DISCOVERY AND MINING OF THE ARGYLE DIAMOND DEPOSIT, AUSTRALIA

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In 1983, the Argyle mine was established as the first major diamond-mining operation in Australia. Almost immediately, it became the world's largest source of diamonds in terms of the volume (carats) produced. The discovery, development, and operation of this mine challenged conventional beliefs about diamond geology, mineral processing, and the marketing of gem diamonds. In its peak year, 1994, the mine produced over 42 million carats (Mct) of rough diamonds, which represented 40% of the world's production. A large proportion of this staggering output consists of small brown-to-yellow—as well as some near-colorless and colorless—rough diamonds. A major cutting industry developed in India to process these diamonds into cut gems. The Argyle mine is also noted for the production of a very limited amount of rare pink diamonds.

The Argyle mine, located in a remote northeastern region of Western Australia, is currently the world's largest producer of diamonds by volume (figure 1). Production in 2000 reached 26.5 million carats (approximately 25% of annual world production), following a peak in 1994 of 42.8 million carats, which was 40% of the diamonds produced worldwide that year. The Argyle mine is known not only for the very large quantity of diamonds it produces, which vary from brown to yellow and from near-colorless to colorless (figure 2), but also for the consistent recovery of a small number of pink diamonds. Prior to 1998, no plans had been finalized for the mine to continue past 2002. In October of that year, however, a decision was made to cut back the 400 m (1,300 ft) high west wall to widen and deepen the pit. With the orebody apparently extending to depth, plans now call for open-pit mining to continue until at least 2006, with a possible transition to an underground operation at that time.

The Argyle mine provides a good example of the modern techniques used both to find viable diamond deposits and to recover the gems on a large scale. Therefore, this article discusses the exploration methods employed to discover the first economic deposits of diamonds in this area of Australia, as well as the mining and recovery techniques used at the mine. The Argyle AK1 pipe represented the first major deposit of diamonds found in lamproite (a kind of volcanic rock similar to kimberlite), the discovery of which called into question prevailing theories of diamond occurrence. We also briefly summarize the gemological characteristics of Argyle diamonds.

The Argyle mine is 100% controlled by Rio Tinto Ltd. (although until late 2000 it was a joint venture with Rio Tinto [56.8%], Ashton Mining Ltd. [38.2%], and the Western Australian Diamond Trust [5%]). It was the first large-scale operation for recovering diamonds in Australia. The ore grade is currently around 3.0 ct per tonne of host rock, which is three to 10 times higher than the typical grade at other primary diamond deposits. (Note: In

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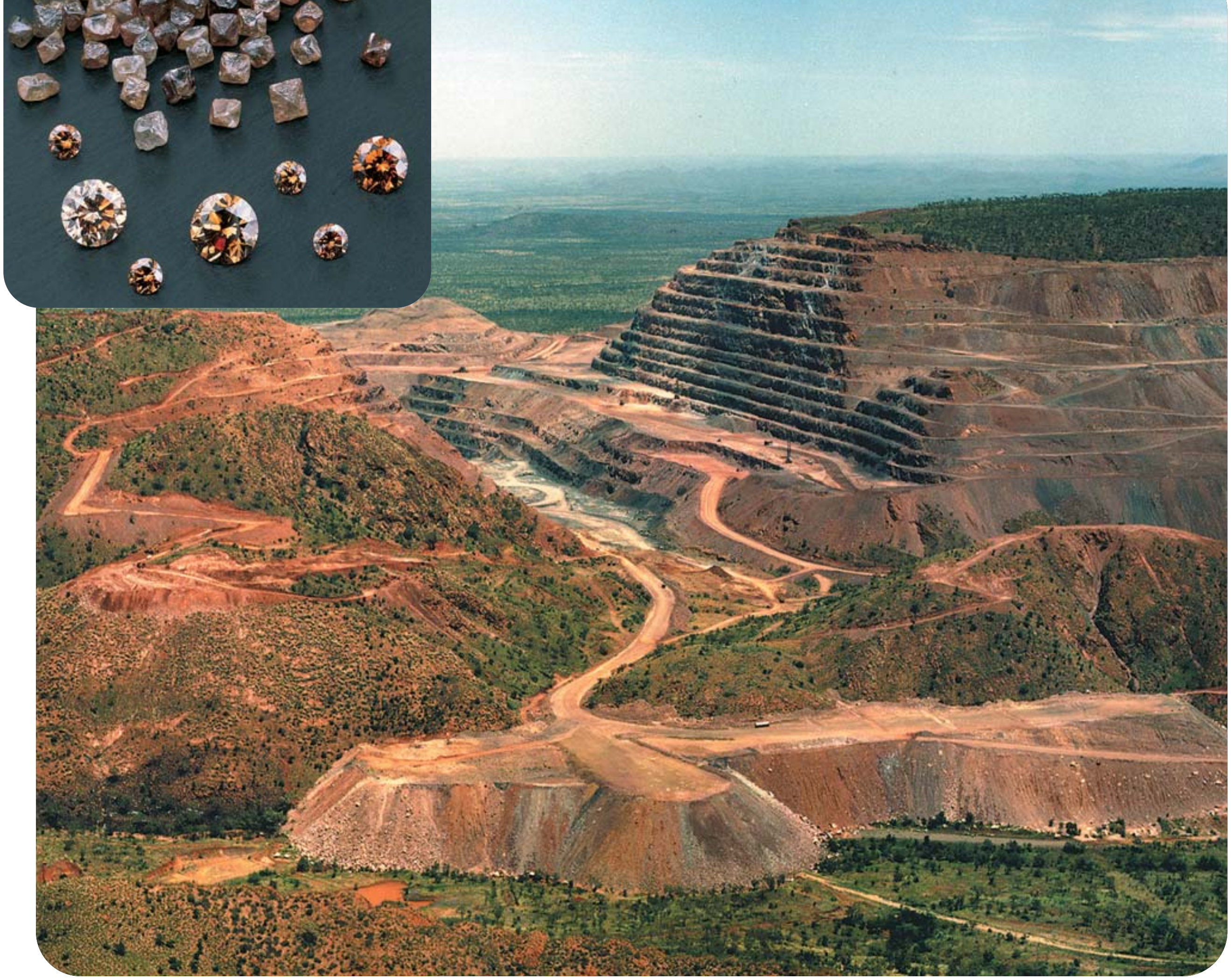

Figure 1. This aerial view of the Argyle mine, looking southwest, shows a portion of the AK1 pit. The shape of the open pit closely follows the outline of the lamproite pipe. In both the foreground and at the opposite end of the pit are dumps where the reddish brown overburden rock has been moved for storage. Since 1985, when mining of the orebody commenced, approximately 550 million tonnes of lamproite ore and overburden rock have been removed from the open pit. Brownish diamonds, such as the crystals and round brilliants shown in the inset, are commonly produced and marketed as "cognac" or "champagne" diamonds. The three largest diamonds weigh 4.11, 4.07, and 2.19 ct; inset photo by Shane F. McClure.

accordance with the usage in other diamond mines throughout the world, volumes of rock are expressed here in metric tonnes, where 1 U.S. short ton = 2,000 pounds = 0.907 metric tonnes.) However, even with this high grade, diamonds comprise only 0.0001% by weight of the ore, so sophisticated ore-processing methods are necessary to extract this very small proportion of diamonds from the very large amount of host rock. In addition, the company conducts its mining activities in an environmentally and socially responsible way.

LOCATION AND TERRAIN

Location and Access. The Argyle mine is situated in the northeastern part of Western Australia, approximately 120 km (75 miles) by road southwest of Kununurra (the nearest town), 540 km (335 miles) southwest of Darwin, and 2,200 km (1,370 miles) northeast of Perth, the state capital (figure 3). The AK1 pipe is located at the headwaters of Smoke Creek in a small valley in the southern end of the Matsu Range, which is the southeastern extension of the Ragged Range (figure 4). Associated alluvial diamond deposits occur along Smoke Creek and Limestone Creek, which drain the AK1 pipe to the north and southeast, respectively. Both drainage systems then turn northeast toward Lake Argyle, 35 km (22 miles) downstream from the mine.

Access to this region is by commercial air flight from Perth or Darwin to Kununurra, and then by a short chartered flight to a landing strip at the mine site. Alternatively, one can travel two hours by vehicle from Kununurra along a paved highway and

then on a dirt road to the site. Access to the mine site is allowed only with prior permission.

Climate and Terrain. In this region of tropical savannah, rainfall averages 700 mm (about 28 inches) per year. Most precipitation occurs in the wet season of January and February, when temperatures can reach 45°C (110°F). Local vegetation is sparse, consisting mostly of occasional small trees along with more numerous bushes and grasses. The

Figure 2. A range of colors produced at the Argyle mine can be seen in this selection of rough diamonds. Note also the variety of crystal shapes, including a relatively small proportion of octahedra and macles, and abundant rounded or irregular shapes. These crystals vary from about 0.5 to 1 ct; as such, they are larger than the crystals typically recovered from the mine, which have a mean size of less than 0.1 ct.

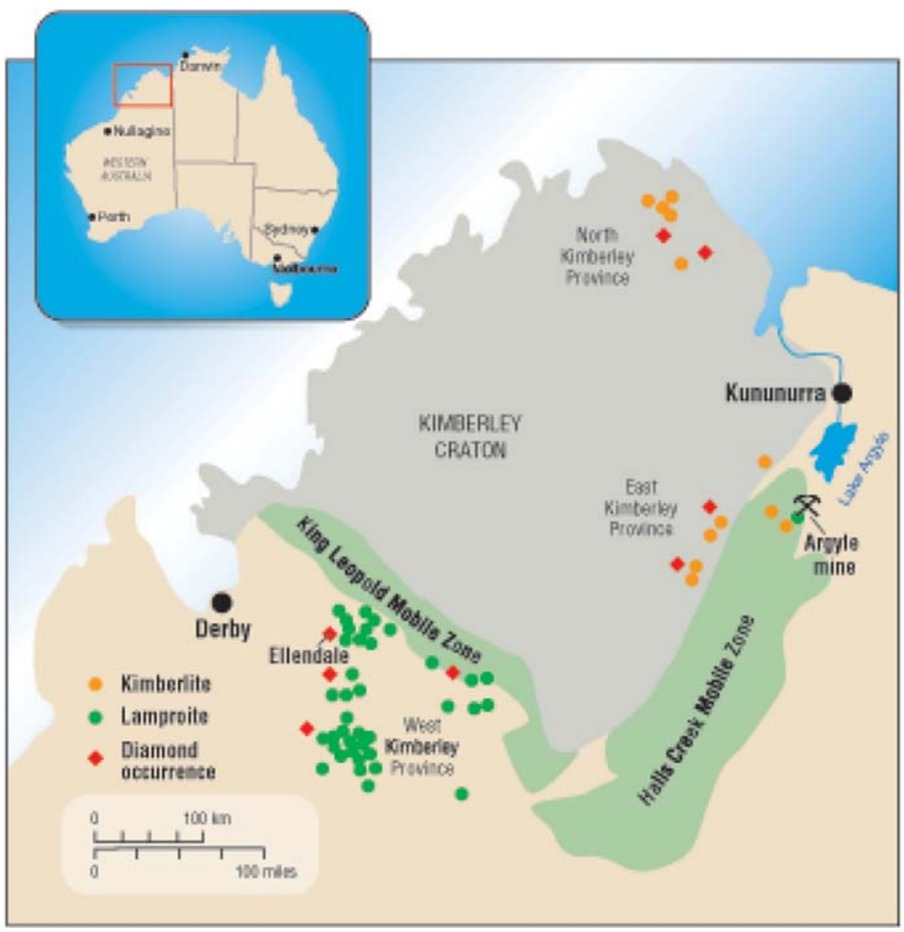

Figure 3. This generalized sketch map shows the locations of kimberlites, lamproites, and diamond occurrences in the Kimberley craton region of Western Australia. The Argyle mine is situated east of the Kimberley craton, near the eastern margin of the Halls Creek Mobile Zone. Other diamond deposits (not yet developed) are located at Ellendale to the southwest of the craton, and at two kimberlites within the northern part of the craton. The first Australian diamonds were found by gold prospectors in alluvial deposits near Nullagine (see inset) in 1895. Adapted from Atkinson et al. (1984b, figure 3B).

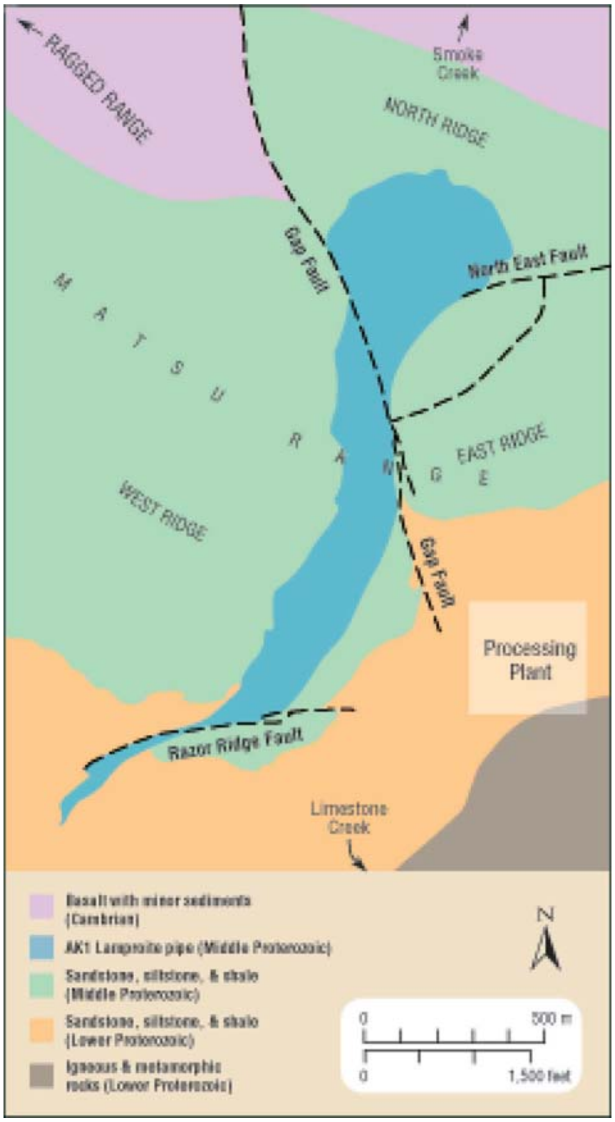

Figure 4. The tadpole-like shape of the Argyle AK1 lamproite pipe, which is broadest to the north and narrowest to the south, is evident in this simplified geologic map. The pipe is located within resistant rocks of the Matsu Range that here form the East and West Ridges.

region is characterized by the presence of bulbous boab trees and abundant termite mounds. Other than the hills of the Matsu and Ragged ranges, much of the terrain surrounding the mine area consists of broad, flat plains. This region contains a few small Aboriginal communities. All materials and supplies must be brought in from Kununurra by truck or aircraft if they cannot be generated at the mine site.

DISCOVERY OF THE ARGYLE DIAMOND DEPOSITS

Exploration for Diamond Host Rocks. In 1895, gold prospectors first found diamonds by accident in stream gravels at Nullagine in Western Australia (figure 3, inset). Many thousands of carats of diamonds were recovered from this and other alluvial deposits in various parts of the country over the next 50 years, but not until the introduction in the 1960s of modern geologic exploration concepts and techniques were diamond-bearing pipes—the primary sources—finally discovered (Geach, 1986; Janse, 1992).

Beginning in the 1970s, as a result of renewed interest in mineral prospecting in Western Australia, the geologically ancient shield areas in this region were selected as prime targets for diamond exploration. A shield area, or craton, is a portion of the continental crust that has been geologically stable (i.e., not involved in mountain building, faulting, deformation, etc.) for billions of years. The geologic settings of the diamondiferous kimberlite pipes in southern Africa were used as models for the selection of shield areas in Western Australia for diamond exploration (see Jaques et al., 1986; Haggerty, 1999).

Although kimberlites were believed to be the only terrestrial source of diamonds at the time, Prider (1960) had suggested that a petrologically related volcanic rock known as lamproite might also host diamonds in this part of Australia. Both the discovery of alluvial diamonds at Nullagine and the occurrence of lamproites along the tectonic margins of the (ironically named) Kimberley craton (in northern Western Australia) were additional reasons for selecting the shield areas of Western Australia for diamond exploration (figure 3). Clifford (1966) had observed that the known diamondiferous kimberlites in southern Africa were restricted in their occurrences to ancient cratons that had been tectonically stable for at least the past 1.5 billion years. This condition was met, at least in part, by the geologic conditions of the Kimberley craton (Deakin et al., 1989).

Following the discovery of several alluvial diamonds in the West Kimberley region along the Lennard River (Ellendale area) in 1969, a consortium of mining companies, collectively known as the Kalumburu Joint Venture (succeeded by the Ashton Joint Venture), began systematic diamond exploration throughout this region. Their objective was to discover an economic diamond deposit that would be amenable to mechanized, large-scale, low-cost,

Figure 5. Two geologists sample stream gravels in a remote portion of the Kimberley region in Western Australia to locate diamond indicator minerals. The size of the region, and its remoteness, meant that a helicopter was needed to reach sites targeted for diamond exploration. Here, the geologists are excavating a heavy-mineral sample from gravel trapped behind a natural rock dam in a creek. A special geologic laboratory was set up in Perth to evaluate the mineral content of such samples.

open-pit mining. Since only minor quantities of alluvial diamonds had been recovered from this region during the previous century, with no primary diamond sources known at the time, these exploration efforts in the Kimberley craton were highly speculative. Nevertheless, early in 1976, geologists from this consortium found certain minerals (such as ilmenite, chromite, chrome diopside, and pyrope garnet) in stream-gravel concentrates which indicated the presence of diamond-bearing host rocks.

To reduce the need for costly bulk-rock sampling, geologists devised rapid evaluation methods to check gravel samples for these diamond indicator minerals (figure 5). Reconnaissance alluvial sampling using these techniques over an area of 200,000 km^2 revealed a classic suite of kimberlite indicator minerals—as well as a different suite of minerals that are now known to be characteristic of lamproites (although their significance was not recognized immediately)—at several locations within and around the Kimberley craton.

Careful geologic fieldwork, combined with airborne magnetometer surveys and subsequent testing for the presence of diamondiferous host rocks, led to the eventual discovery by a number of companies of more than 80 kimberlite and lamproite occurrences within and around the Kimberley craton. To date, however, only one of these occurrences, the Argyle deposit, has been developed into a mine. Other potentially significant diamond occurrences, which at present are being evaluated for their economic viability, are two lamproites located at Ellendale in the West Kimberley province and two kimberlites in the North Kimberley province. In most of these instances, the diamondiferous rocks were discovered in strongly deformed tectonic belts along the margins of the Kimberley craton, and not within the rocks of the craton itself.

Discovery of the Argyle Pipe and Alluvial Deposits. In August 1979, following almost eight years of geologic exploration in the Kimberley region, two diamond crystals were found in a 40 kg sample of gravel collected in Smoke Creek. Further sampling upstream led to the discovery of alluvial deposits along this creek. Then, in early October 1979, the exploration team reached the headwaters of Smoke Creek, which drains a small northward-facing valley in the Matsu Range, and found a large, high-grade primary diamond deposit in an olivine lamproite that is now referred to as the AK1 pipe (figures 4 and 6). The separate Limestone Creek alluvial deposit was identified two years later, after the completion of further gravel sampling in the area.

GEOLOGIC SETTING OF THE ARGYLE MINE

The Kimberley craton consists of a central core of a thick series of nearly flat-lying sedimentary and volcanic rocks that were deposited between 1.9 and 1.6 billion years ago. These rocks form the Kimberley Plateau. They are underlain by a basement of crystalline igneous and metamorphic rocks, which are not exposed on the surface of the plateau. Recent investigations have indicated that the basement is of Archean age, that is, more than 2.5 billion years old (Graham et al., 1999). This central Archean craton is bounded along its southeastern margin by the Halls Creek Mobile Zone (geographically called the East Kimberleys), and along its southwestern margin by the King Leopold Mobile Zone (geographically called the West Kimberleys; again, see figure 3). Diamondiferous kimberlites have been found on the central Archean craton, whereas diamondiferous lamproites have been found in or near the associated mobile zones. This came as a great surprise to geologists at the time, because—apart from alluvial deposits—significant quantities of diamonds were only known to occur in kimberlites located on Archean cratons (Clifford, 1966; Janse, 1992). The diamondiferous rocks of both types occur as volcanic dikes, pipes, and crater deposits—which are typical modes of emplacement for kimberlite and lamproite magmas (Hawthorne, 1975; Mitchell, 1986, 1989).

Geologic Setting of the Argyle AK1 Pipe. The AK1 olivine lamproite pipe (or diatreme) is located approximately 7 km (4.5 miles) west of the Halls Creek Fault, which forms the eastern boundary of the Halls Creek Mobile Zone (Boxer et al., 1989). This mobile zone is formed by an exposed basement of crystalline metamorphic rocks intruded by later granites, which range in age from 2.5 to 1.8 million years; that is, they are younger than the rocks of the central Archean Kimberley craton. Rocks in the Halls Creek Mobile Zone have been strongly deformed by faulting and folding, and form a landscape of flat plains and low ranges. The northern part of the belt is overlain by northerly dipping sedimentary and volcanic rocks that range in age from 1.5 billion to 500 million years; some of these form the Ragged Range, which rises up to 450 m (1,500 ft) above the basement plain. The Argyle pipe intruded these younger rocks along a pre-existing fault. The diamond deposit was preserved from erosion by resistant outcrops of these rocks, which enclose the upper part of the pipe and the crater. In areas further south, where the host rocks have been eroded, similar pipes and craters have been worn down to a root zone of a few dikes and stringers, such as the Lissadell Road Dike Zone (Janse, 1992). For a discussion of the structures of a pipe and a diatreme, see Kirkley et al. (1991).

Figure 6. This 1983 aerial photograph (looking northeast) shows the valley in the Matsu Range (slightly to the left of center here) where the Argyle AK1 lamproite pipe was discovered after extensive regional exploration for diamonds. Lake Argyle is visible in the distance. The orientation of this photograph, which was taken before diamond-mining operations began, is opposite that of the photo in figure 1. Today, most of this valley floor is occupied by the Argyle open pit.

DESCRIPTION OF THE DIAMOND OCCURRENCE

The AK1 Pipe and a Model for Its Formation. In cross-section, the AK1 pipe exhibits the typical carrot-like structure of a diatreme. When first discovered, the pipe occupied the entire valley floor along Smoke Creek. The pipe itself is not oriented vertically, but is tilted northward at an angle of approximately 30°. Its outline on the surface resembles the shape of a tadpole, with its enlarged "head" to the north and its narrower "tail" elongated in a southerly direction. It is almost 2,000 m (1.2 miles) long, and it varies in width from approximately 600 m (1,950 ft) at the head to 150 m (500 ft) along the tail (see figure 4). This elongate shape is thought to have resulted from post-intrusion faulting and the regional tilting of the pipe.

When found, the AK1 pipe had a surface area of about 50 hectares (~125 acres). However, it is brecciated and fault-bounded on several of its outer contacts, so the original intrusion may have been larger. Radiometric dating (using the rubidium-strontium and potassium-argon methods) of the lamproite rocks within the pipe indicates an emplacement age of 1.178 −0.047 billion years (Pidgeon et al., 1989). The diamonds themselves are age-dated at approximately 1.58 billion years (Chapman et al., 1996). Geologic study has revealed the presence of both tuffaceous and magmatic varieties of lamproite within the pipe (derived from volcanic ash falls and magma crystallization, respectively; Jaques et al., 1986, 1989b,c).

According to a geologic model proposed by Boxer et al. (1989), the lamproite magma that formed the AK1 pipe rose within a zone of weakness in the crust along the mobile belt into overlying quartz-rich sediments. Subsequent interaction of the heated magma with groundwater in these permeable sediments resulted in a series of volcanic explosions

Figure 7. In this view looking northeast from the AK1 lamproite diatreme, one can see the area where initial mining for alluvial diamonds took place, in the loosely consolidated gravels along the drainage system of Smoke Creek.

over an extended period of time, which produced the rocks within the pipe itself. Ejection of large amounts of magma, accompanied by the downward migration of the explosive activity within the pipe, produced a subsidence of the volcanic rocks and surrounding sediments. In turn, this led to the formation of a volcanic crater that eventually filled with groundwater as well as with ash and sediments. More detailed descriptions of the geology of the AK1 pipe can be found in Atkinson et al. (1984a,b), Boxer et al. (1989), Jaques et al. (1986, 1989b,c), Janse (1992), and Smith (1996).

The Associated Alluvial Deposits. As the result of erosion of the orebody over geologic time, diamonds were distributed along the entire length of Smoke Creek (which drains the pipe to the north) from the headwaters (at the pipe) to where the creek enters Lake Argyle (35 km to the northeast; see Deakin et al., 1989). These alluvial diamonds occur in coarse, poorly sorted, massively bedded, and loosely consolidated gravels (figure 7). The diamondiferous areas are divided into the Upper and Lower Smoke Creek deposits, with the former extending the first 2–3 km from the pipe, and the latter extending further downstream. These alluvial beds vary from 1 to 1.7 m (3 to 5 ft) in thickness. Both the Limestone and Gap creeks drain the pipe to the southeast, and their alluvials initially form steep, piedmont fan-type sediments, followed by low terrace and floodplain sediments that can range up to 3.5 m (11 ft) in thickness.

The alluvial deposit contains a range of diamond qualities and sizes, which vary with the distance from the source and the degree of erosion. The ore grade of these alluvial deposits drops off dramatically at distances beyond approximately 10 km downstream from the headwaters of each creek.

ECONOMIC EVALUATION OF THE ARGYLE DEPOSIT

Evaluating Diamond Deposits. As mentioned earlier, diamonds represent only an extremely small percentage of the host kimberlite or lamproite (typically one part per million [5ct/tonne] or less). Determination of the economic viability of a deposit requires an assessment of both the grade of the ore (i.e., how many diamonds it contains), and the average value of the diamonds within the deposit. Both provide a value for each tonne of ore, which is then compared with the costs of recovery and processing to determine if the deposit can be mined economically.

Mining companies face several technical challenges in their attempt to assess the ore grade of a diamond deposit. Since diamonds form discrete crystals that are disseminated at very low concentrations in the host rock, a large amount of material must be sampled (i.e., by large-diameter core-drilling or mechanized excavation) to obtain a statistically significant quantity of diamonds. Such large host-rock samples (each weighing several tonnes) are expensive to excavate and process, especially in remote regions. In addition, numerous drill samples are typically needed to assess the overall spatial extent of the potential orebody.

Evaluating the Argyle Primary and Secondary Deposits. At the AK1 pipe, the mining consortium determined that 2,000 carats would be statistically sufficient to provide an estimate of the value ($/ct) of the diamonds. The evaluation program was conducted between September 1980 and November 1983. First, 182 holes were drilled in a systematic grid pattern both to examine the lamproite orebody and to delineate its outer limits for use in estimating the total amount of ore present (known as the ore reserves). Then, 91 larger-diameter holes were drilled within the orebody to estimate the grade (i.e., carats of diamonds per tonne) in the ore reserves using standard geostatistical methods.

This evaluation program revealed that only the southern part of the pipe was economically viable. The resulting estimate was that 60 million tonnes of ore, containing 6.8 ct/tonne of diamonds (the proven reserves), and 14 million tonnes at 6.1 ct/tonne (the probable reserves), occurred to a depth of 350 m (1,150 ft) below the surface. These ore grades are the highest known for any primary diamond pipe (a typical grade at other mines—such as at the Premier, Finsch, and Kimberley mines in South Africa—is on the order of 0.5 to 1 ct/tonne).

The final step in the evaluation program involved bulk sampling of the lamproite to identify the best mechanical techniques to liberate the diamonds from the host rock. By the end of 1982, approximately 400,000 carats of diamonds had been recovered from 60,000 tonnes of ore.

During the same period as the evaluation study, a feasibility study was undertaken to establish the most economical plan by which the AK1 orebody could be mined to sustain at least a 20-year mine life. As part of both studies, the associated alluvial deposits were tested by a program of systematic trenching. Representative sediment samples collected from these trenches were processed through a small-scale heavy-media separation plant to recover any diamonds. Prior to the start of mining in early 1983, probable ore reserves in the alluvial deposits were demonstrated to be 2.5 million tonnes, with grades between 3.0 and 4.6 carats of diamonds per tonne.

As the result of the evaluation and feasibility studies, the company decided on a two-phase development program: (1) initial mining, using the small-scale plant, to recover diamonds from both the alluvial deposits and the loose rock on the surface above and around the perimeter of the AK1 pipe; and (2) mining of the lamproite orebody itself. Concurrent with the first phase, construction began on a large-scale commercial recovery plant, so that the mine could operate on a 24-hour-per-day, 7-day-per-week schedule, to process ore recovered during the second phase.

Mining of the alluvial and surface deposits began in 1983. By the end of 1985, more than 17 million carats of diamonds had been produced. At that time, exploitation of the AK1 pipe began, with the expectation that the mine would process 3 million tonnes of ore—and as much as 25 million carats of diamonds—per annum. As of January 2000, the remaining proven AK1 ore reserves were 61 million tonnes of lamproite ore with an average grade of 2.9 ct/tonne.

Removal of Overburden. As mentioned above, the diamonds were first discovered at the mine site in a small valley at the headwaters of Smoke Creek. Initial drilling established that the extent of the lamproite pipe was actually larger than the area of this small valley; portions were overlain by hills of the Matsu Range (the ridges on both sides of the valley seen in figure 1). To widen the pit enough to reach these portions, it was necessary to cut back the sides of these hills at a specific angle. Thus, a very large amount of non-diamond-bearing overburden had to be removed, which formed a crucial component in planning the operation of the mine. It costs just as much to excavate a tonne of waste overburden as it does to remove a tonne of lamproite ore.

Drilling and explosives are used to break up the overburden and ore (figures 8 and 9). A large mechanized shovel loads the material into a truck for

Figure 8. Mobile drill rigs at Argyle make holes for the explosives needed to mine the ore.

Figure 9. At Argyle, explosives are used to break up the lamproite ore and its overburden, so that it can be removed more easily.

transport either to the processing plant if it is ore, or to the waste storage area if it is overburden (figure 10). The trucks can haul 180–240 tonnes of rock per load. Five shovels are currently in operation, each of which costs US$7 million; there are 18 trucks, each of which costs approximately US$3 million.

One of the fortuitous features of the Argyle mine is that until recently much of the extracted ore was located above the surrounding plain, so that a "hill" of ore was gradually leveled as mining progressed, rather than the ore having to be hauled up from a pit. The cost of transporting rock downhill (the recovery plant is located in the plain south of the Matsu Range) is substantially cheaper than hauling it uphill. At the mine's present level within the pit, however, approximately 7.5 tonnes of overburden must be removed to reach one tonne of the diamondiferous ore. Eventually, the cost to recover a carat of diamonds will exceed the value of those diamonds, and the mine will no longer be economic. If the lifespan of the mine is to be extended, alternative recov-

Figure 10. A mechanized shovel loads broken rock into a large truck for transport. The human figures in the insets provide some idea of the immense size of both the mechanized shovel and truck.

TABLE 1. Argyle diamond production from primary (AK1 pipe) and secondary (alluvium) sources, 1982–2000.[a]

Production	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	**Total**
AK1 pipe																				
Ore processed (Mt)	—	—	—	0.4	3.2	3.5	4.7	4.9	5.1	6.0	6.8	7.0	7.9	8.9	10.2	10.4	11.2	9.5	10.4	110.1
Diamond production (Mct)	—	—	—	1.7	29.2	30.3	34.6	32.8	31.7	33.4	36.6	38.4	39.7	37.5	39.4	38.6	38.9	27.8	25.4	516.0
Alluvium																				
Ore processed (Mt)	0.1	1.1	1.5	1.1	—	—	—	0.8	1.9	1.3	3.5	3.9	4.6	5.3	6.8	5.9	6.3	5.9	4.9	54.9
Diamond production (Mct)	0.3	6.2	5.7	5.3	—	—	—	1.6	2.1	1.6	2.5	2.5	3.1	2.4	2.6	1.6	1.9	1.9	1.1	42.4
Total diamond production (Mct)	0.3	6.2	5.7	7.0	29.2	30.3	34.6	34.4	33.8	35.0	39.1	40.9	42.8	39.9	42.0	40.2	40.8	29.7	26.5	558.4

[a] *Source: Argyle Business Services. Abbreviations: Mct = million carats, Mt = million tonnes; a dash indicates no ore processed or diamonds produced.*

ery methods (such as underground mining) must be used. At the present time, company management is evaluating how best to proceed with underground mining to ensure optimal cost effectiveness.

RECOVERY OF THE DIAMONDS

Table 1 and the bar chart in figure 11 illustrate the enormous quantity of diamonds produced annually from the Argyle mine. Separating diamonds from kimberlite or lamproite ore requires a primarily mechanical, multi-step liberation process (figure 12). In general, the ore must be broken down into progressively smaller pieces (figure 13), until the diamond crystals can be physically removed with little or no damage. At the Argyle mine, this process involves five basic operations:

1. Crushing the ore (in several steps)
2. Scrubbing the broken rock fragments with water to remove dust
3. Screening the ore into specific size fractions
4. Starting from a particular size fraction of the ore, concentrating the diamonds and other heavy minerals (e.g., garnet) using a heavy medium
5. Separating the diamonds from the other heavy minerals by means of X-ray luminescence technology

In the final step, X-rays are used to make the diamonds luminesce. An optical sensor triggers a blast of air to remove each diamond from the concentrate. These X-ray sorters, which were developed specifically for use at the Argyle mine, can detect approximately 200 diamonds per second at peak sorting rates.

Virtually the entire processing operation is mechanized, with almost all of the machines monitored and managed from a central control room. As a result, very few workers (other than maintenance personnel) can be seen around the processing plant outside the central control room and the diamond recovery building.

SOCIAL AND ENVIRONMENTAL ISSUES

Personnel. Development of the Argyle mine was not limited to technical and engineering challenges; there was also the major issue of obtaining a skilled workforce at the mine site. Because of the mine's extreme isolation, it was decided that, rather than construct a new town to house the mine staff and their families, workers would be brought from Perth (a three-hour flight) for a two-week working shift.

Figure 11. This bar chart shows the amount of diamonds produced on an annual basis at Argyle during the period 1982 through 2000.

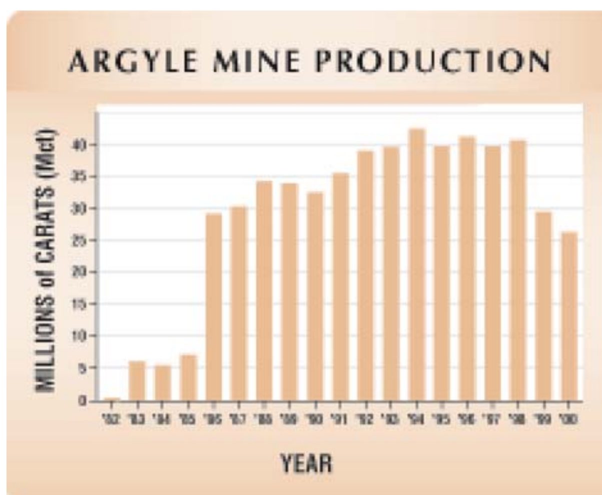

Figure 12. Processing of the diamonds at Argyle is a highly mechanical multi-step process. This view of the processing plant, looking southwest, gives some idea of the size of the operation (which covers 16.3 hectares).

Originally, the mine managers were located at nearby Kununurra and commuted daily by air to the mine; in recent years, this has changed to a weekly commute from Perth. During the mine's peak years, there were some 800 employees. Today, there are some 750 permanent and contract employees and about 300 working on site at any one time. During their two-week shift, workers stay at a permanent village located a short distance from the mine site, where there are both living and recreational facilities. At the present time, mining operations take place on a 24-hour-a-day, 7-day-a-week schedule.

Protecting and Rehabilitating the Local Environment. Efforts to minimize the negative impact of mining operations on the local environment and communities began at the outset and continue to the present time. These efforts include:

1. Minimal disturbance of the local environment (protection of local vegetation, water conservation and reclamation, and regular assessment of water quality in streams and groundwater in the surrounding area)
2. Appropriate consultation with Aboriginal traditional owners
3. Rehabilitation of areas where mining has been completed
4. Limitation of the emission of greenhouse gases
5. Use of hydroelectric power
6. Prompt reporting of any environmental incidents to local authorities

Because of these efforts, the Argyle mine was awarded an ISO (International Standards Organization) 14001 certification in 1997. This provides independent verification that the mine operators are following international best practices with regard to environmental management.

Final Disposition of the Mine Site. Although, as noted above, open-pit mining is planned only until 2006, underground operations could extend the life of the Argyle mine to 2018. Whatever the future operations, eventually the mine site will have to be decommissioned. This will involve removal of the processing plant and all mining equipment, and rehabilitation of the land used for both alluvial mining and waste rock dumps (with regular future monitoring of this rehabilitated land to ensure that any environmental problems are promptly detected and corrected). Vegetation native to the local area is already being replanted on reclaimed land in order to rehabilitate the environment as much as possible to a condition that existed prior to mining. The open pit will be converted into a lake by gradual filling with groundwater.

DIAMOND SORTING AND VALUATION

After the diamond rough is received at the company offices in Perth, it undergoes a sorting process to prepare it for open-market sale. The prices achieved provide the monetary basis from which government royalties can be determined. The rough diamonds are sorted on the basis of size, shape, color, and "purity" (clarity). For sorting of diamonds on such a large scale, broad quality categories had to be established. An overall price was then assigned to each category. For pieces of rough smaller than 1.5 ct, Argyle (with the assistance of an associated company) developed proprietary automatic machines to sort the diamonds by color into 37 price categories, and by purity (clarity) into 104 price categories. These machines are capable of processing 12,000 to 30,000 diamonds per hour. Pieces larger than 1.5 ct are sorted by hand into a wider variety of categories using 2× head loupes or 10× hand loupes. The skills developed were established over a long period of time, based on expertise recruited by Argyle.

DESCRIPTION OF THE DIAMONDS

Table 2 summarizes typical gemological characteristics of Argyle diamonds (modified and updated from Chapman et al., 1996). Several other researchers have published additional scientific and gemological studies of Argyle diamonds (see Harris and Collins, 1985; Hofer, 1985, 1998; Kane, 1987; Keller, 1990; Tombs, 1990; Kaneko and Lang, 1993; Duval et al., 1996).

Typical Production from the Mine. In terms of percentages and quality categories, production consists of 5% gem, 25% industrial, and the remainder termed *near-gem*, which receive substantial processing to extract a normally low-value polished diamond. The near-gem proportion has increased over time as a result of the skills and technology of the diamond manufacturing companies in India. For the associated alluvial deposits, the percentage of

Figure 13. In a roller coaster–like operation, the crushed lamproite ore moves by conveyor belts between different stages of processing throughout the plant. Photo by James E. Shigley.

TABLE 2. Typical gemological characteristics of Argyle diamonds.[a]

Characteristic	Brown	Near colorless to light yellow	Pink to red[b]
Approximate proportion of total	72%	27%	<<1%
Type	Ia	Ia	Ia or IIa
Nitrogen content	100–500 ppm	500–1000 ppm	10–100 ppm
Nitrogen aggregation	B>A	B>>A	A>>B
Color zoning	Planar in one or more (111) slip planes	None	Planar in one or more (111) slip planes
Anomalous birefringence ("strain")	Banded or cross-hatched (tatami) pattern	May show banded or cross-hatched (tatami) pattern	Banded or cross-hatched (tatami) pattern
UV fluorescence	Dull green (LW>SW)	Blue (LW>SW)	Blue (LW>SW)
UV phosphorescence	Dull yellow or inert	Yellow	Yellow
Visible spectrum	Increasing absorption toward the blue region, with 415, 478, and 503 nm bands	415 nm band	Broad 550 nm band; increasing absorption toward the blue region; weak 415 nm band

[a] *Adapted from Chapman et al. (1996), with recent updates from Argyle.*
[b] *Also seen, <1% of total, are blue and green diamonds.*

Figure 14. In the mid-1980s, a marketing campaign was launched to educate consumers about "champagne" and "cognac" diamonds. This program was based on the development of categories of diamonds using the C1 to C7 scale for increasing amounts of brown color. The seven diamonds shown here represent these categories; they range in weight from 0.48 to 0.56 ct. Photo by Maha Tannous.

gem diamonds is higher relative to the other two categories.

The vast majority of this production consists of small, brown to near-colorless diamonds that are labor intensive to polish because of their size. More than 90% are cut in India, destined for use in the jewelry industry (Sevdermish et al., 1998b). As an indication of the size of the mine's production, we believe that each year's polished output would be sufficient to pavé set the entire surface of a tennis court.

Characteristics of the Rough. The mean size of the Argyle rough is less than 0.10 ct (for crystals larger than 0.8 mm). The largest diamond crystal recovered to date (found in late 1991) weighed 42.6 ct. It has been retained in its rough state and now forms part of the company's diamond exhibit at the mine.

More than 60% of the Argyle diamond crystals are irregular in shape. Macles (twins) comprise about 25%, while 10% are naated or polycrystalline aggregates. The remaining 5% either show some resorption, as evidenced by their rounded dodecahedral shape, or are sharp-edged, planar, octahedral-dodecahedral crystals. Approximately 72% of the diamonds are brown, with most of the remaining stones yellow to near-colorless and colorless. Fewer than 1% are the very rare pink, grayish blue, and green diamonds.

Most Argyle diamonds exhibit evidence of having been plastically deformed following formation in the earth's mantle or during their ascent to the surface. This is apparent in their highly strained character when observed with crossed polarizing filters. The plastic deformation is thought to cause both the brown and pink colors, although the exact origins of these colors are still uncertain (Fritsch, 1998, pp. 34–36, 38–40; Chapman and Noble, 1999). Argyle's rough diamonds are commonly recognized by evidence of etching internally and on their surfaces (i.e., etch channels and hexagonal depressions or pits, as well as frosted surfaces).

Inclusions are found in the vast majority of Argyle diamonds (Jaques et al., 1989a). Graphite is the most abundant inclusion, and is generally seen as black spots. Garnet, olivine, and sulfide minerals have also been identified. A high percentage of the included diamonds contain more than one mineral species.

MARKETING OF ARGYLE DIAMONDS

The discovery of the Argyle orebody was greeted with interest, but also with dismay and uncertainty in some quarters of the jewelry industry. As with the introduction of production from any new mine, there were anxieties about the sudden influx of such a large number of diamonds into the marketplace, especially the impact of Argyle material on existing diamond prices. Based on an understanding of established marketing principles, the company's management implemented a phased marketing strategy that ultimately overcame these concerns.

Nature of the Product. Argyle's marketing challenge has always been closely tied to the nature of the diamonds it produces. At the time of the discovery of the mine in 1979, India was emerging as an important cutting center for diamonds, and manufacturers there were anxious for more material (Sevdermish et al., 1998a,b). India also could provide the affordable labor needed to make the mine's production economic. A relationship with the Indian cutting industry became the platform for Argyle's marketing efforts, which focused on bringing the smaller and mainly colored diamonds to the trade. Between 1983 and 2000, manufacturing of diamonds in India grew 201% in volume and 151% in value; these percentages continue to grow (as reported by the Indian Gem and Jewellery Export Promotion council).

Marketing Brown and Pink Diamonds. With the very large percentage of brown diamonds in its production, the company recognized that initially there would be a high level of resistance to this material at the retail level. By setting up a small manufacturing unit for larger (>0.5 ct) brown diamonds beginning in the mid-1980s, the management was able to carefully evaluate the gem potential of this kind of diamond. Efforts to use the large production of brown diamonds proved successful with the introduction of a marketing campaign for "champagne" and "cognac" diamonds throughout the mid-to-late 1980s (using what was called a C1 to C7 scale for increasing amounts of brown color—figure 14). For the pink diamonds, Argyle uses four principal categories: pink, purplish pink, brownish pink, and pink "champagne." These colors are in turn graded according to color intensity in a range from very faint to very intense. Today, the Argyle brown and pink diamonds are widely recognized worldwide.

Figure 15. The Argyle mine has become well known for the small but consistent number of pink diamonds it produces annually. These polished Argyle diamonds illustrate the range of pink colors that may be seen, from Fancy pink (the two round brilliants on the left, 0.81 and 0.55 ct) through Fancy Deep pink (the 0.48 ct emerald cut right of center) to Fancy Intense purple-pink (far right, 0.28 and 0.41 ct). Photo by Jennifer Vaccaro.

Sales Agreements and Marketing Efforts. Between 1983 and 1996, most of the rough diamonds were marketed via two sales agreements with De Beers. The first agreement (1983–1991) helped provide industry and investor confidence in the viability of the mine. It also gave company staff members time to establish expertise in the sorting and valuation of their diamonds, as well as in marketing them. Diamond industry analysis conducted during this period laid the foundation for the market intelligence systems that were eventually developed, and they guided Argyle's later efforts to gain a competitive advantage in the marketplace.

Critical to the company's marketing strategy, from as early as 1983, was the capability to sell some of the diamonds directly into the trade. This capability provided both a check and a confirmation for the rough diamond prices received within the contractual agreements. In addition, company management felt that total reliance on a third party between the mine and the consumer might limit their ability to obtain maximum prices for the rough. The company opened a direct sales office in Antwerp in 1985, and a second representative office in Mumbai (Bombay) in 1989 for customer liaison.

This first sales effort through Antwerp was for the near-gem diamonds, which at the time were considered Argyle's least attractive product. In its second contractual agreement with De Beers (1991–1996), the company incorporated the provision for independent sales of a wider range of product categories, which included all of the pink diamonds and a selection of near-gem material. Market research and manufacturing tests had indicated that the unique merits of pink diamonds (figures 15 and 16), before available only sporadically and in very limited quantities, had not been fully exploited. Although the production of pink diamonds at Argyle was also limited, it was consistent. Therefore, the company set out to add value to their overall production by establishing their pink diamonds as the material by which the Argyle mine would be best known.

In 1996, when the second agreement with De Beers had ended, the company began to market its entire production of diamonds through its Antwerp office. Efforts to build product demand lead to several initiatives, at the forefront of which was the launching in 1994 of the Indo-Argyle Diamond Council (IADC), a cooperative agreement with a

Figure 16. Beginning in 1985, the more exceptional pink diamonds from each year's production at the mine were sold individually in special auctions known as "tenders." These three diamonds were sold at the 1998 (top, 1.45 ct Fancy Intense pink), 1999 (bottom left, 0.59 ct Fancy purplish red), and 2000 (bottom right, 0.50 ct Fancy Deep purplish pink) tenders.

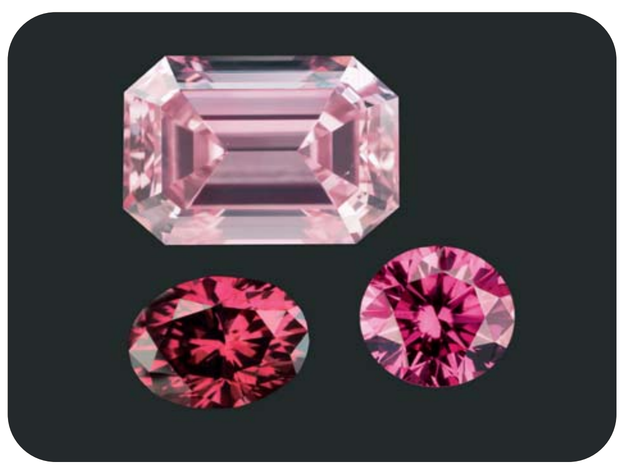

Figure 17. Brownish diamonds, such as the crystals and round brilliants shown here, constitute an important part of Argyle's production. Photo by Shane F. McClure.

number of Indian jewelry manufacturers. Although market research had indicated some reluctance on the part of the U.S. jewelry trade to purchase diamonds and diamond jewelry that originated from Indian manufacturers, Argyle was able to help overcome this reluctance because of its knowledge of the U.S. market and its understanding of dynamics within the trade.

Argyle Pink Diamonds. Beginning in 1985, the more exceptional pink (to red) diamonds from each year's production were sold individually at special auctions known as "tenders." Viewings are held in New York, Sydney, Tokyo, Hong Kong, London and Geneva. These events were held for invited clients. Each was preceded by the distribution of a tender catalogue. The size of these polished pink diamonds averages about one carat; around 40 to 50 carats are sold at these auction events each year (see, e.g., "Argyle Diamond's pink diamond tender 1985–1996," 1997), with prices achieved typically in excess of US$100,000 per carat. To put the true rarity of these special "pink" diamonds into perspective, of every million carats of rough diamonds produced at the mine, a mere one carat is suitable for sale at one of these auctions. Since 1985, more than 700 stones have been offered for sale at the tender at a total weight of almost 550 carats (again, see figure 16).

CONCLUSION

The Argyle mine is a good example of a modern, open-pit mining operation where diamonds are recovered economically on a large scale. Its discovery produced a new understanding among geologists of the conditions of diamond occurrence. As with diamond deposits in other remote regions, development of this mine required innovative solutions for processing the lamproite host rock and constructing the needed infrastructure. In 2000, the mine produced 26.5 million carats of diamonds from approximately 15 million tonnes of lamproite ore processed. Manufacturing of this immense quantity of diamonds, mainly in India, has provided an abundant supply of smaller, mainly brown to near-colorless diamonds for use in less expensive jewelry. The company's "champagne" and "cognac" marketing campaigns stimulated increased sales of brown diamonds in the jewelry trade (figure 17). High-profile auctions of the very rare pink to red diamonds continue to capture trade and consumer attention. ●

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