman, 1988; Janse, 1992). Archons (Slave, Rae, Hearne, etc.) are the most favorable areas for economic diamondiferous kimberlite pipes. Although no economic kimberlites have been found thus far on a proton, diamonds have been found in kimberlite pipes in the Trans-Hudson Orogen. Kimberlites have also been found in the Grenville tecton, at least one with traces of diamonds. Specific diamond-bearing occurrences noted are: CW—Colorado-Wyoming; FC—Fort à la Corne; KL—Kirkland Lake; LE—Lake Ellen; LG—Lac de Gras; NO—Noranda; PC–Prairie Creek; SI—Somerset Island; SL—Sturgeon Lake.

Canada. There has never been a profitable diamond mine in North America. Although the occurrence at Prairie Creek (Crater of Diamonds State Park, near Murfreesboro, Arkansas) produced an estimated 100,000+ ct during the period 1907–1933 (Waldman and Meyer, 1992), it was not economic. The diamondiferous kimberlites found subsequently—for example, in clusters in the State Line district of Colorado and Wyoming, in the Lake Ellen group near Crystal Falls, Michigan, and at scattered localities elsewhere in the United States and eastern Canada (Janse, 1992; Waldman and Meyer, 1992)—have also been noneconomic. However, the United States is situated mostly on geologically less favorable protons and tectons (figure 14), whereas Canada has some of the largest areas of the world that are underlain by archons. Recent exploration activity in Canada has revealed the existence of several diamondiferous kimberlites that may prove to be economic. On the basis of this favorable geology and the intensity of the current exploration, we predict that Canada will be a major producer of diamonds by the second decade of the 21st century.

Isolated discoveries of diamonds were reported in the *United States* as early as the 1840s, in North Carolina, Georgia, and California (e.g., see Kopf et al., 1990). The most significant, from the point of view of exploration, were the diamonds found in glacial drift in Ontario and the Great Lakes states as early as 1863. Almost a century ago, Hobbs (1899) concluded that the diamonds had been transported by glaciers, and that the apex of the fan along which they traveled indicated that the source was located in the James Bay Lowlands (figure 15).

Exploration was particularly intense in this area of *eastern Canada* during the late 1970s and early 1980s, but no kimberlites were reported (Brummer, 1984; Janse et al., 1989; and Reed and Sinclair, 1991).

Figure 15. Early evidence of possible diamond-bearing kimberlites in North America are the diamonds found in glacial deposits in the Great Lakes states. The diamonds are believed to have originated from the James Bay Lowlands of Ontario. This map of the region shows the limits of Pleistocene glaciation and the last glacial advance, the known diamond occurrences in glacial deposits, the total number of diamonds found in each state (e.g., Indiana, 34), and the paths that the diamonds may have taken from their presumed source(s) in the James Bay Lowlands. Note that of the more than 80 diamonds that have been found in glacial deposits thus far, only two were in Canada: the 0.25-ct South Porcupine and the 33-ct Peterborough. After Hobbs (1899) and Brummer (1984).

A few kimberlites in other parts of eastern and northern Canada, such as on Somerset Island (Rae archon), north of the Arctic Circle, and near Kirkland Lake, Ontario, and Noranda, Quebec (both in the Superior archon), reportedly have uneconomic amounts of diamonds. Numerous other kimberlites are known in the Grenville tecton, at least one of which—at Ile Bizard, 15 km west of Montreal—yielded 10 small diamonds (Brummer, 1984). Some exploration activity continues today in eastern Canada, particularly in Ontario.

In *western Canada*, five diamonds were allegedly found in glacial drift near Cumberland House in eastern Saskatchewan in 1948, but this has never been substantiated; the first major staking rush occurred in 1961, about 6 km west of Prince Albert. Two diamonds, each about a quarter inch (0.64 cm) in diameter, were reportedly found. (See Strnad, 1991, and Gent, 1992a and b, for the history of diamond exploration in Saskatchewan.)

The present exploration activity in Saskatchewan started in 1987, when Monopros Ltd. (De Beers's exploration company in Canada) staked property; in November 1988, Monopros announced the discovery of a diamondiferous kimberlite about 30 km northwest of the site of the 1961 staking. Soon thereafter, several other companies filed claims for diamond exploration in various parts of Saskatchewan (figure 16).

In September 1989, joint-venture partners Uranerz Exploration and Mining Ltd. and Cameco Corp. announced the discovery of seven kimberlite pipes in the Fort à la Corne area (figure 17). They subsequently announced the recovery first of microdiamonds (<0.5 mm in diameter) and then of four larger diamonds. Two years later, clusters of kimberlite pipes were discovered under a 100-m-thick glacial overburden; all of the 15 sites (out of 70 potential) that were drilled proved to be diamondiferous. To date, Uranerz and Cameco have reported the recovery of 160 small diamonds, weighing a total of 7 ct; the average stone is 0.04 ct, and the largest is about 0.5 ct. There has been no official report of the quality of these stones. The best preliminary grade reported for any kimberlite tested is low, about 0.1 ct/mt, but the average grades of these pipes are typically much lower (0.01–0.02 ct/mt). However, because of the thick overburden, the large-scale bulk testing that is necessary for meaningful evaluation has not been completed.

In 1992, kimberlite-specific garnets and chrome diopside were identified in glacial-till samples taken in the southwestern part of Saskatchewan close to

Figure 16. Since 1987, more than 50,000,000 acres have been staked or claimed for diamond exploration in western Canada. This map shows the locations staked as of mid-December 1992. Most of the exploration activity is for kimberlites, although that in the vicinity of Dubawnt Lake is for lamproites. The dashed line in southwestern Saskatchewan, in the vicinity of Val Marie–East Poplar, encompasses an area of many small claims.

the Montana border (Swanson and Gent, 1992), but no kimberlite pipes have yet been announced. Geologically, this area is within the favorable Wyoming archon. As of December 7, 1992, approximately 1,794,000 acres (726,000 ha; 2,800 sq. mi.) had been staked in Saskatchewan for diamond exploration (M. R. Gent, pers. comm., 1992).

In British Columbia, Alberta, and the western part of the Northwest Territories, intermittent exploration for diamonds has been in progress for as much as 20 years by major mining companies such as Cominco, BP Minerals, Lac Minerals, De Beers operating via Diapros and Monopros, Falconbridge Exploration, and Corona (Godwin and Price, 1986; Dummett et al., 1987).

Of particular importance in this exploration has been the identification of certain characteristic heavy minerals, referred to as indicator minerals (specifically, pyrope garnet, ilmenite, chrome diopside, and chromite), that are associated with kimberlites. The dispersion of these minerals into secondary concentrations such as alluvials has been used in diamond exploration since the 1870s in South Africa and elsewhere (Dummett et al., 1987; Atkinson, 1989;

Figure 17. This drilling operation is designed to recover ore from buried kimberlite that has been identified in the Fort à la Corne area of Saskatchewan by geophysical techniques. Note the many meters of drill pipe on the bed of the truck.

Jennings, 1990). Although indicator minerals do not provide conclusive evidence that a kimberlite is diamondiferous, they (rather than diamonds) are typically used to locate kimberlites because they are more abundant than diamonds and more recognizable. Thus, they are more likely to be found in any reasonably sized sample.

In western Canada, various types of glacial deposits, such as eskers (long, narrow, sinuous ridges of material deposited by a stream flowing under a glacier), perform the same function as rivers in dispersing minerals from a kimberlite. Although more difficult to follow and interpret than an alluvial trail, a glacial trail should lead to the primary source of a dispersed mineral (the same concept used by Hobbs in the Great Lakes region; again, see figure 15). Folinsbee (1955) did the first thorough geological study, including the use of heavy minerals, of the Point Lake–Lac de Gras area of the Northwest Territories (again, see figure 16). Years later, such a trail of heavy indicator minerals eventually led one exploration company—Dia Met Minerals Ltd.—back to the Lac de Gras area in search of diamonds (Richards, 1992; Walsh, 1992).

Beginning in 1989, Dia Met Minerals began to acquire ground in the area, eventually staking 1,500,000 acres (606,000 ha). In April 1990, a geologic structure was discovered under Point Lake (figure 18) that indicator minerals and geophysical surveys strongly suggested was a kimberlite pipe.

In August 1990, Dia Met entered into a joint venture with BHP-Utah (now known as BHP Minerals), the North American arm of the major Australian mining company Broken Hill Proprietary Ltd. About a year later, the presence of diamondiferous kimberlite was confirmed when a hole drilled at an angle from the shore penetrated this rock under Point lake. Eighty-one small diamonds, all less than 2 mm in diameter, some reportedly gem quality, were subsequently recovered from 141 m of drill core weighing 59 kg. Early in 1992, 160 tons (still a relatively small sample) of kimberlite were obtained, from which 101 ct of diamonds were recovered (0.63 ct/ton). Twenty-five percent of these were reported to be "gem quality" (excluding near-gems); a few were in the 1–3 ct range. In September 1992, it was announced that nine additional kimberlite pipes had been discovered in the same general area, all containing diamonds in variable proportions. Although the grade of the Point Lake deposit, 0.63 ct/ton, is very good by average world standards for primary deposits, and approximately 80 million tons of kimberlite have already been delineated, there has been no clear statement or independent confirmation as to the actual quality of those stones categorized to this point only as "gems."

The discovery of the Point Lake and nearby kimberlites (now known as the Lac de Gras kimberlite field) has resulted in the largest and most exciting staking rush in Canadian mining history. In the Northwest Territories, as of December 14, 1992, at least 19,365,000 acres (7,840,000 ha) had been staked by

Dia Met, Monopros, and at least 50 other companies and individuals (again, see figure 16). It is anticipated that the entire Slave archon will be staked by the end of January, 1993.

Staking is now proceeding eastward (near Dubawnt Lake) to the Rae archon, portions of which contain the largest geologic province of lamproitic rocks in the world (Peterson, 1992). Similar rocks are found as far south as southern Alberta. It is significant that of the only 25–30 lamproite occurrences known worldwide, seven of these contain diamonds.

In Alberta, intermittent and very secretive diamond exploration has been in progress for at least 15 years, much of it also based on heavy-mineral sampling in conjunction with geophysical surveys. In 1990, Monopros acquired 1,680,000 acres (680,000 ha) in the Peace River area. Several small diamonds now have been reported from various locations in glacial till and other alluvial materials in Alberta, but none yet from any kimberlite occurrence. However, the province is underlain by parts of several archons, so there is good geologic potential for kimberlite pipes. Further, the infrastructure and climate are certainly more conducive to efficient exploration than is the case in the Northwest Territories, and the province recently enacted legislation that encourages exploration for minerals. As of December 11, 1992, about 28,400,000 acres (11,500,000 ha) had been staked for diamond exploration in Alberta (again, see figure 16).

From the above discussion, it is clear that North America, in general, and western Canada, in particular, has good long-term potential as an economic source of diamonds. Reasons include: (1) it has the largest craton in the world, including six major archons; (2) it is underexplored relative to South Africa and many other cratonic areas of the world; (3) good-quality diamonds, some over 15 ct (Hobbs, 1899; Brummer, 1984) have been found in the glacial deposits; and (4) the infrastructure and political situation are among the best in the world.

Antarctica. Any discussion of future sources of diamonds would be incomplete without at least mention of Antarctica because of its favorable geology and geologic relationship to other diamond-producing areas.

The continent of Antarctica encompasses about 14,250,000 km^2 (the United States, including Alaska, covers 9,372,000 km^2), of which about 98% is permanently covered by a continental ice sheet averaging 2,000 m in thickness. Geologic knowledge is based on limited rock exposures on the edge of the continent, or those projected through the ice sheet, in addition to geophysical data (e.g., aeromagnetic surveys). Geologically speaking, Antarctica is the last frontier.

Antarctica today is divided into East and West Antarctica (figure 19) by the Transantarctic Mountains, which extend about 4,500 km from the Ross Sea to the Weddell Sea, reaching heights of 4,000 m (Dalziel, 1992).

The larger of the two, East Antarctica, has the greatest potential for diamonds because geologically it is a craton. Although more than 99% of its surface is covered by ice, four archons have been identified. The present East Antarctic craton formed 1.0–1.3 billion years ago, and became part of an ancient supercontinent that eventually broke up more than 570 My ago. Starting in the Cambrian and until middle Jurassic time, an interval of about 350 My, Antarctica formed the core of a second supercontinent known as Gondwanaland. Over the next 160 My, Gondwanaland

Figure 18. Evidence of the first kimberlite pipe in the Northwest Territories was discovered in April 1990 by C. E. Fipke, of Dia Met Minerals, under Point Lake (in foreground, looking northeast toward Lac du Sauvage at the top of the photo). The surface of the kimberlite lies about 50 m (150 ft.) below the surface of the lake, which is 600 m across. The white objects on the northeast shore are trailers. A drilling rig may be seen on the shore about 100 m to the left of the trailers. From this position, an angle hole was drilled under the lake in September 1991, which confirmed the presence of diamond-bearing kimberlite. Photo taken in late July, 1992; courtesy of B. T. Evans, Tyler Resources, Inc., Calgary, Alberta.

Figure 19. On the basis of what little is known about the geology of this remote region, Antarctica may have great potential as a source of diamonds. The East Antarctic craton is probably the second largest in the world (after North America). Four archons, not covered by the ice cap, have been identified on the east side of the continent.

broke up to form South America, Africa, India, Australia, and Antarctica (see Tingey, 1991, and Dalziel, 1992). Thus, all the present diamond-producing regions of the southern hemisphere, as well as in India, have a common geologic history. Johnson et al. (1989) list Antarctica as one of several favorable regions for large, as yet undiscovered, kimberlite provinces.

At this time, consideration of Antarctica as a source of diamonds is academic, if for no other reason than international agreement forbids any mining. Further, legislation recently passed in the United States (Antarctic Protection Act of 1990; 101st Congress) prohibits U.S. nationals and companies from engaging in any type of mineral-resource activities in Antarctica (Molnia, 1991). Nevertheless, the fact remains that the East Antarctic craton is huge, and it contains archons. If scientific advances in the next century match those of the last 100 years, it is conceivable that diamonds could be mined economically, and in an environmentally acceptable manner, by the end of the 21st century.

CONCLUSIONS

A study of diamond production over the past 120 years shows that although most rough has come from Africa, this situation is rapidly changing. There is also a steady geologic shift toward increased production from primary sources (kimberlite and lamproite pipes) at the expense of secondary sources, mainly alluvial deposits.

The growth of the near-gem market, especially since 1980, has resulted in rough now being classified as cuttable and industrial. The explosion in diamond production during this period, however, has had little impact on the availability of good-quality gems; such cut stones 0.5 ct and larger still constitute only a very small percentage of the diamonds produced annually. At the same time, with the greater economic freedom in once-"closed" areas of Eastern Europe and Asia, major new markets are poised to develop.

Thus, the need for steady sources of good-quality diamonds continues. The most significant long-term deposits are those that occur offshore, such as the marine deposits off of southern Africa, and those primary deposits with significant reserves of ore. Although marine deposits have great long-term potential, they are restricted by the technological challenges of exploration and mining in deep seas. On the other hand, once the economic value of a primary kimberlite or lamproite deposit has been established, it is much easier to mine.

The most likely major source for greatly increased production from primary deposits within the next 10 years is Sakha and elsewhere in the Russian Federation, because the locations of potentially economic kimberlite pipes are known. Canada is likely to be a major producer of diamonds 10–25 years from now, but it is doubtful that significant production could start before the end of this century, owing to the long time it takes to evaluate a pipe and then bring it into production. A hundred years from now, the ecological environment permitting, technological developments might well provide for mining beneath the ice cap in Antarctica, probably the last great terrestrial source of diamonds.

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