Feature

Diamonds: geology, gemmology, technology

Diamonds – rough stones, cut stones, host rocks, historical jewellery, contemporary jewellery, and hi-tech materials – were the stars of an exhibition at the Natural History Museum in London in 2005, the biggest of its kind the Museum had ever staged. Why diamonds are so rare, how they have been valued through history, and the links between the unique properties of diamond and its use were the key themes of the exhibition.

Andrew Fleet, Alan Hart and Frances Wall
Department of Mineralogy,
Natural History Museum,
Cromwell Road, London,
SW7 5BD, UK
a.fleet@nhm.ac.uk

Diamonds are rare for three reasons: they form deep within the Earth in very localized places beneath continents; an extremely unusual kind of volcanic activity is needed to bring them to the surface; and then only about 20 per cent of them are of gem quality, the remainder used for a variety of industrial uses.

Diamond formation may have been favoured by conditions occurring in the relatively young Earth because many, though not all, diamonds which are mined formed around three billion years ago; just one-third of the Earth's current lifespan. Most diamonds formed at a depth of 140–200 km, near the base ('keels') of the oldest parts, the cratons, of the Earth's continents (Fig. 1). These ancient continental areas have seen little geological change for at least the last 2.5 billion years. Thickening of these geologically stable crustal areas has ensured that diamonds could form at the unimaginable pressures of more than 45 thousand times that of the Earth's atmosphere, and furnace-like temperatures of above 950 °C. Yet the exact process that forms diamonds is still unknown. At shallower depths, under lower pressures and temperatures, pure carbon remains in the form of soft graphite, rather than its harder cousin. There is good evidence that diamonds were not simply formed by metamorphic (high pressure, high temperature) alteration of graphite to diamond, but were more likely to have formed by precipitation from a carbon-bearing melt, or by precipitation from a carbon dioxide, carbonate or methane–bearing fluid moving through the mantle.

We do know that diamonds are brought to the surface by rare volcanic eruptions of kimberlites and lamproites (silicate magmas which have less silica but more potassium than a typical basalt, and which are rich in dissolved carbon dioxide). These magmas originate in the Earth at depths of more than 150 km, probably at the base of, or just below, the thickened plates of the cratons, far deeper than other volcanic magmas. They find their way through fractures in the overlying rock and scavenge pieces of debris from these rocks as they ascend. Among the debris are diamonds.

The magmas begin rising at the speed of a slow-moving car (10–30 km/h) and end up travelling one hundred times faster. This acceleration is essential in ensuring that the diamonds neither alter to graphite as the pressure and temperature decrease, nor are oxidized to carbon dioxide. Initially the magma is

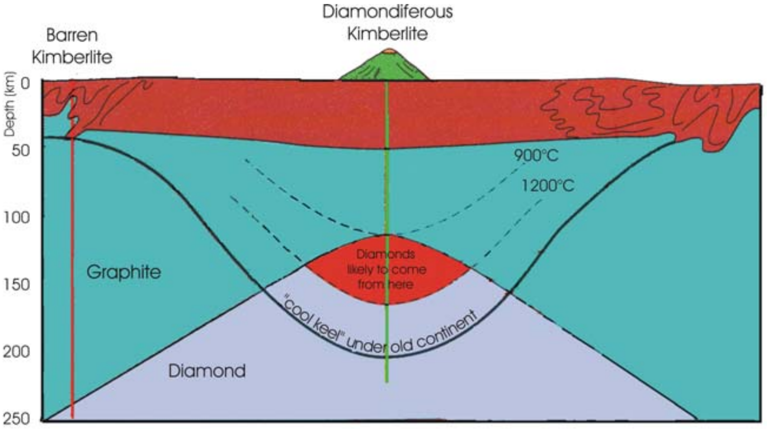

Fig. 1. Cross-section of the continental crust and mantle below showing the 200-km thick 'cool keel' in which there is a stable environment for diamond crystallization. Kimberlite eruptions carry diamonds from here to the surface. Modified and redrawn with permission of Cambridge University Press from *The Nature of Diamonds*, edited by G.E. Harlow.

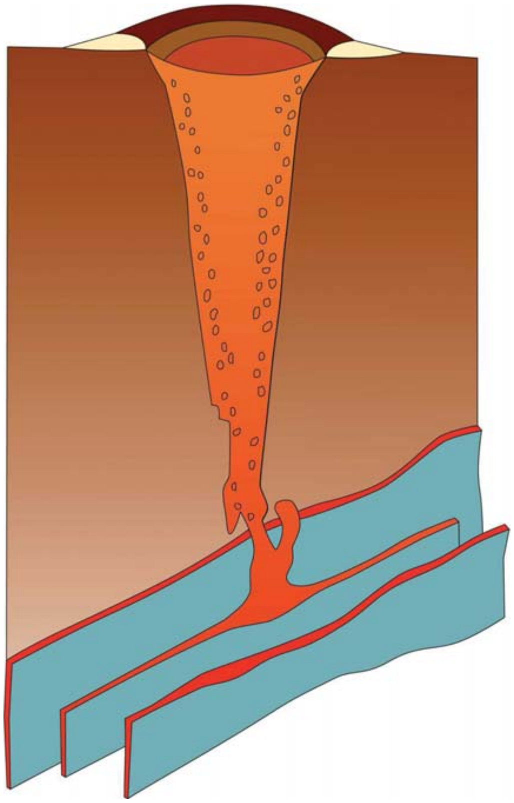

Fig. 2. Cross-section of a typical kimberlite diatreme pipe. Deep down the kimberlite was travelling as a series of dykes. The 'carrot-shaped' profile starts from about 2.5 km where gases exsolved from the magma and blasted the kimberlite the final distance to the surface. Redrawn with permission of Cambridge University Press from *The Nature of Diamonds*, edited by G.E. Harlow.

about as viscous as toothpaste. As it nears the surface, the pressure lessens and dissolved carbon dioxide comes out of solution, like a freshly opened bottle of champagne, blasting the magma to the surface and forming a carrot-shaped 'diatreme pipe' (Fig. 2). Different eruptions may follow one another through the same pipe at intervals from days to millions of years apart. Such eruptions have occurred throughout the Earth's history but, as explained above, are not linked to the actual process of diamond formation. The kimberlites that brought the diamonds of South Africa to the surface erupted during the last 100 million years, and are about three billion years younger than the diamonds that they contain. Only about 6000 pipes formed by such eruptions are known and only about one in every 200 pipes contains diamonds in economic quantities. No person has ever witnessed a kimberlite or lamproite eruption; the last occurred about 47 million years ago (Fig. 3).

Despite their undoubted explosive power, the largest kimberlite volcano, Mwadui in Tanzania, is only 146 hectares in area, just 2 per cent of the size of Mount St Helens. Kimberlite volcanoes have shallow craters which are surrounded by low tuff rings of debris thrown out by the volcano. These debris cones are relatively easily eroded by running water, and the material is washed back to fill into the crater or carried away by streams and rivers. Over time the pipes themselves are eroded, or covered by sediments such as desert sands or the debris from ice sheets. Some of the diamonds eroded are either incorporated in the alluvial deposits of rivers, or transported to the sea where they may be carried along the coast or across the sea-floor by prevailing currents.

Exploring for diamonds

Everything about the formation of diamonds and kimberlites and lamproites makes them difficult to find. They are restricted to the oldest areas of the continents, notably areas of southern Africa, Russia, Australia, eastern South America, Canada and southern India – and within these vast areas looking for the small, rare kimberlite and lamproite pipes is like looking for the proverbial 'needle in a haystack'. All the early finds of diamonds were from river gravels. Diamond-bearing pipes were not discovered until 1871 when prospectors in South Africa followed up chance finds made by local people. Today, chemical analysis is used to identify 'indicator' minerals (garnets, chromites, pyroxenes of certain composition which formed with the diamonds but are more abundant) that can be found in sediments above and downstream from where the pipes occur. In some cases, geophysical tools, which measure resistivity and magnetic field, can be used to identify anomalous areas which might suggest the presence of diamond-bearing pipes.

Fig. 3. Artist's impression of a kimberlite eruption; no one has ever witnessed an eruption of this kind. Created by N. Russell and colleagues, and used with his permission.

Fig. 4. 'The Aber Diamond'. This 1.76 ct diamond was found in a core of kimberlite taken from a discovery drillhole in the Diavik property, Northwest Territories, Canada. The discovery led to development of the Diavik Mine and helped set off the Canadian diamond rush. Aber Diamond Corporation Collection. © 2005 Natural History Museum.

Even when located, very few pipes contain diamonds in economic quantities. Samples from across a pipe have to be retrieved by drilling to prove the presence of diamonds in economic quantities (Fig. 4). Something like 0.8 grams (4 carats) of diamonds in every tonne of rock (think of that ratio!) is a high grade of discovery. Finding river or marine sands and gravels with sufficient diamonds to justify an extraction operation involves similar careful exploration, sampling, evaluation and risk.

Even more rare diamonds

Not all diamonds from the Earth's interior have formed from primordial (original) mantle carbon. A minority are derived from the carbon of organisms and carbonate minerals formed at the Earth's surface and carried into the mantle by descending tectonic plates, only to be brought back again by kimberlite and lamproite volcanoes. These diamonds are associated with eclogite, a rock consisting of the minerals garnet and pyroxene, which formed from ocean-floor lavas carried in the descending plates. Eclogite boulders in kimberlite pipes may contain as much as 10 weight per cent diamond.

Even more rare, are diamonds formed where continents collided due to plate tectonic processes. Occasionally these collisions carried carbon-containing surface rocks to great depths, where they experienced the ultra-high pressures necessary to form diamonds, before being brought rapidly to the surface by plate tectonic forces – with their diamonds still intact. Such diamonds, though, are tiny 'microdiamonds', measuring only a few tens of micrometres in diameter (a human hair is about 100 micrometres in diameter).

Over the last 20 years or so scientists studying diamonds have discovered that a few formed at depths as great as 700 km. These are invaluable as they provide the only 'samples' of the deep Earth that we can ever see. They often contain tiny inclusions of other minerals from the surrounding mantle, incorporated in the diamond as it crystallized. Although the inclusions generally measure only a few tenths of a millimetre, they can be studied to give us clues as to what the Earth is like at depths of hundreds of kilometres. These mineral fragments tell us, for example, that the mantle down to about 700 km has old ocean floor, carried there by descending plates, mixed in with peridotite which was formed as the Earth grew.

The ultimate sources of all the carbon incorporated into the Earth were stars that grew and disintegrated before the solar system even existed. Carbon formed in these stars when hydrogen and helium fused together by a process known as nucleosynthesis. Most solar system carbon has now taken part in innumerable reactions and processes, but some, in the form of nanometre-sized diamonds, is still found in the same form as it when it was first incorporated. These diamond samples from the ancient universe are found in 'primitive' meteorites and are the rarest of all diamonds. Astrophysicists also find other evidence of diamonds in stars; one recent discovery suggested that a 4000 km-wide 'white dwarf' (a collapsed star) in the Centaurus galaxy consists entirely of diamond.

Other meteorites have created diamonds on impact with the Earth by generating high pressures, shock waves and vaporization. Examples occur in the building stone that makes up the walls of the town of Ries in Germany. The 'suevite' impact rock contains tiny diamonds generated when the area was hit by a meteorite 15 million years ago.

Revealing the beauty of diamonds

The carbon atoms which make up diamond are densely packed in a regular array held together by strong bonds. This is reflected in the relatively high density and extreme hardness of diamond, and despite being the hardest natural material known, its structure allows it to be perfectly cleaved in four directions. This property is exploited by cutters who use the extreme optical properties of diamond in the way it reflects, bends and disperses light in order to achieve the maximum brilliance and 'fire' of their final cut gemstone (Fig. 5).

Conventionally diamonds have been valued for being colourless and clear. At the moment though coloured stones, like many of the major stones that appeared in the 2005 exhibition, are fashionable (Fig. 6). These so-called 'fancy coloured' diamonds are rare: estimates suggest that, depending on the

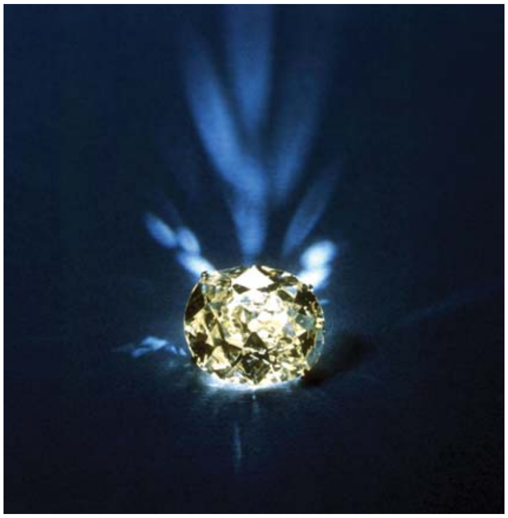

Fig. 5. The Eureka, a 10.73 ct yellow diamond cut from a 21.25 rough stone which, in 1866, was found in cemented river gravels and is the first diamond to have been recorded coming from South Africa. © De Beers.

Fig. 6. Additions. A collection of 36 coloured gems, total carat weight 35.72, made over the last 7 years by Alan Bronstein and Harry Rodman to add to their famous Aurora Collection of 260 fancy coloured diamonds. © Aurora Gems.

Fig. 7. 'Run of mine'. A sample of a parcel of diamonds from a South African mine showing the wide variation in colour and size. © Diamond Trading Company.

source, between about 1 in every 500 to 1 in every 10 000 gem-quality diamonds is coloured (Fig. 7). In some cases, the colour results from the presence of tiny amounts of elements other than carbon, e.g. the presence of nitrogen, producing yellow hues, or the presence of boron-creating blue ones. Other colours result from atomic-scale defects in the diamond structure; pink and red diamonds are typical of this. Green diamonds are produced by radiation damage of the structure; a rare natural phenomenon which can, however, be imitated in the laboratory. Black diamonds are 'coloured' by the presence of mineral inclusions, or can be produced by irradiation.

Diamonds in history

Prior to the eighteenth century, diamonds were known only in Asia, and particularly from India. Recent evidence suggests that fine diamonds were being used to polish high quality stone axes in China as early as about 2500 BC. A few diamonds reached the classical worlds of Greece and Rome, but these were just small, unworked octahedral stones that were used in rings (Fig. 8). They were thought, because of diamond's hardness, to ward off illness, poisoning and madness.

Diamonds from India reached Europe in later medieval times and were used to adorn the rich and powerful. In the fifteenth century, cleavage or grinding of an apex of the octahedron and polishing were introduced, probably from India, to form table cut stones, which were used in rings and jewellery. During the sixteenth century diamonds began to be used both in crucifixes and other religious objects, and more widely in the secular jewellery of the rich. In the seventeenth century diamonds became very much a fashion statement for European courtiers (e.g. the diamond earrings of 'The Three Musketeers') and European traders began to visit India specifically to seek diamonds and other gems to supply this market.

By about 1700 the supply of diamonds from India to Europe began to dry up. Discoveries of diamonds in the river gravels of Brazil in 1720 replaced this dwindling supply, and the Portuguese rulers of Brazil

Fig. 8. Gold Roman ring with uncut diamond, dating from late third – early fourth century, one of the earliest known diamond rings. From the Zucker Family Collection/Precious Stones Company (New York). © 2005 Natural History Museum, London.

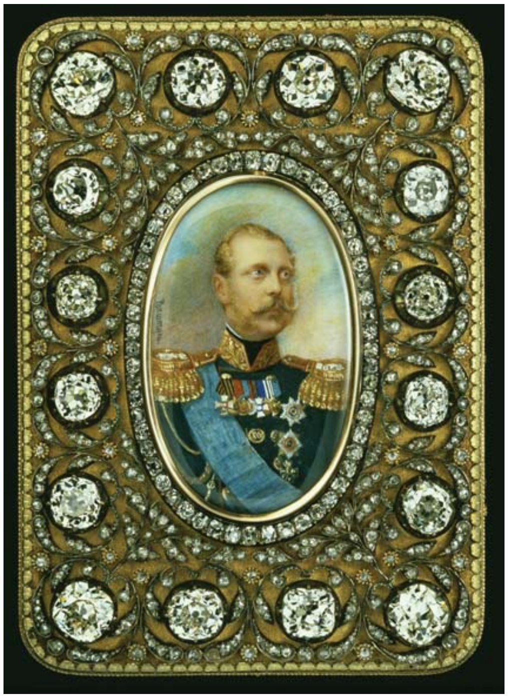

Fig. 9. The Murchison snuff box made in Russia in 1867. The box is set with 16 large, old brilliant-cut diamonds in a design of smaller rose-cut diamonds. The portrait is of Czar Alexander II who presented the box to Sir Roderick Murchison in recognition of his geological exploration in Russia. © 2005 Natural History Museum.

gained a monopoly in supply which they franchised, notably to Dutch merchants. These diamonds continued to be used for royal regalia and the jewellery of the privileged but they also became everyday adornments for the very rich, being incorporated into buttons and shoe buckles.

During the first half of the nineteenth century diamonds again became in short supply while new wealth, fuelled by spreading industrialization and new fashions for floral jewellery increased demand (Fig. 9). The discovery of diamonds in South Africa in the 1860s initiated a diamond ‘rush’ which was able to meet this demand, and which still forms the basis of the modern diamond trade (Fig. 10). The ‘rush’ was triggered by the discovery of alluvial diamonds, but the primary source of diamonds, the kimberlite pipes, was recognized in the early 1870s.

In the twentieth century new markets opened up for diamonds in North America and throughout the world. While high value gave aura and mystique to diamonds for the rich, affordable diamonds also became available to the many. New mines in a number of countries and new alluvial workings met the increasing demand. Botswana became a major producer and deposits were found elsewhere in Africa, sometimes tragically fuelling conflict. Diamonds from Russia added to the supply and the discovery of diamonds in lamproites in Australia opened up new exploration opportunities. Most recently new resources have been found under the glaciated terrain of northern Canada.

Making diamond

Diamond has fascinated scientists and technologists since 1797 when the English chemist Simon Tennant showed conclusively that diamonds consist of pure carbon. From early in the nineteenth century attempts were made to make diamonds in the laboratory. At first these were driven by scientific curiosity but later industrial need became the incentive. Early experiments were hazardous. James Hannay, a Scottish chemist, regularly reduced his laboratory to ruins as he tried to generate the high pressures needed to form diamond by heating oil in iron tubes. Eventually he found some tiny diamonds in one of his experimental runs and in 1880 claimed to have synthesized diamond. Nearly a century later, in 1962 these were shown to be natural, rather than synthetic diamonds. Possibly a sense of self-preservation led one of Hannay’s employees to ensure that diamonds were found!

In the 1940s industry began developing safe, high-pressure apparatus and two companies made a simultaneous breakthrough in the creation of

Fig. 10. ‘The 616’, a 616-carat uncut octahedral crystal from South Africa; the largest single diamond crystal in the world, greater in weight than any known cut diamond today. It came from the Dutoitspan Mine in Kimberly, South Africa. © De Beers.

synthetic diamond. Late in 1954, scientists at General Electric in the USA were able to show in a series of repeatable experiments that they could synthesize diamond. The previous year ASEA, a Swedish company, had achieved the same feat but for reasons that are unclear had made no announcement. The General Electric experiments were run at pressures of 100 000 atmospheres and 1600 °C. What proved critical was to have a metal such as iron present in the apparatus as well as carbon. With their first patent, General Electric claimed that diamond could be synthesized from any carbon-rich material, and to justify their claim their scientists made diamond from a wide range of substances including crunchy peanut butter! High pressure, high temperature processes for making diamond became established on an industrial scale in the early 1960s. Synthesis by explosive shock was also developed by some companies. Together these processes are used today to provide large quantities of small diamonds for industrial use.

Diamond, the hi-tech material

The hardness and resistance to wear of diamond means that it has found many uses in abrasive and cutting tools, from oil-field drilling bits and saws for stone to manufacturing machinery and polishing pastes. Diamond is routinely manufactured and used for such purposes along with the 80 per cent or so of diamonds mined each year which are not of gem quality. However, diamond technology is not just dependent on the fact that diamond is the hardest known substance, as the gem also conducts heat readily, expands and contracts little with changing temperature, transmits light and other electromagnetic radiation with great efficiency, and is resistant to a wide variety of chemicals. Any one of these properties would make diamond a valuable material, but together they give it some unique technical uses.

In the mid-1980s, a process of diamond manufacture called chemical vapour deposition (CVD) opened up new industrial uses. CVD does not rely on high pressures but on high temperatures of over 2000 °C which are used to react a gas mixture containing methane. The process ‘fools’ the carbon present to deposit as small crystals of diamond, rather than as graphite – the most stable form of carbon at low pressures. The resulting diamond, usually deposited as a thin wafer on silicon, consists of a dense mass of small crystals. The particular benefits of the CVD process are that it provides diamond which can be grown to variable, often considerable, sizes and made to a specified purity.

Ultrathin diamond blades can be made for surgical and laboratory instruments (Fig. 11); an ultramicrotome blade used to cut very thin slices of organic tissue for examination in electron microscopes could divide the thickness of a banknote 4000 times!

Fig. 11. Surgical scalpel with blade of optical grade CVD material. Laser light can be directed through the crystal to cauterize as the scalpel cuts. © Element Six Ltd.

Diamond’s combination of properties are also exploited in other ways. The Venus space probe used a natural diamond measuring 18.2 mm in diameter and 2.8 mm thick as a window for some of its apparatus and CVD diamond windows are used in applications ranging from industrial plants to guided missiles. We all may eventually have diamond working inside us: the biocompatibility and wear resistance of diamond make it a good potential material for artificial hip joints, and looking further ahead, if diamond can be made into a semiconductor, we could have diamond ‘biosensors’ watching for signs of disease and even tiny diamond electronic computers and machines moving around inside us repairing damage.

Looking to the future, high quality mined diamonds will continue to provide rare gems for jewellery, whether for engagement rings or for rich extravagancies, as they have over the centuries. Most mined diamonds, though, and a range of synthesized diamond are likely to find increasing use in industry and science for tackling a host of established and new technical problems.

Suggestions for further reading

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