

Diamond indicators



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Towards the end of the 19th century, diamond mining in the Vaal River of South Africa reached such a feverish pitch that prospectors were forced from its crowded river banks and led to discover, by sheer accident, kimberlite – the volcanic host rock for diamond. Since that first discovery in 1870, hundreds of kimberlites have been found. Nearly all of them were discovered through the systematic analysis of kimberlite indicator minerals.



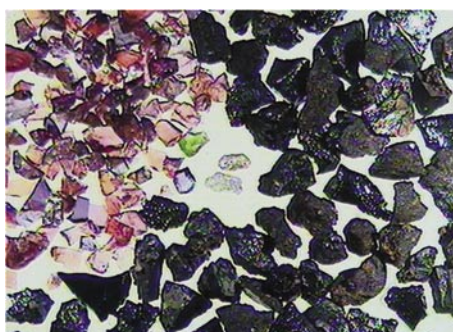
Unlike any other geochemical or geophysical tools used in diamond exploration, the analysis of indicator minerals can identify potentially economic diamond deposits that may be hundreds of kilometres from the exploration sample site. Diamond indicator minerals were formed under similar conditions to diamond, but are significantly more abundant, and so more easily found in an exploration sample. The few indicator grains that may make or break a discovery are sampled in the field, concentrated in the laboratory, and identified under the microscope. However, finding indicator minerals, prioritising them by chemistry and tracking them back to their source are not simple tasks.

Indicator geochemistry is certainly not infallible and numerous kimberlites exist where diamonds are absent in the presence of good indicator chemistry, or are present when the chemistry is poor. The dispersion of indicators into the secondary environment is a complex interplay of weathering and erosion, for which increasing indicator abundance cannot simply be associated with a proximity to the source.

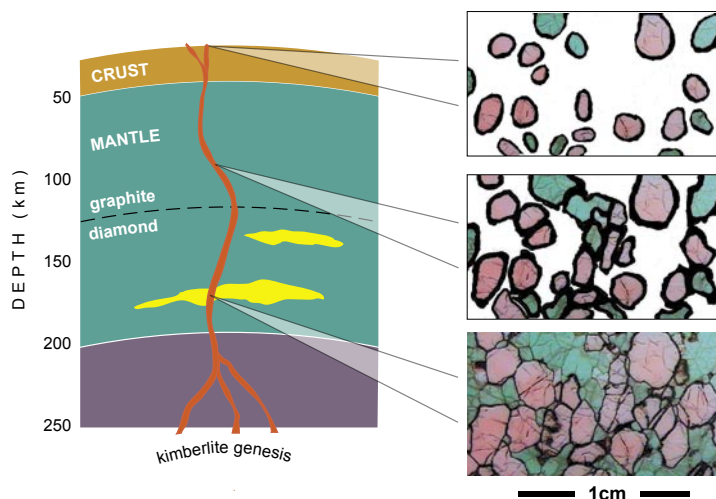
Of all indicator minerals, diamond itself has historically been the most useful in locating primary igneous hosts for diamond. The

experience at the Vaal River bore this out as the prospectors who found Dutoitspan only stopped to dig there because diamonds had been spotted on the ground. By the end of the nineteenth century minerals other than diamond became recognised as important indicators for diamond deposits. Pyrope, ilmenite, and chrome diopside were the principal candidates, and these were the minerals that were systematically tracked up one of the minor tributaries of the Pienaars River leading to the discovery the world-renowned Premier kimberlite.

Formation: Most indicator minerals, including diamond itself, actually form deep in the Earth's upper mantle, at pressures and temperatures greater than can be achieved in the crust. The upper mantle consists mainly of the olivine-rich rock known as peridotite, (after the old term *peridot* used by jewellers for gem-quality olivine), and it is in this parent rock that most diamond forms. However, the zones containing diamond are either rare or are rarely encountered by kimberlite magma. Of the hundreds of kimberlites discovered, very few contain sufficient diamond to warrant a diamond mine.



The classic kimberlite indicator mineral suite with garnet (red), chrome diopside (green), picroilmenite (black), and two diamonds at centre.



A cross-section through the upper mantle shows kimberlite genesis at depth, which passes through diamond-bearing zones of the mantle (yellow). The kimberlite magma dissolves the parent rock and reacts with the melt to form kelyphite rims (black) on the minerals, as shown on the inset. Physical transport to the surface further disaggregates and disseminates the parent rock, leaving indicator minerals that are then dispersed into the secondary environment.

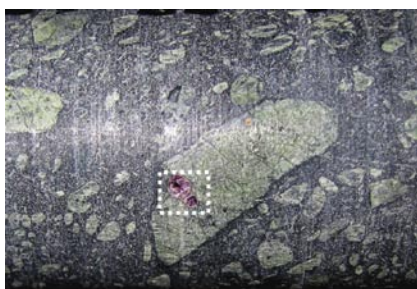
When kimberlite magma forms it is significantly less dense than the surrounding solid rocks and so it blasts its way through them on its ascent to the surface. If zones of diamond-bearing rock are in its path, they become fragmented and incorporated into the kimberlite magma. The fragments ('xenoliths') are foreign to the magma and are not in chemical equilibrium with it. The magma immediately begins to dissolve the xenoliths, destroying the constituent minerals, including diamond. It is only because kimberlites ascend at such a rapid rate, estimated from tens to hundreds of meters per second, that diamond is preserved. The one indicator mineral that may actually form in kimberlite and is not derived from a mantle parent rock is chromian picroilmenite (picroilmenite).

The diamond indicator suite:

Mantle-derived rocks, especially the parent rocks of diamond, are uniquely rare at the Earth's surface. The indicator mineral chromian pyrope is particularly rare, iron-rich ilmenite is commonly found on the Earth's surface, but picroilmenite is relatively rare. However, chromian diopside, chrome spinel and forsteritic olivine can occur in a wide variety of mantle rocks exposed on the Earth's surface following the upheaval of tectonic plates. These minerals are also found in other mantle-derived igneous rocks that reach the Earth's surface, but which are too hot or ascend too slowly to transport diamond. Fortunately, in most cases these are found on the younger margins of continents, whereas nearly all kimberlite diamond mines are positioned in the older cratonic centres. Hence, indicator minerals found in samples

collected from the cratonic portions of continents, are most likely derived from kimberlite. The eclogite indicators pyrope-almandine and omphacite are more challenging because both can occur in some crustal rocks exposed at the earth's surface.

Recovery: The amount of material that must be examined for indicator minerals is greatly reduced by exploiting the densities and magnetic properties of the different minerals. The mineral grains of an exploration sample are passed through heavy liquids and magnetic separators. Mixing the mineral grains into specialised 'heavy' liquids (high densities) enables crustal minerals with relatively low densities to float while indicator minerals, which have densities greater than 3 g/cm³, to sink. There are, however, some crustal minerals with densities greater than 3 g/cm³ (often with iron-rich compositions). However, owing to the presence of iron, these crustal minerals can be removed using a strong magnetic field to leave the indicator minerals, which are not generally magnetic.



Remnants of a garnet harzburgite diamond parent rock (light green) are disseminated through this kimberlite (dark blue). Pyrope is the largest fragment in detail a light brown kelyphite rim.

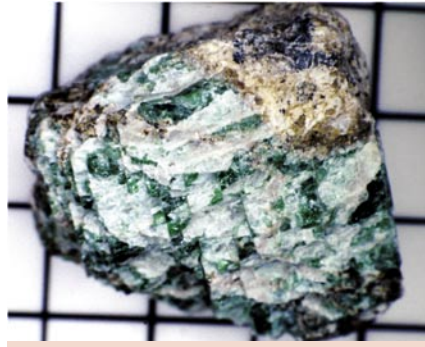
Characteristics of Indicator Minerals:

There are several unique physical characteristics that make indicator minerals effective in diamond exploration. They are distinctive in appearance, rare in crustal rocks, physically separable from other minerals by metallurgical techniques, and resistant to weathering and transport. When preserved, their surface features can reveal whether the deposits being sought are the product of single or multiple cycles of weathering and transport.

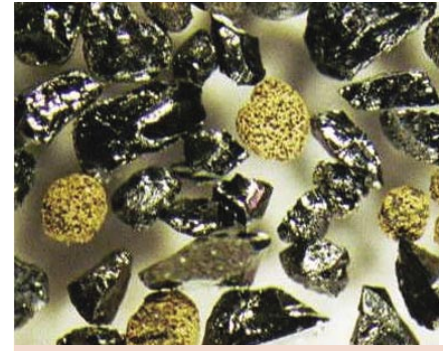
Indicator minerals develop distinctive physical features both in the mantle and during their ascent in the kimberlite. These include fractures and shells of particular appearance. On silicate indicator minerals a kimberlite reaction product forms a shell called *kelyphite*, whereas on picroilmenite and less often on chromite the shell consists of calcium and



A pyrope nearly 3 cm in diameter has numerous parting planes that are altered. This grain will break down quickly in the secondary environment to produce indicator grains only a few millimetres in diameter.



A chrome diopside is also nearly three centimeters in diameter but has cleavage planes filled with altered material. It will also break down quickly



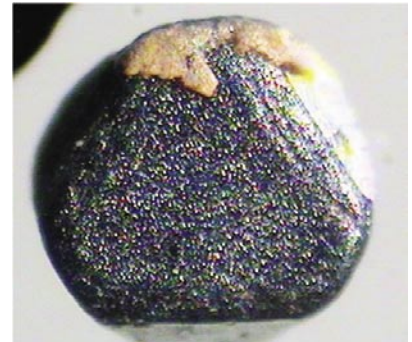
Smaller picroilmenite grains are still coated with tan coloured leucoxene rims, whereas larger grains have no rims, possibly because larger grains will lose their rims more rapidly.

or titanium oxides referred to as *leucoxene*. Beneath the kelyphite or leucoxene a subdued surface pattern develops which is called 'orange peel' because of its texture.

The primary features observed on indicator minerals are important because they are systematically modified by weathering and transporting actions as the minerals enter the secondary environment after reaching the Earth's surface. Weathering consists of physical weathering, where mineral breakdown occurs largely as a result of freezing and melting of water, and chemical weathering, caused by chemical reactions of minerals with water. Chemical reactions proceed more easily at higher temperatures; so chemical weathering dominates in temperate to tropical environments, but in arctic or arid conditions, physical weathering of indicator minerals will dominate. In nearly all

environments, some combination of the two modes occurs.

Each indicator mineral responds differently to weathering and transport. For example, soft and friable kelyphite and leucoxene shells are removed from their igneous host as a result of weathering and transport. Chrome diopside can rapidly undergo weathering along cleavages in



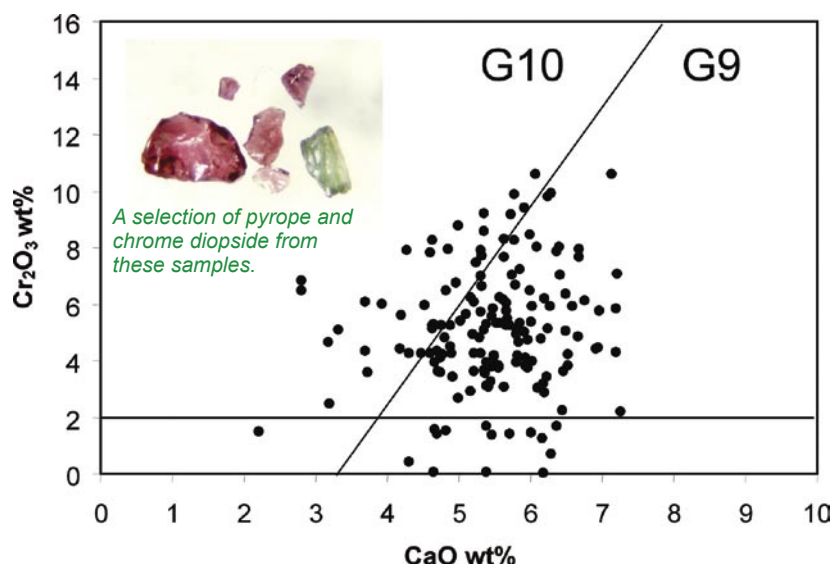
A single octahedral chromite grain with a remnant of leucoxene rim and a textured (orange peel) surface.

tropical climates and is quickly removed from the indicator exploration suite under such circumstances. With extreme chemical weathering, the silicate indicator minerals are vigorously attacked along their 'parting' surfaces leaving only picroilmenite, chromite, and diamond to lead the explorer back to an igneous host.

Indicator Chemistry: In the mid-1960s the invention of the electron microprobe made indicator minerals significantly more important. The electron microprobe provides non-destructive chemical analysis of small mineral grains, including mineral inclusions extracted from diamond. Scientists in South Africa and in the former Soviet Union soon recognised that pyrope inclusions in diamond have uniquely 'restricted' compositions with respect to calcium (as CaO) and chromium (as Cr₂O₃). The simplest and most widely used relationship is the 'G10' or 'Gurney Plot' developed by Dr. John Gurney. He recognised that pyrope grains correlate



The modern kimberlite indicator suite.



Pyrope grains from exploration samples that led to the discovery of the Ekati diamond mine plotted in terms of calcium and chromium. The diagonal line separates diamond-favourable G10 garnets on the left from less favourable G9 garnets on the right. The number of grains in the G10 region was significant at the time, and prompted a 600 kilometre search for the source of the indicators.

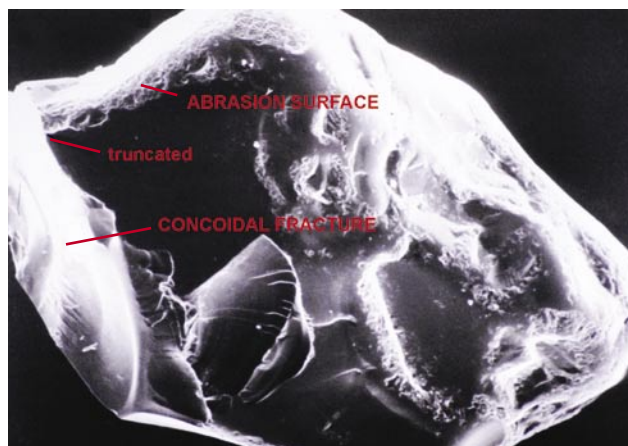
positively for CaO versus Cr₂O₃, except for some that clustered to the side of this dominant trend. These pyrope grains were similar in composition to pyrope inclusions in diamond, and were more common in mine concentrates of economic kimberlites. Dr. Gurney placed a line at 2% Cr₂O₃ to exclude low-Cr pyrope from consideration, then plotted a second line to include most of the better composition pyrope. He then determined that 15% of the data points were within this preferred region, whereas 85% were outside the area of interest. This 85% line became the boundary that separated the diamond-favourable G10 pyrope from the more commonplace G9 pyrope grains. This simple plot became the driving force leading to the discovery of the world-renowned Ekati diamond mine in arctic Canada.

Target prioritisation:

Although uniquely restricted compositions are found in pyrope grains recovered from mine concentrates of economic kimberlites, they are rare in kimberlites devoid of diamonds. The recognition of a unique chemistry for diamond's co-genetic pyrope was a significant advancement in diamond exploration, because kimberlite target areas could now be prioritised on the basis of pyrope compositions from exploration samples. Even more strikingly, the pyrope with compositions most similar to those included in diamond occurs as a bluish purple variety. For a diamond explorer with an eye trained for subtle colour variations, diamond potential could be gained from visual inspection of the pyrope colours in

the samples without the need for microprobe analysis. However, as the microprobe became cheaper and faster to operate, visual identification of the classic indicator minerals became less stringent as final confirmation ultimately rested upon the chemical analysis.

Significant compositional discoveries then followed for other indicator minerals. Chromite inclusions in diamond have restricted MgO and Cr₂O₃ contents, and similar grains can be found in abundance in economic kimberlites. Though not derived from a diamond parent rock, picroilmenite from economic kimberlites have increased relative MgO and Cr₂O₃ contents at the expense of FeO and Fe₂O₃. The picroilmenite seems to record the diamond-destroying ability of a kimberlite since greater Fe₂O₃ content indicates an oxidizing, reactive composition that is not conducive to diamond preservation. For the first time, prioritization of exploration areas could be accomplished based on the chemistry of pyrope garnets in the samples.



This pyrope is devoid of orange peel texture, and shows abrasion surfaces truncated (arrow) by a new conchoidal break suggesting extensive transport from its igneous host.

Since indicator minerals are orders of magnitude more abundant in kimberlite than diamond, analysing indicators from only 50-100 kg of kimberlite could qualitatively assess diamond potential without immediately processing tonnes of kimberlite. For recent kimberlite discoveries, the assessment was determined by comparison of its indicator mineral chemistry to that of kimberlites with known diamond grades. It became important to sample every kimberlite, diamondiferous and barren,

in order to assess properly the indicator chemistry for new discoveries. Hence, diamond exploration companies amassed huge indicator chemistry databases, both from published sources and from surreptitious sampling expeditions.

The electron microprobe also confirmed that the chemical features for eclogitic minerals within diamonds—in some cases very large diamonds – were also unique. Pyrope-almandine from diamond-bearing eclogite has detectable sodium in its structure, and omphacite has detectable potassium. In both cases neither element normally fits into the silicate mineral but appears to be forced into the crystal structure owing to increased pressure, which implies a genesis deeper in the mantle. The classic indicator suite of pyrope, picroilmenite and chromite was expanded to include E-type pyrope-almandine and omphacite. The E-type indicator minerals from diamond eclogite are unique compositionally, but not visually. Many other mantle and crustal minerals are similar in appearance and so require identification by microprobe analysis.



Mammals and insects can be natural concentrators of indicator minerals. The harvester ant collects mineral grains from the surface to construct cone-shaped ant mounds.

but this required a more sensitive instrument than the electron microprobe.) Most recently, a method to obtain both pressure and temperature estimates from chrome diopside has been developed in which Cr_2O_3 content is measured relative to other components in its structure. Visual and chemical studies of altered mantle xenoliths have also established that the disturbance of mantle rocks by the diamond-destructive

fluids responsible for dissolution is expressed by an increase in TiO_2 content of the pyrope. Pyrope with elevated TiO_2 content in an exploration sample could indicate that a diamond-favourable parent rock had suffered a diamond-destructive event.

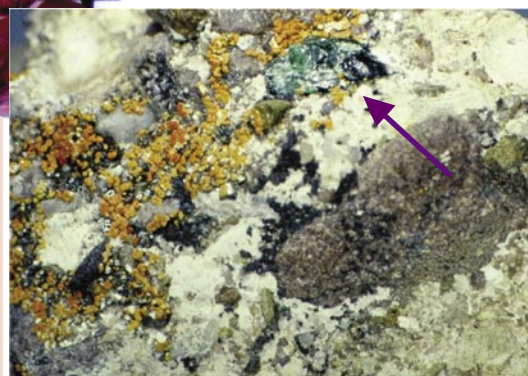
Exploration for indicators: The effectiveness of indicator minerals can be enhanced or diminished by human and animal impact on the area of interest. In North America, Australia, and southern Africa, kimberlites have been discovered through the identification of indicator minerals thrown onto the surface by burrowing insects and mammals.

It is important to be aware of atypical or non-kimberlite indicator minerals that may also serve to identify igneous host rocks for diamond. The early exploration programmes in Australia used kimberlitic zircon and crustal andradite garnet as the indicator minerals to successfully locate kimberlitic rocks.

Regardless of continent or region, nearly every world-renowned diamond mine in an igneous host rock has been discovered through the systematic use of indicator minerals and future discoveries will undoubtedly be based on applying and refining information gained from indicator analysis.



Density-separated grains from an antmound include pyrope and chrome diopside over five millimetres in diameter (grid in cm). These grains have experienced multiple transport cycles, and are derived from conglomerates which also included chrome diopside (arrowed) over two centimeters in size.



Chemical classification: Chemical classification schemes were developed to identify all indicators for diamond co-genesis and preservation. The mantle formation temperature can be estimated from pyrope by quantifying the minor component MnO. (An earlier scheme for obtaining temperature by examining NiO in pyrope and ZnO in chromite also was developed,

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