N.P. POKHILENKO

DIAMOND ROAD THREE BILLION YEARS LONG

Diamond is one of the most mysterious minerals on Earth. For many centuries it has been in the focus of attention as the most expensive, romantic and desired precious stone. According to ancient legends, diamonds are like people: they have a life of their own. Their origin and history had been a mystery for a long time. The analytical methods enabling to study the composition, structure and age of diamonds and of the micro mineral inclusions contained in them were developed only at the turn of the 21st century.

How do diamonds form in the Earth's upper mantle; what stages of evolution do they pass through after they come up to the upper level of the Earth's crust; and, finally, how can we find them?

Answering these questions is Nikolai P. Pokhilenko, director of the Institute of Geology and Mineralogy of the Siberian Branch of the Russian Academy of Sciences (SB RAS), corresponding member of RAS, who has played the key role in the discovery of the unique diamond deposit on Snap Lake, Canada

If you want to find a diamond deposit, you should start with a geological map showing types and ages of rocks, as well as irregularities of the region's geological evolution. Most attractive for diamond exploration are the most ancient areas of the Earth's crust containing magmatic rocks of the *basalt* type. In such areas it is worth looking for the so-called volcanic pipes. Since they incorporate magnetic minerals, pipe locations can be detected with the help of aeromagnetic survey: they will show as magnetic anomaly zones. Ancient platforms, in whose limits the Earth's crust stabilized in the Archean, are present on practically all the continents: they occur in Siberia and in Africa, in North and South America, in Australia and in China, in Northern Europe, and in India.

In order to search for diamonds, one should very well understand, first, how their crystals grow in the Earth's depths and, second, how they are brought up to the Earth's surface.

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Sphere of interests: mineralogy, petrology and geochemistry of the upper mantle and kimberlites; diamond fields, methods of their exploration and prediction; evolution of composition and structure of the lithospheric mantle of ancient platforms.
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Practically all *primary diamond deposits* are related with volcanic pipes formed by kimberlite *breccias**, which is why they are called kimberlite pipes. Kimberlites are rocks of mantle origin formed at vast depths as a result of the complicated process of partial melting of the rocks composing various layers of the Earth's mantle. A lot of kimberlite melts form in the layers below the boundary of graphite to diamond transition. A pressure of 40,000 atmospheres exerted at a depth of about 140 km is required to start diamond crystallization. Taking into account the relatively low magnitudes of heat flows present in the lithosphere of ancient platforms (40 mW/m2 and sometimes even lower), the temperature at such depths is about 900 °C.

To form a diamond, a free carbon system (after all, a diamond is crystallized carbon) requires, apart from pressure and temperature, a small amount of oxygen — otherwise carbon will oxidize and turn into CO (carbon monoxide) or even into CO_2 (carbon dioxide).

A growing diamond crystal captures fragments of its environment. These fragments can be crystalline inclusions of minerals, and inclusions of melts or fluids. Nitrogen might become an element of the diamond's crystalline lattice (later to be qualified as an inclusion). At first, diamond captures nitrogen in the form of separate atomic centers called "C-centers". Later, as a result of diffusion, two atoms of nitrogen approach each other and merge, creating a pair called "A-center". Then A-centers merge to create B-centers, which are planes consisting of nitrogen atoms. If C-centers dominate in a crystal and there is a lot of nitrogen present, the diamond will be yellow in color. During the transformation of nitrogen C-centers to more complicated A- and B-centers, the diamond becomes colorless.

As it grows, a crystal of artificial diamond may also capture fragments of its native environment: for example, fragments of an iron-nickel alloy in the case of an iron-nickel melt. Metallic inclusions occur in the diamond body, and as their number increases, diamond quality is deteriorating. However, if this diamond is annealed at high *P—T*-parameters, it strives to get rid of inclusions and pushes them out.

* Breccia — rock composed of fragments of various rocks melded together.

Absolute majority of diamonds formed at the early stages of our planet's geological history, around 3 billion years ago. The kimberlite pipes, however, from which crystals are extracted are usually much younger. In South Africa, their age is estimated to be from 2.4 billion to 30 million years; in Brazil, it ranges from 1.7 billion to 180 million years; in Canada, from 560 to 52 million years; and in Yakutia, from 450 to 140 million years. A diamond province usually features kimberlite pipes of different age (for example, in South Africa 14 episodes of kimberlite magmatism were detected)

The fates of diamonds vary depending on the conditions in which they formed.

Let us look at the case when there is a diamond "embryo" and a diamond crystal grows around it (i. e. carbon is crystallizing). In the process of crystal growth, some exterior factors make it break. New diamond layers start to grow on the broken crystal, and again it strives to take the shape of octahedron classical for a diamond.

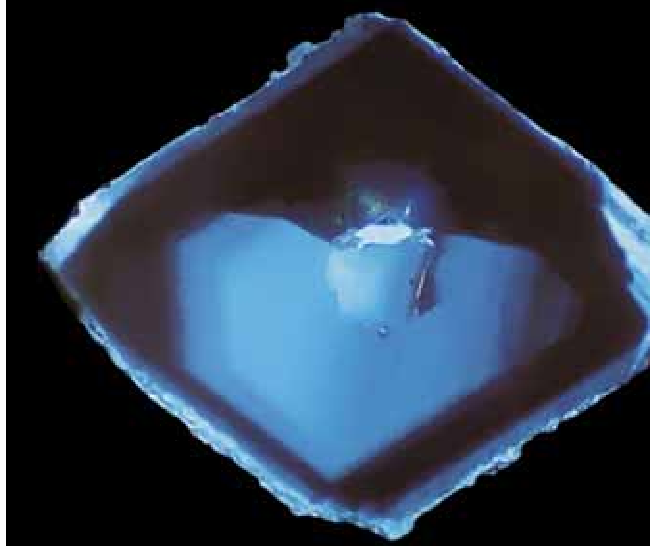
Some deposits have a lot of high quality diamond crystals wrapped in a shell containing a lot of nitrogen in atomic form. This envelope looks scummy, which degrades the quality of the diamond and, hence, its cost, although it can be easily removed during the gem-cutting process.

Turning a diamond into a sparkling brilliant requires more than just cutting it accurately. The diamond itself should be isotropic, i. e. homogenous in its physical properties and enabling a light beam to travel straight through without any deviations caused by the crystal's optical defects.

The value of a brilliant depends on its pureness, color, size and faceting. A diamond is deemed to be pure if no inclusions are visible in it at a tenfold magnification.

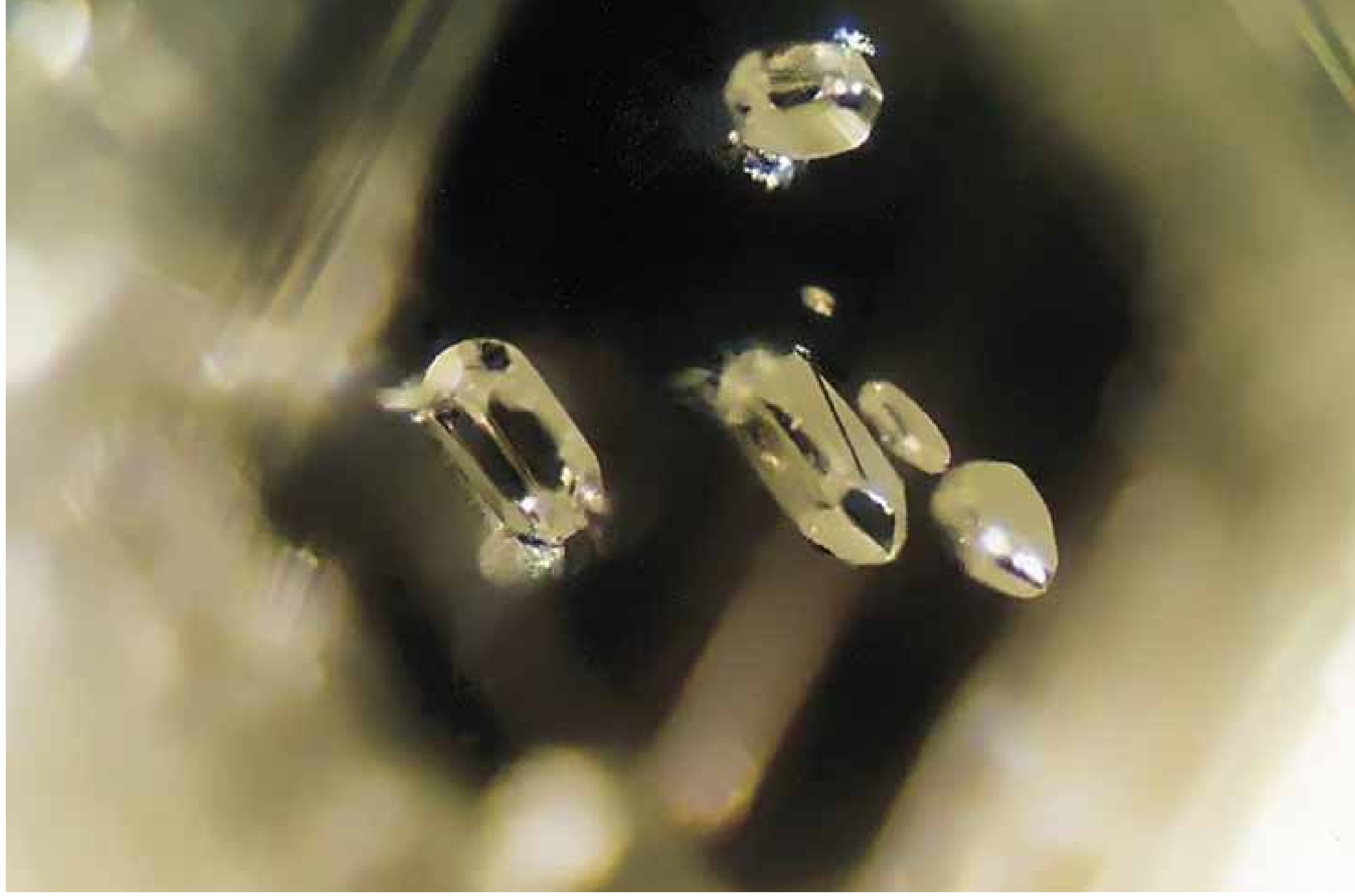
For diamonds "unlucky" at their birth, a set of methods designed to improve the quality of brilliants to be obtained from them has been created. If there is a crack in a diamond, the filling method is implemented: the crack is filled with another material (although with time this diamond's properties may change). If a diamond has a dark inclusion, a channel is drilled with a laser beam; material which removes or changes the inclusion is directed toward it along the channel. Such gems are called "refined".

At present, economically valuable diamond fields have been found on practically every continent where ancient platforms are located (except Antarctica, which has not been well explored). Diamond mines of India, Africa, and Australia became known in the century before last; later, diamond fields were discovered in Asia (Yakutian Diamond Province), in Europe (Arkhangelsk Diamond Province), and in North and South America (Canada, Brazil, Venezuela). Thus, there is good reason to assert that a layer of rock enriched by diamonds exists (or existed at certain stages of geological history) under all ancient platforms, and, hence, there are not so few diamonds on Earth



A pure diamond that has had "a hard life". This snapshot shows the diamond's "life story": you can see that the conditions were changing (the areas differ by intensity and color of luminescence)

This picture shows the history of crystal's growth and dissolution



Crystalline inclusions of olivine in diamond

How diamonds come up to Earth's surface

Let us assume that in the Archean a 50-kilometer thick layer of diamondiferous rocks formed at a depth of 150—200 km in the lithosphere (the upper part of the "solid" Earth). And after around 2 billion years, *the plume* (deep-seated magma welling up to the basement of the lithosphere) formed at the border of the Earth's core and lower mantle. Melts comprising the plume ascend vertically along the spiral towards the surface of Earth and are even able to come out on it. As the plume reaches the bottom layer of the cold stable lithosphere, it causes partial melting of rocks in its lower layers and, as a rule, brings more oxygen than "diamond hunters" would wish. *Kimberlite melts* form at extremely low degrees of partial melting (1.5—1.3 vol. %) of depleted ultra-basic rocks of the lithosphere mantle, which a short time previously have been enriched, to a variable extent, by low-melting components. These melts have low viscosity, form a thin membrane of inter-granular space, and can exude and form comparatively small chambers of kimberlite magma. During tectonic activation, certain deep-seated fractures of kimberlite-generating zones of ancient platforms, connecting such chambers with the Earth's surface, become channels for an exceptionally rapid (in the first hours) ascent of kimberlite melts to the Earth's surface.

Most diamond deposits (95 %) are related to kimberlite melts, which well up along the cracks and crush diamondiferous rocks on their way, carrying out diamonds and rock fragments of ancient lithospheric mantle from mantle depths.

It can be said that kimberlite pipes are ancient volcanoes, which play the role of transporters bringing up mantle rocks

The layer of rocks enriched by diamonds lies at a depth of over 150 km. At the same time, magmatic melts under the continents normally form at smaller depths (100 km and less). The exception is magmas connected with mantle plumes and superplumes, welling up from abyssal depths and originating at the border between the core and the mantle. It is with these phenomena that the largest episodes of magmatism in the Earth's history are connected. These are, primarily, flood basalt provinces — gigantic lava plateaus — where millions of cubic meters of mantle lavas flooded the Earth's surface for 1—2 million years (to appreciate the scope of this phenomenon, you can compare it with the total volume of all buildings and structures mankind has created throughout its history — it is less than 100 km^3!)

and minerals to the earth surface. Remember how a brook carries various debris and small flakes of gold which it has washed out of its shores. In our case the "brook" does not flow on the surface but comes up from the Earth's depths, sub-vertically towards the earth surface. This is magma rapidly ascending in response to high pressure. Viscosity of a kimberlite melt can be compared with the viscosity of oil poured into a car engine. And the speed of its ascent under pressure is also comparable with the speed of a car (around 60—70 km/hour). It covers the whole distance from the place where a melt forms to the earth surface in two to three hours. In this case, the diamond does not have time to graphitize.

If a melt moves slowly, making stops in mantle depths, but within the area of thermodynamic stability of graphite, a diamond can rebuild its crystal lattice and turn into graphite. And if oxygen potential in the melt is high, the crystal can simply burn down.

Kimberlite magma containing a lot of volatiles (CO_2 and H_2O) starts to boil at a depth of 4—5 km from the Earth's surface. To illustrate, let us look at how a pressure cooker works. As the pressure inside the cooker is high, the water boiling temperature will be not 100 °C but around 120—140 °C, or even higher. However, if we open the cooker top, steam will swiftly go out — it will look like an explosion — and the temperature will quickly drop down to 100 °C, which is the water boiling temperature at 1 atm.

When kimberlite (and not only kimberlite) magma starts boiling, an explosion takes place and volcano pipes form, which are immediately filled with magma. After the explosion the temperature quickly drops down. In the North, fragments of Mesozoic wood which did not burn because the temperature had dropped down very quickly can be found in the breccias of the vent parts of kimberlite pipes. You can still use this Mesozoic wood to make a fire.

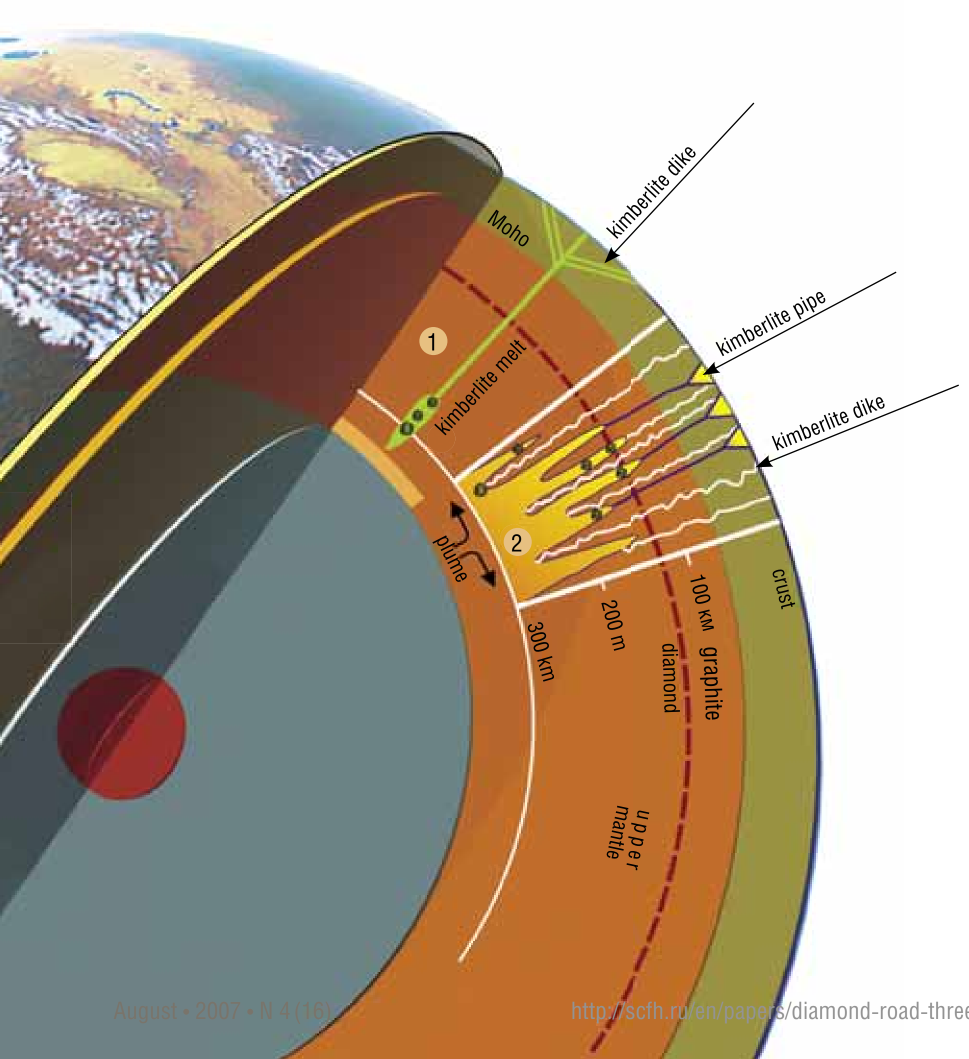
So, if a rapidly going up flow of kimberlite magma crosses a layer of diamondiferous rocks, a diamond pipe forms.

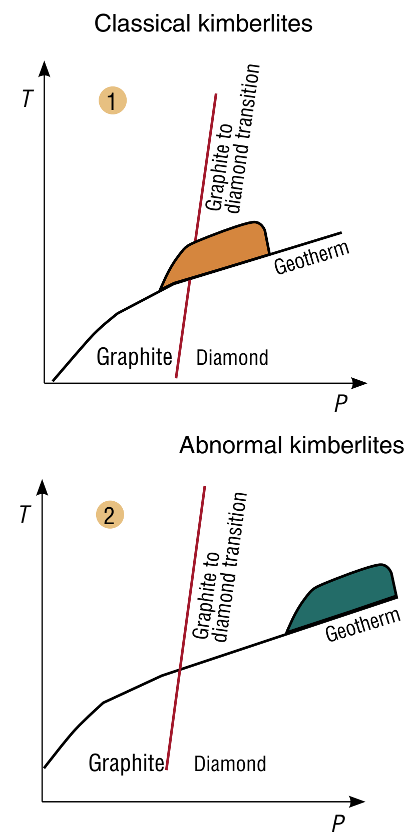
If a magma flow crosses relatively shallow mantle layers, where pressures correspond to the graphite stability areas, then a pipe containing no diamonds at all will form.

In order to understand how diamonds are found, the process of diamonds' ascent to the surface should be examined "from outside". What are the signs that help geologists who have selected a potentially diamondiferous area decide whether they should continue their exploration? How exactly is prospecting for diamonds carried out?

After the map has shown a presumably promising area and aeromagnetic survey has revealed structures with magnetic anomalies, a more detailed exploration begins. Geologists conduct pan sampling of alluvial deposits of the river system, if any. In the north of Canada, they often sample glacial deposits. The samples are checked for kimberlite indicators: pyropes, picroilmenites, chromites, chrome-diopsides, and, if you are very lucky, diamonds. The presence of these minerals in the samples is direct evidence that there are kimberlites in the region, and the presence of diamonds points to the existence of diamondiferous kimberlites. In Siberia, a pan is a traditional tool used in exploration for indicator minerals. The initial stage of work may be considered to be successfully completed when geologists see mineral indicators or, possibly, diamond crystals in their pans. After that more detailed, laborious and much more expensive explorations begin involving a system of geophysical methods including aero and land surveys, and validation of discovered geophysical anomalies by massive pan sampling, which is followed up with drilling the most promising among them.

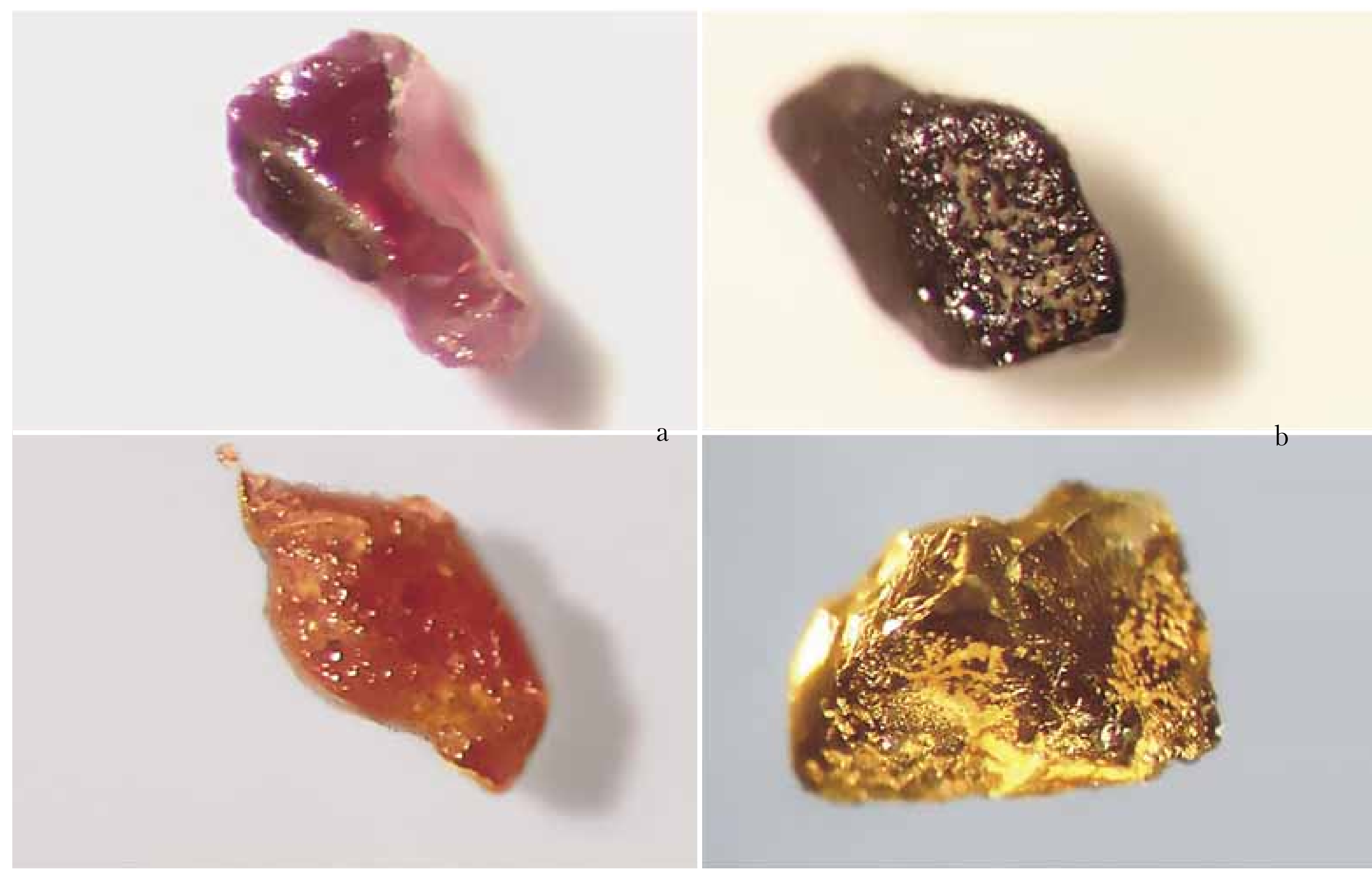
Let us assume that kimberlite has been found. The aim of the next exploration stage is to outline the pipe contour. In order to do this, it is necessary to make more prospecting shafts or to drill several wells along the pipe body and compare the data obtained with the configuration of geophysical anomalies. Then the main question should be answered: is the pipe found diamondiferous? This question is far from idle, if you take into account that in Yakutian Diamond Province only fifteen out of thousand kimberlite pipes contain enough diamonds to be qualified as commercially valuable.





Origin of kimberlites of various genetic types (boundaries between the Earth's shells are shown without regard for scale)

Indicator minerals: pyrope (a) and picroilmenite (b)



In the late 1960s – early 1970s, the distinguished Russian mineralogist (currently Academician of RAS) Nikolai V. Sobolev was the first in the world to develop, upon comparative analysis of the results of his research of the composition of crystalline inclusions in natural diamonds, the mineralogical criteria to estimate diamond grade in kimberlites. Basing on these criteria, a team of Siberian geologists headed by N. V. Sobolev created a set of brand new mineralogical methods which, at early exploration stages, enable prospectors to evaluate the diamond potential of kimberlites not yet found. Underlying these prediction techniques is study of the composition of indicator minerals such as pyropes and chromites.

The problem is that it is not always possible to extract a representative number (first hundreds of mineral grains) of indicator materials and to evaluate, from their composition, the diamond potential of the pipe, since kimberlites can be absolutely different.

For example, in the pipe called Mir (Yakutia), 1 ton of kimberlite contains 20 kilograms of indicator minerals including more than 5 kilograms of Cr-pyropes. Similar pipes have a large train which enables one to find the pipe itself. Walking along the river, a geologist can see pyropes right under his feet and find the pipe following this track. As compared with the Mir pipe, anomalous kimberlites of the Nakyn field (Yakutia) and *dike complex* of Snap Lake (Canada) contain 100 times less indicator materials per 1 ton of rock (i. e. 200–300 grams per ton), although these kimberlites are distinguished for their diamond potential.

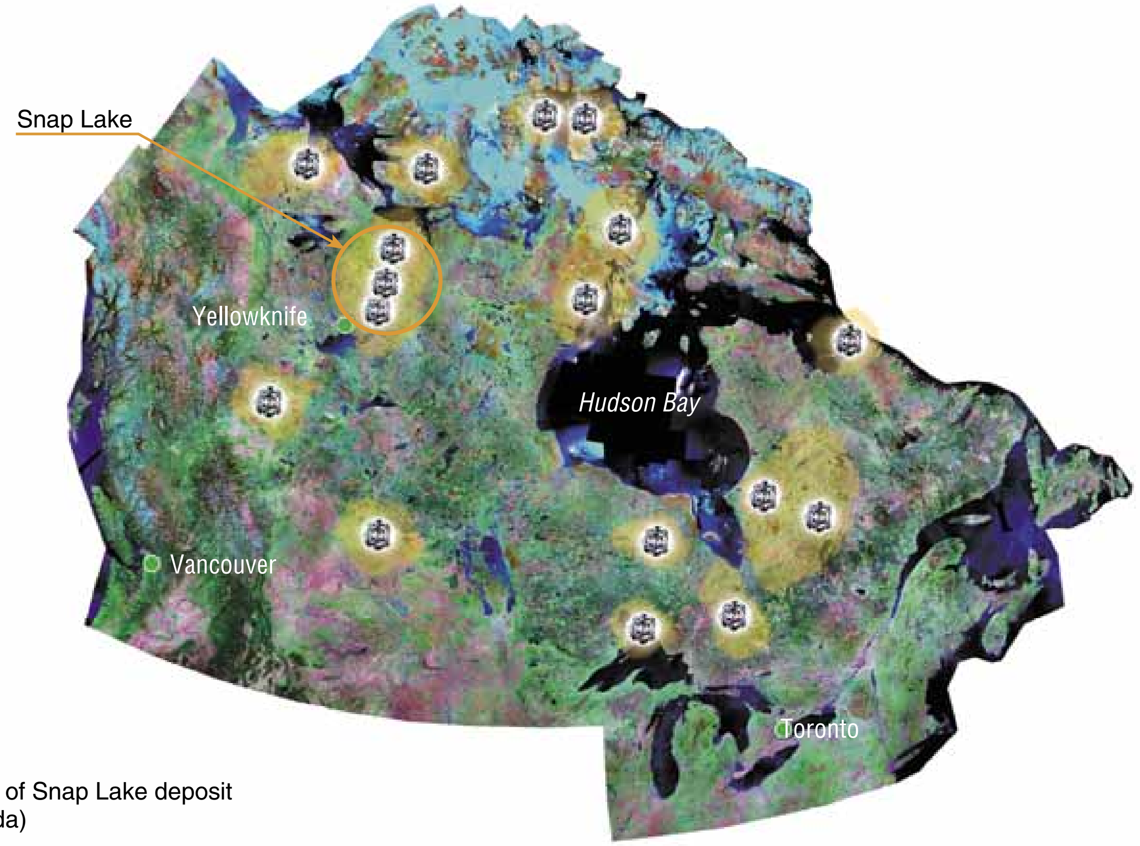
Search for pipes may pose other problems. The pipes whose kimberlites contain an increased amount of magnetic materials (magnetite, titano-magnetite, etc.) can be discovered by geophysical methods because they show magnetic anomalies. There are kimberlites, however, that contain a very small amount of magnetic minerals, so magnetic survey alone fails to detect them.

Snap Lake Mystery, or How to Search for Diamonds

This is a story about how a Siberian geologist and his international team found in Canada a large diamond deposit with unique characteristics. The Canadians called this finding "world-class discovery"

In Canada we discovered kimberlites with a very low content of both indicators and magnetic minerals: they formed a complex of flat-dipping dikes comprising the Snap Lake deposit. Afterwards it was found that only a small fragment of the main dike showed on the surface. Geologists from De Beers and two other Canadian companies who worked there earlier failed to notice not only the signs of this dike complex but also the trains of the two classical kimberlite pipes, which we had found 20 km to the east of Snap Lake three years before the deposit was discovered. More than three years of exploration and evaluation work done by our predecessors in this area produced negative results: no signs of kimberlite presence were found, and the area was announced hopeless. Winspear Resources Ltd., the company which invited us in the end of the 1994 season (in mid-August), owned six other licensed areas in the central part of Slave Province, at the flanks of the kimberlite

Sampling on the Mackenzie River



Layout of Snap Lake deposit (Canada)

field discovered by Canadian geologist Chuck Fipke in 1991–1992 near the lake Lac de Gras. The company geologists thought them to be promising, but after several weeks of work we felt bored because the geological characteristics of these areas were quite poor. So, having found no signs of anything worthy, we asked to let us work in that "hopeless" claim of 2,500 km² located 120 km to the south of the Lac de Gras field, which had been discovered earlier. The company had neither an exploration camp set up there nor stock of helicopter fuel. Taking into account the fact that the results of earlier explorations were totally negative, it took us a lot of efforts to obtain permission to work there, and only for three days at that.

For your information, a comparatively reliable exploration of such an area usually requires three or four months in the field, a searching party including a group of geophysicists and a crew of miners, as well as some mobile drilling equipment. All in all, over a hundred people should be involved.

What I had was two assistants and a helicopter with a deficit of fuel, which was unsatisfactory by any standard. Having analyzed, during four nights, very sparse geological data related to this "worthless" claim (in the daytime we had to continue working in other licensed claims), we selected three areas (an area per working day), 15 km² each. The first day was wasted because we received an order from the company management to explore a site within an area where Canadian geophysicists saw a promising anomaly. We did not find anything there, but spent a day and burnt some fuel.

The next day we spent an hour and a half surveying the three areas we had chosen from the helicopter: we had to decide at which of them we will be working in the following two days. We quickly realized that we were not up to exploring the westernmost area because we were short both of time and of fuel. We made a landing at the central area but half an hour was enough for us to understand that it was not worth a try either. Then we decided to spend the rest of

This is how the open-pit mine of Jericho kimberlite pipe (Canada) looks. *Photo by N. Podgornykh*

our time working in the third area. Its structural features were impressive: in its proximity (5 km to the north), there was an extensive fault structure, more than 600 km long, crossed by a bounding fault which was intersecting the two-kilometer lake. This bounding fault was crosscut by three local faults converging in the lake and forming the so-called "fault star". Together with me in the helicopter was my Canadian assistant Walter Melnyk (now President of the Canadian company Nordic Diamonds Ltd.). I told him that if I were a kimberlite, I would surely make this place my home. Having studied carefully the chart of the latest ice-flow movement for the entire region and having taken into account the direction of ice-flow movement in this particular area, we chose sites for landing and sampling. In the very first sample I saw a couple of grains of picroilmenites and a gorgeous grain of purple pyrope. And yet, in view of the closeness of the "fault star" center (~1.5 km), where I was hoping to find kimberlite, this number of indicators did not please me — although in itself it was a very important result: the minerals found clearly pointed to kimberlite presence in the region, which meant that a new kimberlite field was discovered in the north of Canada. My fevered, due to the systematic lack of sleep, mind plus my work experience in Yakutia and in the Arkhangelsk province for 26 field seasons prompted me that something was wrong with ice-flow movement. As we were landing, I noticed, in three hundred meters, a granite outcrop polished by the ice-flow (a "granite forehead", as we put it in Russian). I told my assistants and the pilot to have lunch, and ran toward this "forehead" by myself. There I measured the azimuth of ice-flow scratches and found out that the real direction of ice-flow movement was different from that indicated in the chart by 16°. I quickly came back. Lunch had to be canceled — on the map we determined where the "correct" sample was to be taken: the adjusted projection of the "fault star" center to the place of tills (glacial drifts) occurrence and — onward together with my assistant! In half an hour I saw hundreds of indicator minerals in my pan: pyropes, picroilmenites, and several fragments of kimberlite. The rest was just a matter of skill. In three hours we knew that three-fourths of the pipe was located under the lake. We informed the company management about our findings. They were ecstatic — fuel, people, and money were no longer in short supply... Drilling equipment was flown to us, and the site for the first borehole was indicated: at 14 meters it entered kimberlite and went through it for over 150 meters. The new kimberlite field was discovered! This was sensational news for the company, for mass media and for the stock market...

In two weeks we discovered indicator mineral train of another pipe, completely submerged under the lake. We drilled it in March, when the ice became strong enough to support the equipment. Both pipes turned out to be diamondiferous, although their diamond grades were much too low for commercial development.

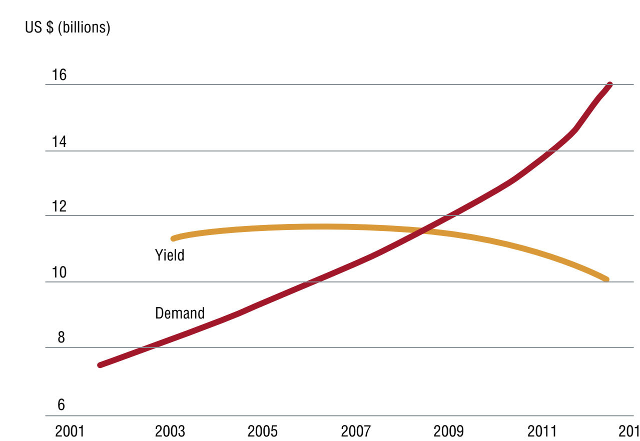
By the very end of 1994 field season, the decision was made to take samples from the area located to the west of the pipes discovered. A large fault ran subparallel to the main fault structure there. The fault was intersecting the northern part of quite large Snap Lake. And, once again, a system of bounding faults connected with the main fault structure was discovered in the lake area. Single grains of kimberlite indicator minerals — chrome pyropes and chromites — were found as a result of lab research in several samples taken to the west of the lake.

In the season of 1995, three Russian geologists traveled to Canada: our team was joined by one of the world's leading specialists in mineralogical methods of prospecting for diamond deposits, Doctor of Geology and Mineralogy Valentin P. Afanasiev and my wife, Lucy, who had spent eight field seasons predicting and prospecting for diamonds in the north of Yakutia. We had to evaluate the prospects of the western part of the licensed claim, whose area comprised over half of the entire claim area, for which we had not had time in the previous season. During a month and a half of full-schedule work we managed to trace 25 km of the trains going from the two pipes discovered in the previous season, but did not find any signs of new bodies in the west. The trains of the previous pipes went seven kilometers to the south of the positive samples, taken to the west of Snap Lake. This meant that the earlier discovered pipes could not have been the original sources of indicator minerals found in the lake area. And if this was true, then some other kimberlites should exist there. This conclusion made us apply to the company management with a request to move our works to Snap Lake before the end of the season. During the last two weeks (they were very cold: it was snowing on August 16) we took hundreds of samples in six profiles and saw indicator minerals right in our pans (Lucy was the first to find an excellent pyrope).

We worked out that the width of the indicator mineral train of the dike to the west of Snap Lake was around 3 km, and its length was around 1.5 km; beyond this contour indicator minerals were practically lacking. At the beginning of the train, the maximum amount of indicator mineral grains was no more than 15-20 counts; nonetheless, I assumed that we were dealing with something absolutely unique: among the minerals discovered there were some abnormally high-chromium pyropes and chromites, whilst picroilmenites were completely lacking, whereas in the pipes we had found previously in the area they dominated. The most important fact was that alongside the rare indicator minerals, diamonds occurred regularly: in Canada nobody had found diamonds in till samples (glacial drifts) before.

When I was asked directly whether there were any signs of classical diamondiferous pipe, I answered "No", but I added that most likely "something unique" existed there, which could be of serious commercial interest.

By the time of our arrival in Canada in March 1996, the funds allocated for prospecting the claim had almost run out; and the 70 drill-holes my foreign colleagues-geologists had made in the lake waters in spring gave virtually negative results. My Canadian colleagues concluded, on the basis of geophysical survey data, that a series of kimberlite bodies existed under the lake, and suggested they should be drilled. I strongly objected to massive drilling, believing that the area was not yet ready for it, and advised to drill only three out of 136 anomalies contemplated, but nobody listened me: everybody wanted quick results. By the way, drilling revealed two small (20 and 50 cm) kimberlite dykes at two out of the three anomalies I had singled out, and this was the only positive result of the whole drilling program... A season of very nervous work was before us — the money was drying up, and the situation in the



Diamond demand versus extraction:
Scenario of development (in current prices)

company was complicated — but, after all, we did find this goddamned kimberlite with high-quality diamonds and a very good diamond potential, although the kimberlite itself turned out to be abnormal, both by its appearance and by its petrological and geochemical characteristics. The body geometry was also abnormal.

At first we assumed that what we discovered was a vertical dike, but later we found out that its location was peculiar: it was inclined at 10—11° and was, on the average, around 3.5 meters thick and over 3.5 km long.

Thanks to such geometry of the body, the deposit we found had 53 million tons prognostic reserves of valuable diamondiferous rocks, located at a depth of up to 1 km, and the price of diamonds contained in the ore was $18 billions. No deposit with similar features has yet been discovered anywhere in the world.

Now let us turn to mathematics. Imagine that you have purchased such a deposit. The development of 53 million tons of ore will take 26 years, provided that 2 million tons of ore is extracted per year and equipment operates for 25 years. Total expenditure for the equipment, construction of an airport and a factory, power supply, salaries to the factory personnel, and other accompanying expenses will comprise around $50 per ton, whilst a ton of ore contains $360-worth of diamonds. Hence clear profit amounts to more than $300 per ton. You will pay 17 % profit tax to the Canadian government, and the rest of the profit will belong to you.

In 2008, according to analysts' prognoses, the world's leading country in diamond extraction will be Botswana (South Africa) with around 26 % of the world's diamonds (in value terms, not in carats); Russia, mining around 25 %, will be on the second place; and Canada with 12 % will take the third place.

The situation with diamond mining is similar to the situation with oil and gas extraction: the easier deposits have already been explored and are being developed, while these left unexplored have a more complex geology.

Diamond explorations used to be conducted in easy areas, with rivers running along deep valleys (a river valley could be 300 m deep and 20 km wide). Distinct areols of indicator minerals found on the slopes of the valley pointed towards kimberlite pipes involved in modern erosion processes. Today, the situation is much more complicated. Diamond explorations are conducted in the conditions of underdeveloped river systems with narrow and shallow valleys. At times, valley areas make up less than 10 % of the whole exploration area, and ancient rocks that may contain kimberlite are bridged over by a layer of much younger sedimentary or, which is much worse, magmatic rocks, whose thickness can be dozens or even hundreds of meters. All this requires some revolutionary, more sophisticated systems of prognostic and exploring methods, adapted to the prospecting conditions of each specific area. Hundreds millions of dollars can be wasted without any notable achievements if old methods are applied.

Similar situation with prospecting can be observed in Yakutia, in other regions of the Siberian platform, in the north-western part of our country, in Canada, in Africa, and in South America... diamond deposits, yet unexplored and securely hidden by nature, bide their time and wait for their pioneers!

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Crystals of Yakutian diamonds
Photo by A. Pavlushin (the Institute of Diamond Geology and Precious Metals of SB RAS, Yakutia)