

GEOLOGY AND DEVELOPMENT OF THE LOMONOSOV DIAMOND DEPOSIT, NORTHWESTERN RUSSIA

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The Siberian craton in Russia hosts many of the country's famous diamond mines. The Lomonosov mine, however, occurs within the boundaries of a different craton—the Baltic shield, most of which lies in Europe. Unlike many diamond mines in South Africa, Canada, and Siberia, the Lomonosov deposit is not in a stable Archean geologic setting. Similar to the Argyle diamond mine in Australia, Lomonosov is in a younger Proterozoic orogenic (or mountain-building) region. Fancy pink diamonds at both these localities likely relate to these Proterozoic tectonic processes. Along with other diamond mines in Proterozoic geologic regions, the Lomonosov deposit (and its fancy-color diamond inventory) demonstrates that the diamond potential of these regions should not be overlooked.

Russia has been a major diamond producer for more than half a century. Most of its diamond mines occur in the semi-autonomous Sakha Republic within the geological bounds of the Siberian craton. However, over the last 12 years, Alrosa, a public joint-stock company (with both government and private ownership) operating through its subsidiary Severalmaz, has started development and mining at the Lomonosov diamond deposit, the first Russian diamond mine outside the Siberian craton. This deposit occurs in the northwest of the country within the Baltic shield (part of the larger East European craton). Since this region is part of the European continent, Lomonosov is Europe's first diamond mine.

Alrosa's Lomonosov deposit comprises six kimberlites that form part of the Zolotitsa kimberlite field, itself part of the larger Arkhangelsk kimberlite province. Two of the six kimberlites—Arkhangelskaya and Karpinskogo I—are currently being mined. They are distinctive for their high percentage of gem-quality colorless goods as well as their production of fancy-color diamonds, especially pink and purple (figure 1).

In August 2016, the authors visited the Lomonosov deposit to document this exciting new diamond locality. The visit included tours of the kimberlite open-pit operations, the processing plant, and the preliminary diamond sorting facilities in the city of Arkhangelsk. The authors also visited Alrosa's central diamond sorting and sales operation, the United Selling Organisation (USO) in Moscow. This article discusses the Lomonosov diamond production within the wider context of Russian diamond mining. Details are also provided on the deposit's nontraditional geological setting, which can be linked to the color origin of its pink and purple diamonds.

HISTORY OF DIAMOND MINING IN RUSSIA

Russia is the world's largest diamond producer by volume, responsible for around 30% of the world's diamond output each year. In 2015 alone, 41.9 million carats of diamonds were mined in Russia, valued at US\$4.23 billion, according to Kimberley Process figures. Of these diamonds, 95% were mined and sold by Alrosa. By production value, Alrosa is second only to De Beers. Approximately 90% of Alrosa diamonds are mined in northeastern Siberia in the Republic of Sakha (formerly Yakutia), while a growing share (now 5%) is mined in northwestern Russia near the port of Arkhangelsk (Alrosa Annual Report 2015). Alrosa does not operate exclusively in Russia and has a stake

See end of article for About the Authors and Acknowledgments.

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Figure 1. The Lomonosov deposit produces a variety of fancy-color diamonds, including pink and purple diamonds. Similar to the pink diamonds from Argyle, these likely relate to their Proterozoic geologic setting, unlike many other deposits that occur in stable Archean regions. Photo by Kevin Schumacher.

in Angola's Catoca mine, which accounts for approximately 5% of the company's diamond production.

There are a few Russian diamond mines not operated by Alrosa. The largest, the Grib mine, is located near Lomonosov in the Arkhangelsk region and operated by the Russian oil conglomerate Lukoil through its subsidiary Arkhangelskgeoldobycha. The Grib mine officially opened in 2014, around 15 years after it was first discovered. It yielded approximately 3 million carats in 2016 and is expected to produce around 4 to 5 million carats annually beginning in 2017. Lukoil recently agreed to sell the Grib mine to Otkritie Holding, with the deal expected to close in mid-2017 ("Lukoil concludes agreement..." 2016).

Although diamonds had been found in various locations around the country for more than 150 years, the possibility of finding commercial quantities in Russian territory was first raised in 1938 by scientists at Leningrad State University (now Saint Petersburg State University), who conducted a study comparing the geology of the Soviet Union with that of diamondiferous regions around the world.

Russian geologists began their search for diamonds in earnest in 1949, noting their strategic value for industrial uses. Around the same time, the United States began building a strategic stockpile of industrial diamonds, mainly from the Belgian Congo (now the Democratic Republic of Congo), for these same reasons. After five years of following garnet indicator minerals, a small team of geologists headed by Larissa Popugaeva found the first kimberlite near the Daldyn River in Yakutia in 1954. The first kimberlite pipe was subsequently named Zarnitsa. While

Zarnitsa was not economic at the time—development only began in 2002—Popugaeva's find led to the discovery of the Mir pipe in 1955. Mir was the first diamond mine developed in Russia, and production commenced in 1959. Russian engineers constructed the town of Mirny nearby to house workers and provide infrastructure for the operation. The Udachnaya pipe, about 250 miles north of Mir and the country's most productive diamond mine by volume, was discovered two years later (Erlich, 2013).

Kimberlite pipes near Arkhangelsk in northwestern Russia were first discovered in the 1960s through airborne geophysical surveys (Stanikovskiy et al., 1974). Magnetic and gravity surveys are commonly used during kimberlite exploration to image the subsurface, as they can distinguish areas that have anomalous rock compositions (such as kimberlite) from the surrounding country rock. Kimberlites will show up as circular magnetic or gravity anomalies that can be seen even if they are buried by younger cover. Any potential kimberlite targets identified through these surveys must be confirmed by drilling, and the kimberlites in the Lomonosov deposit were all drilled in the early 1980s. The deposit itself is named after the eighteenth-century scientist Mikhail Lomonosov, one of the founders of Moscow State University. The Grib mine was named for Vladimir Grib, one of the Russian geologists who discovered diamonds in the area.

After bulk sampling at Lomonosov was completed in 1987, the Soviet central government gave its clearance to develop the deposit. However, the breakup of the Soviet Union in 1991 and the result-

ing political and financial uncertainty delayed the project for years. The new Russian government's priorities for diamond production were focused on existing operations in the Republic of Sakha that could generate quick revenues. As a result, development of the Lomonosov deposit did not begin until 2003.

When the first Russian diamonds appeared in the market in 1961, they were sold through De Beers Consolidated Mines' marketing arm, the Diamond Trading Company (DTC). At that time, however, the African continent was in the midst of an independence movement, with many former colonies becoming sovereign states. The Soviet Union was eager to forge strategic partnerships with these emerging nations, so the officials who managed the USSR's mineral production ended its formal sales contract with the DTC in 1963. Nevertheless, the Soviet Union continued to sell the majority of its production through De Beers for the next 35 years, using a subsidiary and a financial firm in Switzerland as intermediaries. Neither the DTC nor Russia have ever acknowledged this arrangement or released production figures from this time (Shor, 1993, 2009).

In the mid-1960s, the Soviet government directed a portion of Russian diamond production toward building a polishing industry that would generate employment and added value. It also stockpiled a portion of the production for strategic purposes and as a buffer in the event its mines became depleted. The first Russian-polished diamonds began appearing in the market in the late 1960s. By 1980, Russia accounted for an estimated 25% of world output by value (Even-Zohar, 2007). That year also marked the discovery of potential diamond sources in the Arkhangelsk region in the European part of Russia.

Russia's rough diamond production neared 15 million carats annually as 1990 approached, second only to Botswana. Nearly all of its output was from Yakutia, namely the Udachnaya, Aikhal, and Internationalaya pipes. Production at Mir had been suspended to clear flooding in the pit and develop an underground shaft. The Arkhangelsk deposits were still under exploration. Under Mikhail Gorbachev, the Soviet government reorganized its diamond mining and marketing operations, previously managed by various agencies, into a single organization named Glavalmazoloto, while continuing its relationship with De Beers (Even-Zohar, 2007).

In 1991, the Soviet Union dissolved. Eleven of the republics became autonomous states, while four republics, including Yakutia, were granted semi-autonomous status as part of the newly formed Russian

Federation. Yakutia changed its name to Sakha Republic afterward. In the fall of 1992, the central government created a new diamond administration agency and recognized Sakha's semi-autonomous status by giving it substantial equity in its diamond operations (Shor, 1993). The new agency, Almazy Rossii-Sakha, gave the Republic of Sakha 40.5% equity and the right to market 20% of its production. The central government held 32.5%, with the remainder held by other government agencies. The following year, the agency name was shortened to Alrosa, and a subsidiary named Severalmaz ("Northern Diamond") was created to oversee exploration in the Arkhangelsk region (Shor, 1993). Alrosa currently owns 99.6% of Severalmaz shares.

The Russian Federation and Alrosa formalized their relationship with De Beers in 1996 after several years of disorganization, which saw large-scale "leakages" of rough diamond sales outside De Beers' network that had threatened to destabilize the market (Even-Zohar, 2007). In 2006, De Beers and Alrosa began phasing out their sales agreement in yearly increments, largely due to pressure from the European Union. Since then, all of Alrosa's rough production has been marketed directly to diamond manufacturers and dealers (Even-Zohar, 2007). The sales agreement formally ended in 2009.

In 2011, Alrosa reorganized into a semi-government/private equity company (termed a public joint-stock company) and in 2013 issued an initial public offering of its stock. The sale netted US\$1.3 billion, selling 22.07% of the company to private investors and leaving the central government with 43.93% equity, Sakha Province with 25%, and 8% held by various municipalities within Sakha (Alrosa Annual Report 2013).

Today, Alrosa operates 42 Russian diamond deposits: 16 primary sources and 26 alluvial sites (Alrosa Annual Report 2015). The major primary deposits in Sakha are Mir (which opened in 1957), Udachnaya (1971), Internationalaya (1971), Aikhal (1971), Jubilee (1986), Nyurbinskaya (2002), Komsomolskaya (2002), Zarnitsa (2002), and Botyobinskaya (under development). The two pipes at the Lomonosov deposit are Arkhangelskaya (2005) and Karpinskogo I (2014).

CRATONS

What Is a Craton? Cratons are remnants of Earth's earliest crust that have been largely spared from erosion or destruction by tectonic processes. Cratonic regions worldwide contain crust that is at least 2.5 billion years old (Archean) but may also be signifi-

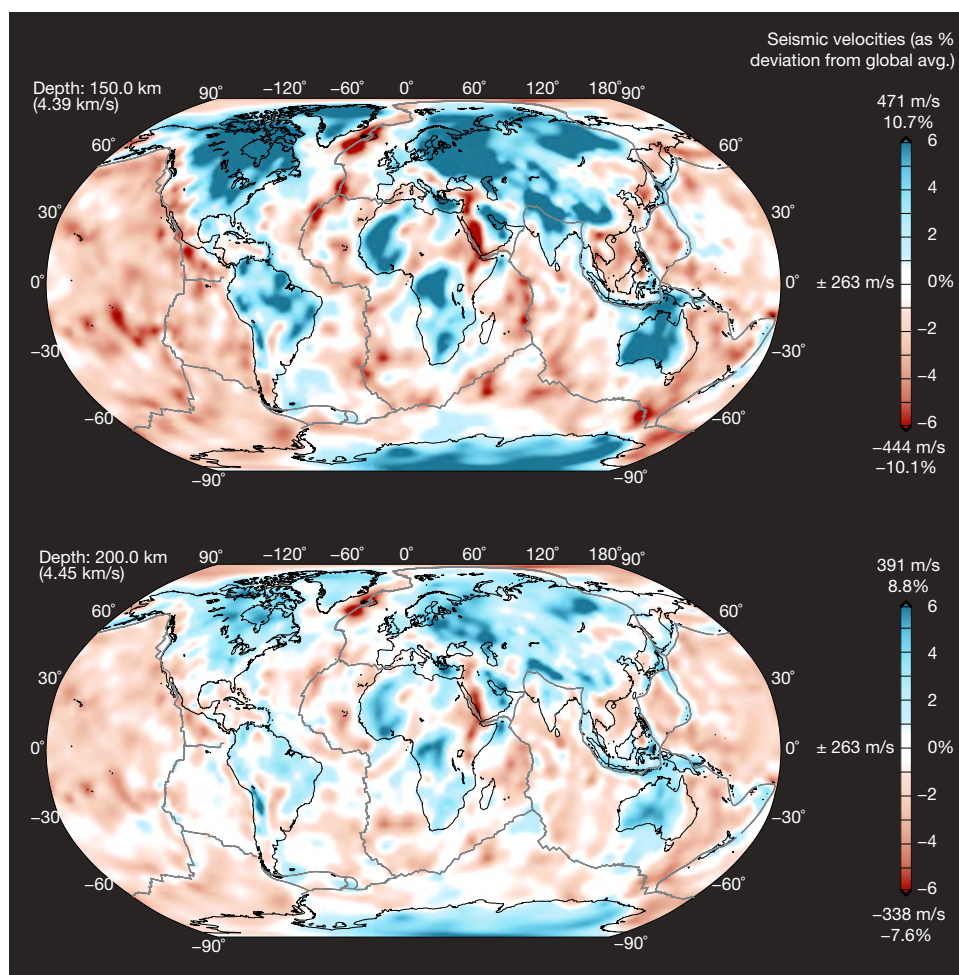


Figure 2. Global seismic shear speed model at depths of 150 km and 200 km (reproduced from Schaeffer and Lebedev, 2013) showing that global diamond-producing areas are all underlain by cratonic lithospheric mantle. These old stable cratonic regions have seismic velocities faster than the global average (shown here by cool colors). Warmer colors represent seismic velocities slower than the global average, indicating tectonically active areas. Major diamond-producing areas such as the Kaapvaal craton (South Africa), Slave craton (northern Canada), Siberian craton (Russia), and the Baltic shield across Scandinavia and western Russia all have fast seismic velocities down to depths of 150–200 km, evidence of deep sub-cratonic lithospheric keels that are conducive to diamond formation.

cantly older—forming within the first 500 million years of Earth’s formation 4.56 billion years ago (Connelly et al., 2012). The oldest rocks on Earth occur in four-billion-year-old gneiss units within the larger Acasta Gneiss complex in the Slave craton of northern Canada (Stern and Bleeker, 1998; Reimink et al., 2016) and in the 3.8–4.3 billion-year-old Nuvvuagittuq greenstones in the Superior craton of eastern Canada (O’Neil et al., 2008). The Yilgarn craton of Western Australia has the oldest mineral grains on Earth—4.4 billion-year-old detrital zircons in the Jack Hills conglomerate (Valley et al., 2014).

The long-term stability of cratonic regions is due to their thick continental roots, which are isolated from the convecting mantle. These continental roots are known as the lithospheric mantle keel. Peridotite in the upwelling convecting mantle melts to form basalt at mid-ocean ridges and ocean islands. This melting removes the basaltic melt component from peridotite, leaving the residual peridotite depleted in elements such as Ca, Al, and Fe, as well as H₂O and the heat-producing elements (such as K, U, and Th).

Due to its depleted character, this residual peridotite is cooler, less dense (more buoyant), and more rigid than the convecting mantle and therefore remains isolated. Lithospheric mantle keels are typically around 200 km thick and can be recognized in global seismic models by their fast seismic velocities compared to the global average (figure 2). Diamond mining regions across the world, such as those in South Africa, Canada, and Russia, are all underlain by thick continental keels that have “cool” temperature profiles conducive to diamond formation. Diamonds do not form in the lithosphere below portions of geologically young continental crust or in oceanic regions, since the temperature profiles in these regions never intersect into the diamond stability field (see Shirey and Shigley, 2013).

Archean and Proterozoic History of the Baltic Shield.

The Baltic (also known as the Fennoscandian) shield, which is part of the much larger East European craton, stretches across Sweden, Finland, and northwestern Russia (Gorbatshev and Bogdanova, 1993).



Figure 3. Simplified geological map of the Baltic (or Fennoscandian) shield in Scandinavia and northwestern Russia. The Baltic shield (part of the larger East European craton) is a stable continental region comprising several cratonic regions—the Norrbotten, Karelian, and Murmansk cratons—that were stabilized during the Proterozoic through mountain-building processes associated with the Lapland-Kola orogen (Daly et al., 2006). The Arkhangelsk kimberlite province lies within the unexposed Lapland-Kola orogen. Basement rocks of the Baltic shield are unexposed in this region due to extensive Proterozoic and Phanerozoic cover rocks, and kimberlites were identified through geophysical surveys. As such, the eastern extent of the Baltic shield is not well defined. Alrosa's Lomonosov diamond deposit is 23 km southwest of the Grib diamond deposit.

It comprises the Archean terranes of the Karelian craton (mostly in Finland) and the Murmansk craton (mostly on the Kola Peninsula), separated by the composite terranes of the Paleoproterozoic Lapland-Kola orogen (figure 3).

The Karelian and Murmansk cratons both have ancient geologic histories, although the Karelian craton appears to be older. It contains crust with an age of at least 3.5 Ga, including some 3.7 Ga zircon grains incorporated from older material (Mutanen and Huhma, 2003; Peltonen et al., 2006). The underlying Karelian lithospheric mantle has similarly old ages—depleted harzburgite *xenoliths* (see box A) have minimum 3 Ga ages (Peltonen and Brüggmann, 2006). Crust in the Murmansk craton seems to be much younger; metamorphic gneisses are mostly between 3.0 and 2.6 Ga (Timmerman and Daly, 1995; De Jong and Wijbrans, 2007).

The Baltic shield has an interesting history that is not typical for many diamond-bearing Archean cra-

tons (see the discussion on Clifford's Rule in box B). Archean continents split apart during widespread rifting and ocean formation during the Proterozoic (between 2.5 and 2.1 Ga; Melezhik and Sturt, 1994; Pesonen et al., 2003). Continental breakup was likely due to an upwelling plume of mantle melts, and xenoliths sampled from the deep crust have ages that overlap with this event (Kempton et al., 2001). After a period of seafloor spreading and ocean development—similar to the geologic setting of modern-day Iceland—these Neoproterozoic terranes were reamalgamated between 1.95 and 1.87 Ga (Gorbatshev and Bogdanova, 1993; Daly et al., 2006).

Closure of the ocean basins was likely through subduction followed by Himalayan-scale mountain building as continents collided. Evidence for subduction includes arc volcanic rocks recognized in the Lapland granulite belt (see figure 3 for location; Meriläinen, 1976; Daly et al., 2001) and lower crustal and mantle eclogite xenoliths from the Grib kimber-

BOX A: ROCKS FROM THE CRATONIC LITHOSPHERIC KEEL

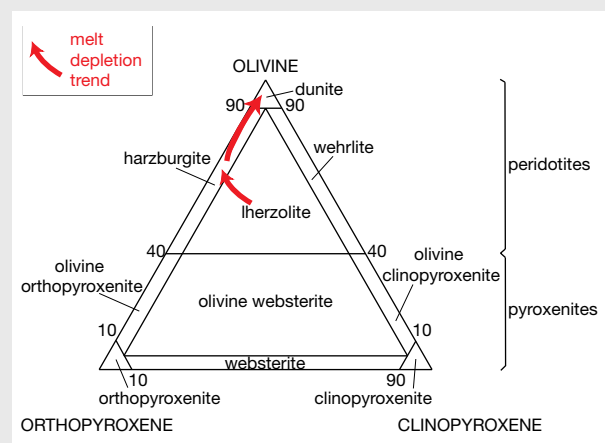
Peridotite is the predominant rock type in the mantle. It contains the minerals orthopyroxene, clinopyroxene, and olivine (figure A-1). Peridotite also contains an aluminous phase that can be either spinel or garnet, depending on depth. At the higher pressure conditions in the diamond stability field, the aluminous phase is always garnet. Peridotite melts to form basalt at mid-ocean ridges and ocean islands. This melting removes the basaltic melt from peridotite, leaving the residual peridotite depleted in elements such as Ca, Al, and Fe. This is because the melt moves upward to dikes that eventually feed shallow magma chambers. Lherzolite, the most fertile peridotite, has not undergone significant melt depletion and will contain some combination of the minerals listed above (figure A-1). With high proportions of melt depletion, clinopyroxene is eventually exhausted in the residual peridotite, resulting in the clinopyroxene-free rock known as harzburgite. With around 40–50% melting, orthopyroxene is also exhausted and olivine dominates the peridotitic assemblage (again, see figure A-1). After these high degrees of melting where most of the Ca, Al, and Fe has been lost, the residual peridotite becomes the most depleted dunite. Importantly, both depleted harzburgite and dunite can be re-enriched by passing melts that could reintroduce many of these minerals and convert peridotite back to fertile lherzolite.

In the absence of rock samples where the full mineral assemblage can be assessed, the relative depletion of the lithosphere can be obtained from the Mg and Fe composition of olivine. This is because the composition of olivine becomes more Mg-rich in residual peridotite that has undergone a higher extent of melting. For example, the most depleted dunitic peridotite will have an Mg# (calculated as $Mg/(Mg + Fe) \times 100$) above 92.8 and fertile lherzolite will have a lower Mg#, around 89–91 (Walter, 1998; Kubo, 2002). These might not look like large differences, but they actually are because the range in olivine compositions in the mantle is small—only about 10% (Mg# from ~85 to 95).

Eclogite is another rock type in the lithospheric mantle, a biminerallitic rock consisting of a sodium-rich clinopyx-

roxene known as omphacite and garnet with pyrope (Mg-rich), grossular (Ca-rich), and almandine (Fe-rich) components. There are two main models for the origin of eclogites in the lithospheric mantle: as high-pressure mantle melts or as former oceanic crust that has been subducted and emplaced into the lithosphere (Jacob, 2004). Despite their scarcity in the lithospheric keel, eclogites are frequently sampled by kimberlites and can therefore provide important insights into the role of subduction in the assembly of the lithospheric keel.

Figure A-1. Classification of peridotites and pyroxenites, the rocks found in the lithospheric mantle. The predominant rock type is peridotite, which comprises olivine, clinopyroxene, orthopyroxene, and an aluminous phase (this is spinel at shallower depths and garnet at greater depths of the diamond stability field). All compositions are projected from this aluminous phase, which is not shown. The most fertile (least depleted) peridotite is lherzolite; the most depleted peridotite, dunite, is comprised mostly of olivine. Eclogite has a basaltic bulk composition and at high pressure and temperature in the mantle recrystallizes to only two minerals: Na-rich clinopyroxene and garnet. Eclogites plot in the clinopyroxenite field at the bottom right.



lite (Koreshkova et al., 2014; Shchukina et al., 2015). The resulting Lapland-Kola orogen comprises several different terranes of Archean crust that were reworked during this Paleoproterozoic event (for example, the Kola province, the Belomorian orogen, the Inari terrane, and the Strelna terrane; Daly et al., 2006).

KIMBERLITES

Origin of Kimberlites. Kimberlites are ultramafic volcanic rocks created by extremely explosive volcanic

eruptions that originate from great depths below continental regions of the earth. As kimberlites rise through the subcontinental lithospheric mantle, they sample their surrounding rocks and transport them to the surface. When the kimberlite contains pieces of mantle rocks, these foreign pieces are called xenoliths. If the xenoliths fragment during transport, the individual mineral fragments of the xenoliths are called *xenocrysts*. Since the final kimberlite is a mixture of volcanic rock and the foreign materials it

picks up on the way to the surface, they are often regarded as hybrid rocks. During diamond exploration programs, the goal is to determine if these mantle rocks sampled an area of the mantle that is “diamond-stable,” increasing the possibility that the kimberlite is economically viable. A kimberlite may predominantly sample shallower mantle within the graphite stability field, or the kimberlite itself may have a composition that is destructive to diamonds, ultimately making the pipe uneconomic to mine. For further information on the origin and eruption of kimberlites, see the detailed review provided in Shirey and Shigley (2013).

Kimberlites on the Baltic Shield. The kimberlites of the Lomonosov mine form part of the Paleozoic Arkhangelsk kimberlite province, which lies northeast of the city of Arkhangelsk. These kimberlites erupted between 390 and 340 Ma into the southeastern extension of the Archean Kola province that was reworked during the Proterozoic Lapland-Kola orogen (Garanin et al., 1999; Shevchenko et al., 2004; Pervov et al., 2005; Kononova et al., 2011; Larionova et al., 2016; see figure 3). This part of the Baltic shield has no exposed cratonic basement rocks. Instead, the rocks at the surface are much younger late Proterozoic to Phanerozoic rocks that overlie the >1.9 billion-year-old cratonic rocks (figure 4).

Other kimberlites in the Baltic shield occur in Finland and Russia (again, see figure 3). In Russia, there are the 1.92 Ga Kimozero kimberlites at Lake Onega (Priyatkina et al., 2014) and the 380–360 Ma Terskii Coast kimberlites in the southern Kola Peninsula (Beard et al., 1998). The 1.2 Ga Kostomuksha kimberlites in Russia are just across the border from Finland’s Kuhmo-Lenttiira kimberlites, and both these kimberlite fields have similar 1.2 Ga eruption ages and Group II kimberlitic compositions (O’Brien et al., 2007). Also in Finland are the Kuusamo kimberlites, which erupted at 757 ± 2 Ma (O’Brien and Bradley, 2008), and the 626–589 Ma Kaavi-Kuopio kimberlite field (O’Brien et al., 2005). Dublin-based Karelian Diamond Resources is developing the Lahtojoki kimberlite at Kaavi-Kuopio. If successful, it will be the first diamond mine in Finland.

Kimberlites in the Arkhangelsk Region. The Arkhangelsk kimberlite province comprises kimberlites with two distinct source compositions (figure 5). These compositions can reflect either different source depths in the mantle or varying amounts of interaction with the diamond-bearing lithosphere.

Nevertheless, kimberlite from each of these groups is currently being mined.

Alrosa’s Lomonosov deposit is mining the mica-rich kimberlites of the Zolotitsa field (again, see figure 4), which have enriched isotopic compositions similar to the South African Group II kimberlites (figure 5). Ten pipes in the Zolotitsa field were confirmed by drilling in the early 1980s. Six of these—Pionerskaya, Lomonosovskaya, Pomorskaya, Karpinskogo I and II, and Arkhangelskaya—have economic quantities of diamond and form part of the Lomonosov deposit. The other four kimberlites in the Zolotitsa field (including the Snegurochka kimberlite) are not part of Lomonosov’s reserves, as they are currently uneconomic.

All the other kimberlites in the area, including the Grib mine in the Verkhotina kimberlite field, are Fe-Ti-rich kimberlites that are compositionally close to Group I kimberlites (figure 5). Apart from Grib, most of the other Fe-Ti-rich kimberlites are diamond-poor

In Brief

- Lomonosov is Alrosa’s first Russian diamond mine outside of Siberia.
- Production started in 2005, and Alrosa is currently mining only two of six potentially economic kimberlites.
- Similar to Argyle, it occurs in a region that experienced Proterozoic mountain-building.
- These geologic processes may be responsible for the pink-purple diamonds at both localities.

and uneconomic. These include kimberlites in the Shochta field, the Kepino-Pachuga field (e.g., the Zvezdochka, Anomaly 697, and Anomaly 688 kimberlites), and the Mela field, which includes some carbonatites (figure 4; Beard et al., 2000).

Although the two groups of Arkhangelsk kimberlites appear to be similar in composition to the traditional Group I and Group II kimberlites, a strict distinction into the two groups does not hold up. Arkhangelsk kimberlites actually have transitional isotopic compositions and mineralogical characteristics that lie between the two groups (figure 5; Mahotkin and Skinner, 1998; Beard et al., 2000).

Regardless of their classification, the isotopic compositions can be used to understand why the kimberlites in the Zolotitsa field are significantly more diamond-rich than the Fe-Ti-rich kimberlites. Zolotitsa kimberlites have Sr and Nd isotopic compo-

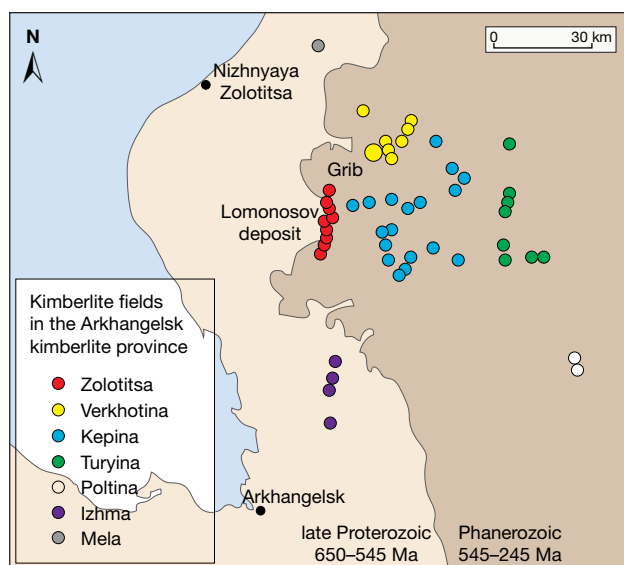


Figure 4. Kimberlitic rocks of the Arkhangelsk kimberlite province, color coded by kimberlite field. These all erupted between 390 and 340 million years ago, near the present-day city of Arkhangelsk in north-western Russia. Several kimberlites of the Zolotitsa field form the Lomonosov diamond deposit. Aside from these and the Grib kimberlite (in the Verkhotina field), all other kimberlites in this province remain uneconomic. The basement rocks of the Baltic shield (older than 1.9 billion years; figure 1) are not exposed in this area, and the rocks at the surface are younger cover rocks between 650 and 245 million years old.

sitions that lie in the “enriched” quadrant in figure 5. These isotopic compositions can only evolve in the lithospheric keel or crust since they have been isolated from the convecting mantle for billions of years. This isolation allows for isotopic compositions to evolve (through parent-daughter isotopic decay and radiogenic ingrowth) that are distinct from the convecting mantle. “Enriched” isotopic compositions in Zolotitsa diamondiferous kimberlites reflect either their origin in, or interaction with, the diamond-bearing lithospheric mantle. This is in contrast to the isotopic compositions of the Fe-Ti-rich kimberlites, which do not show a strong lithospheric mantle signature but instead are very similar to the convecting mantle (figure 5).

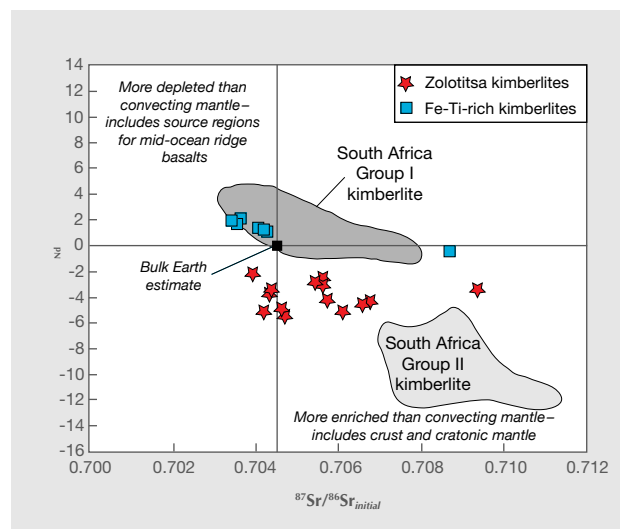
An additional indicator that the Zolotitsa kimberlites are favorable for diamonds is their ilmenite composition. Ilmenites from the Arkhangelskaya kimberlite have compositions that indicate optimal melt conditions for diamond preservation during eruption to Earth’s surface, with high MgO and low calculated Fe_2O_3 that indicate low oxygen fugacity

(Lehtonen et al., 2009). Kimberlites containing ilmenites that indicate high oxygen fugacities may be destructive to diamonds. Even though the kimberlite may be sampling a diamond-rich portion of the lithosphere, these diamonds may not survive during kimberlite transport to Earth’s surface.

THE CRUST AND DIAMONDIFEROUS MANTLE SAMPLED IN THE ARKHANGELSK REGION

Composition of the Lithosphere in the Arkhangelsk Region. Mantle xenoliths and xenocrysts brought to the surface by the Grib kimberlite are predominantly fertile garnet peridotites (around 46% lherzolite), pyroxenites + eclogites (around 11%), and only minor dunites (Kargin et al., 2016; Shchukina et al., 2016; Shchukina et al., 2015), indicating that the mantle keel was not subject to high degrees of melt removal. However, around 14% of the garnets from Grib have high Cr and low Ca contents, so-called G10 compo-

Figure 5. Strontium and neodymium isotopic compositions for kimberlites from Arkhangelsk province, modified from Beard et al. (2000). The estimate for the bulk earth (or convecting mantle) composition is $^{87}Sr/^{86}Sr = 0.7045$ and $^{144}Nd/^{143}Nd = 0.512630$, which is defined as ϵ_{Nd} of 0 (where ϵ_{Nd} is a percentage difference from the convecting mantle estimate). The top left quadrant has isotopic compositions that are more depleted than the convecting mantle and includes the source regions for mid-ocean ridge basalts. The bottom right quadrant has isotopic compositions that are more enriched than the convecting mantle. Compositional fields for South African Group I and II kimberlites are from Nowell et al. (2004).



sitions, that show they are from melt-depleted harzburgites, an important diamond stability indicator (Shchukina et al., 2016). In contrast to Grib, the Arkhangelskaya kimberlite at Lomonosov appears to sample roughly equal amounts of pyroxenite-eclogite (37%) and peridotite (33% fertile lherzolite + 4% depleted harzburgite); see figure 6 and Lehtonen et al. (2008, 2009).

Similar to kimberlites elsewhere that sample compositionally diverse eclogites (e.g., Barth et al., 2001, 2002; Aulbach et al., 2007; Smit et al., 2014), Arkhangelskaya has two different suites of eclogites (Lehtonen et al., 2008) that probably had different formation processes. Many of the eclogites from Arkhangelskaya are not derived from depths sufficient for diamond stability (Lehtonen et al., 2008, 2009). Nevertheless, the abundance of low-Mg eclogites that had oceanic crustal protoliths emphasizes the importance of subduction and collisional processes in the formation of this part of the Baltic shield.

Mantle Geotherms in the Arkhangelsk Region. Grib peridotite xenoliths have pressure and temperature (P - T) arrays (figure C-1; Shchukina et al., 2012; Shchukina et al., 2015) that define a paleogeotherm (pressure-temperature array at the time of kimberlite eruption, 390 to 340 Ma; box C) corresponding to 35–40 mW/m² surface heat flow (i.e., model geotherms, defined in Hasterok and Chapman, 2011). Lomonosov mantle xenoliths are altered compared to fresher xenoliths found at Grib, and there are insufficient fresh xenoliths for inter-mineral geothermobarometry calculations (Lehtonen et al., 2009). However, a paleogeotherm determined to be from Arkhangelskaya clinopyroxene xenocrysts is very similar to the Grib paleogeotherm (figure C-1; Sablukov et al., 1995; Lehtonen et al., 2009). This makes sense considering they are only 23 km apart and erupted at similar times (between 380 and 340 Ma). They are also typical for diamond-bearing cratonic regions worldwide (Mather et al., 2011; Stachel and Luth, 2015). At both Arkhangelskaya and Grib, diamonds are stable at pressures greater than 3.5–4 GPa (below 110–120 km). At shallower depths, any carbon present in the lithosphere will occur as graphite instead.

One difference observed between the paleogeotherms from Grib and Arkhangelskaya is that Grib samples appear to be derived from greater depths in the lithospheric mantle (figure C-1). The two deepest peridotite xenoliths sampled by the Grib kimberlite are derived from >7 GPa/200 km (Lehtonen et al.,

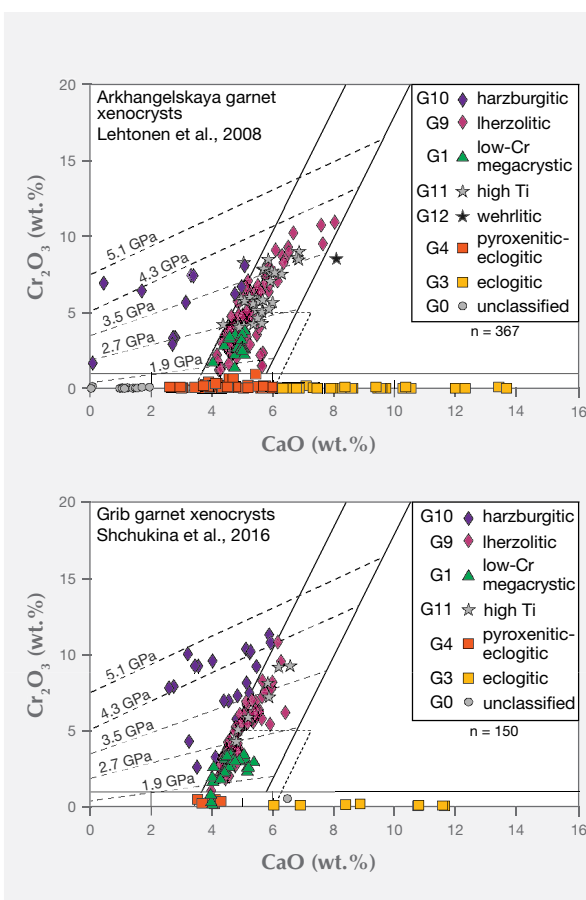


Figure 6. $\text{CaO-Cr}_2\text{O}_3$ compositions of garnet xenocrysts from the Arkhangelskaya and Grib kimberlites (Lehtonen et al., 2008; Shchukina et al., 2016). Each garnet xenocryst is color coded according to the composition of the rock from which it was derived. The compositional classification and their fields on the figure (solid lines) are taken from Grütter et al. (2004). Apart from being used to determine the mantle host rock, these compositions can also yield minimum pressures for depth in the lithospheric keel (dashed lines), enabling the diamond-stable portions of the lithospheric sample to be evaluated. Along the paleogeotherm determined for the Arkhangelsk province (figure 8), diamonds are stable above 3.5–4 GPa. The majority of the peridotitic garnets sampled at Arkhangelskaya are derived from pressures lower than 3.5 GPa and were not sampled from lithospheric regions that would contain diamond.

2009; Shchukina et al., 2012), whereas the deepest clinopyroxene xenocrysts from Arkhangelskaya are derived from shallower depths (5.5 GPa/170 km). However, garnet xenocrysts from Arkhangelskaya (for which only temperatures can be derived, and therefore are not plotted in figure C-1) have Ni-based tempera-

BOX B: CLIFFORD'S RULE AND ITS EXCEPTIONS

Clifford's Rule is a simple diamond exploration strategy based on the observation that diamonds are associated with old cratonic areas that have been tectonically stable since 2.5 Ga (Clifford, 1966). These areas are underlain by thick lithospheric keels that are cooler than the convecting mantle due to ancient melt depletion and have conditions favorable for diamond formation (see the review by Shirey and Shigley, 2013). Clifford's Rule says that although not all kimberlites will be diamondiferous, diamondiferous kimberlites only occur on these old Archean cratons underlain by deep mantle keels.

Contradictions to Clifford's Rule are becoming more prevalent, however, and there are many examples of diamonds mined in regions that have been tectonically active since 2.5 Ga. The splitting apart of continents and their recombination by later collision is common to the history of all continents on Earth. Orogens, which are the result of continental collision, cause rocks to become highly deformed with mineral recrystallization so severe that rocks can take on a "flow" texture. We now understand that diamond-forming fluids can also be introduced into the lithospheric mantle during these collisional processes.

For example, Argyle, one of the world's largest diamond mines and a famous supplier of pink and red diamonds (Shigley et al., 2001), occurs in one such collisional setting—the Proterozoic Halls Creek orogen. Argyle diamonds resided near the base of the lithosphere prior to their transport to the earth's surface. It is in this high-temperature, high-deformation area that Argyle's distinctive brown-pink-red diamonds likely formed (Stachel et al., 2017).

Similarly, the Lomonosov mine occurs within a Proterozoic orogenic setting (for details, see the "Archean and Proterozoic History of the Baltic Shield" section). Subduction-generated rocks have been identified in this part of the Lapland-Kola orogen (Koreshkova et al., 2014; Shchukina et al., 2015), suggesting that subduction played an important role during collision of these terranes and could have been a source of diamond fluids.

It is very possible that Lomonosov's pink-purple-brown diamonds are related to similar processes as the pink-red Argyle diamonds—namely, that they formed

from carbon-bearing fluids released into the lithosphere during Proterozoic subduction events and were subsequently deformed in this tectonically active craton-margin setting. An age-dating study on sulfide and/or silicate inclusion-bearing diamonds from the Lomonosov mine would help determine whether this is in fact the case. But the ability to relate a distinctive, important diamond attribute such as pink color to a specific geologic process is a stunning application of basic research into diamond formation that will assist in the exploration for more such precious gems.

After 50 years, Clifford's Rule largely holds true: Most economic diamond deposits are found in association with old cratonic regions. However, the emerging pattern of diamond localities worldwide relative to cratonic regions suggests that exploration programs for economically viable diamondiferous kimberlites should not dismiss areas of the earth adjacent to these stable cratonic settings. For example, the Argyle and Ellendale mines of Australia occur in orogenic belts surrounding the Kimberley craton. Similarly, the Chidliak deposit under development on Baffin Island in northern Canada occurs in a late Archean terrane that was modified during later Paleoproterozoic collisional processes (Whalen et al., 2010). The importance of these diamond mines, including Lomonosov, for diamond exploration is that they show that economic quantities of diamond can occur in these younger Proterozoic regions.

Although diamonds can be associated with non-subduction refertilization events—for example, diamonds from Ellendale and Canada's Victor mine (Smit et al., 2010; Aulbach et al., 2017)—subduction in collisional terranes remains one of the key mechanisms of introducing carbon-bearing fluids into the diamond-forming regions of the deep Earth (e.g., Kesson and Ringwood, 1989). These subduction-derived fluids also introduce nitrogen, one of the main impurities in diamond. Nitrogen-related defects can contribute to a range of colors in diamonds. Examples of such defects include isolated substitutional nitrogen (N_3 ; C center), N_3 (three nitrogens and a vacancy; van Wyk, 1982), H_3 (two nitrogens and a vacancy; Davies and Summersgill, 1973; Clark and Davey, 1984), and the NV defects.

tures that indicate they derive from a wide range of depths in the lithosphere—all the way to the base of the lithosphere at 1400°C (Lehtonen et al., 2009).

By extrapolating the linear arrays of calculated P - T from both Grib and Arkhangelskaya to where they intersect with the temperature of the convecting mantle (the *mantle adiabat*), a deep lithospheric keel

of around 220 km is obtained (figure C-1; Lehtonen et al., 2009). These xenolith-based estimates of lithosphere depth during the Paleozoic (where kimberlite eruption occurred between 390 and 340 Ma) are consistent with present-day seismic evidence of a thick lithosphere more than 200 km below the Baltic shield (figure 3; Schaeffer and Lebedev, 2013).

The final, amalgamated Baltic shield was constructed during the Proterozoic from several older, smaller terranes (see the “Archean and Proterozoic History of the Baltic Shield” section). The thick lithospheric keel (>220 km; figures 4 and C-1) below the Lomonosov mine and the Arkhangelsk kimberlite province was either preserved from the various Archean terranes (such as the Kola province or the Belomorian orogen) during the Lapland-Kola orogen or reestablished after Proterozoic collision.

Age of the Lithosphere in the Arkhangelsk Region.

As noted in box B, diamond mining regions worldwide are found in association with cratons that preserve the oldest portions of Earth’s crust. Archetypal kimberlites in the Kimberley region of South Africa all erupted through the Archean (>2.5 Ga) crust of the Kaapvaal craton. Similarly, the first kimberlites discovered in Canada, at Lac de Gras, erupted through the ancient crust of the Slave craton.

In contrast, the kimberlites of the Arkhangelsk province erupted through basement crustal rocks that are predominantly of Proterozoic age (<2.5 Ga), probably reflecting Archean crust reworking during 1.95 to 1.87 Ga continental assembly (Lapland-Kola orogen; Daly et al., 2006; Samsonov et al., 2009). Although evidence for older Archean material is found in lower crustal xenoliths from Grib (*magmatic* zircons in granulites with U-Pb ages of 2.72 Ga; Koreshkova et al., 2014), Grib and Pachuga xenoliths also preserve evidence of Proterozoic modification. For example, Grib *metamorphic* zircons all have 1.96 and 1.83 Ga ages (Koreshkova et al., 2014), and Pachuga granulites have 1.9–1.7 Ga Sm-Nd model ages (Markwick and Downes, 2000).

The predominantly Proterozoic crust in the Arkhangelsk region does not exclude the presence of an Archean lithospheric mantle at depth. In northwestern Australia, for example, the Argyle and Ellendale diamond-bearing lamproites erupted through Proterozoic orogens along the margins of the Kimberley craton. However, isotopic analyses of mantle xenoliths and diamond inclusions indicate the presence of Archean mantle lithosphere at both Argyle and Ellendale (Luguet et al., 2009; Smit et al., 2010), suggesting that Proterozoic orogenic activity did not impact deeper portions of the lithosphere.

Since mantle xenoliths from the Arkhangelsk kimberlites have not been extensively dated—unlike the Kimberley craton example given above—it is not known whether the mantle lithosphere has a predominantly Archean or Proterozoic heritage. Some Grib

eclogite xenoliths were recently dated to around 2.8 Ga (E. Shchukina, pers. comm., 2016). They are apparently similar in age to Grib lower crustal rocks (Koreshkova et al., 2014), crustal rocks of the Murmansk craton (Timmerman and Daly, 1995; De Jong and Wijbrans, 2007), and eclogites in the Lapland-Kola orogen (Mints et al., 2010; Herwatz et al., 2012); see figure 2 for localities. These preliminary results suggest that although the basement crust in the Arkhangelsk kimberlite province appears to be predominantly Proterozoic, the underlying lithospheric mantle may be much older and was preserved through later collisional processes, similar to the geodynamic setting in the orogenic belts around the Kimberley craton (Luguet et al., 2009; Smit et al., 2010). Without diamond mining that exposes xenoliths and xenocrysts in the kimberlite, it would be impossible to construct this important deep geologic history.

DIAMONDS FROM THE ARKHANGELSK REGION

Diamond Type and Nitrogen-Based Temperatures.

Nitrogen, the most common impurity in natural diamonds, is used to classify diamond into different “types.” Diamonds with no nitrogen detectable by Fourier-transform infrared (FTIR) spectroscopy are termed type II, whereas diamonds that do contain nitrogen are termed type I. Nitrogen is incorporated into diamond as isolated substitutional nitrogen (N_1 ; C center). With time and temperature, this nitrogen anneals to form nitrogen pairs (N_2 ; A center) and nitrogen aggregates (V_1N_4 ; B center). The conversion from C→A→B centers has been well calibrated so that time-averaged mantle residence temperatures can be calculated (Taylor et al., 1990, 1996). Due to the temperature conditions in the lithospheric mantle, most natural cratonic diamonds contain a combination of A and B centers, termed type IaAB; see Breeding and Shigley (2009) for further details on the type classification of diamonds.

According to Khachatryan and Kaminsky (2003), diamonds from all six kimberlites at Lomonosov are predominantly type IaAB and contain 10–2900 ppm nitrogen. Less than 5% of diamonds from the Lomonosovskaya kimberlite are type II. The same study noted that nitrogen-based temperatures calculated from the percentage of B centers in Lomonosov diamonds are around $1100 \pm 50^\circ\text{C}$. Along the local paleogeotherm (shown in figure C-1), these temperatures indicate that the diamonds were derived from depths between 150 and 170 km, similar to clinopyroxene xenocrysts sampled by the kimberlites.

BOX C: PRESSURE-TEMPERATURE GRADIENTS IN THE LITHOSPHERE (PALEOGEOTHERMS)

Understanding the temperature profile with depth in the lithospheric keel known as a “geotherm” is an important first step toward understanding the diamond-stable portions of the lithosphere. The intersection of the P - T array with the thermodynamically determined graphite-to-diamond transition constrains the minimum depth at which diamond will be present in the lithospheric keel (figure C-1). Calculating a geotherm involves routine analyses of major element compositions of constituent minerals in mantle xenoliths. In coexisting minerals such as garnet and clinopyroxene, the relative proportions of elements such as magnesium, iron, and chromium minerals vary systematically with pressure and temperature. Because of this relationship, simple chemical analyses of the minerals can be used to indicate the temperature and pressure at which the minerals equilibrated.

Once a geotherm and the diamond-stable portions of the lithosphere below a diamond prospective area are constrained, these P - T conditions can be applied to any diamond indicator mineral. For example, Cr-rich clinopyroxene is known to occur alongside diamonds in the

lithospheric keel, but it can also occur at shallower pressures where graphite is stable. If pressures and temperatures are determined for clinopyroxene in diamond exploration samples and compared to the prevailing geotherm, it will become apparent whether these minerals are actually derived from the diamond stability field—in other words, whether the kimberlite is sampling portions of the lithosphere that may contain trace amounts of diamond.

Determining the geotherm also enables geologists to assess the depth of the lithospheric keel at the time of kimberlite eruption. The lithospheric keel is isolated from convection in the asthenosphere because its distinct depleted compositions make it cooler and more buoyant than the convecting mantle. The average temperature in the convecting mantle is around 1300–1400°C (figure C-1) and becomes warmer with increasing depth. Where the deepest samples occur or otherwise where the P - T array of the lithosphere (geotherm) intersects with the temperature of the convecting mantle (adiabat), one indication of lithosphere depth is obtained.

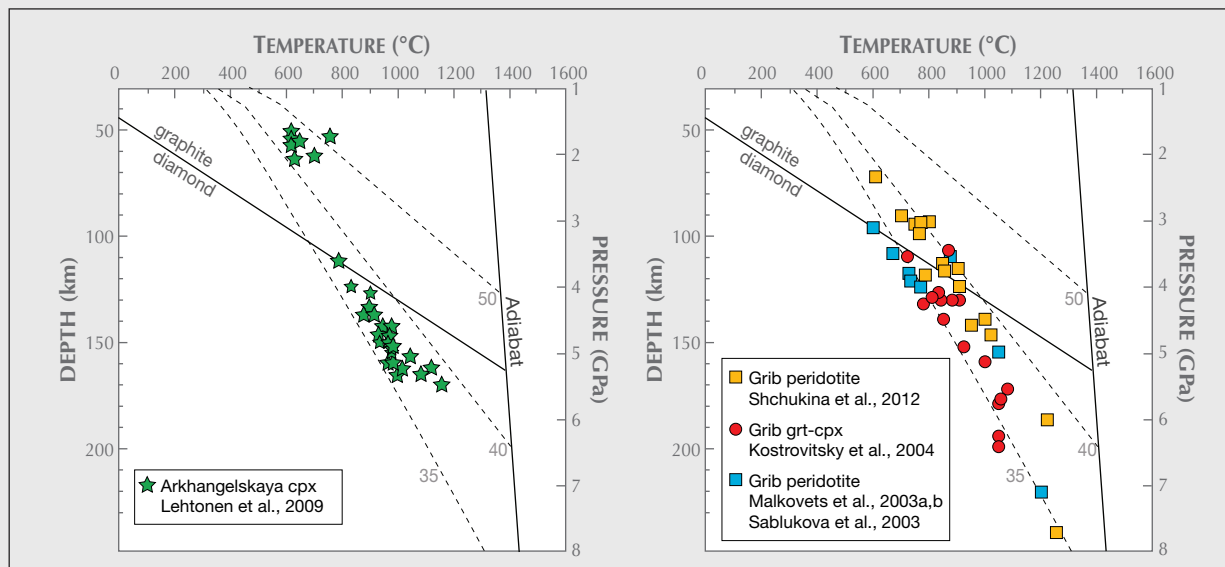


Figure C-1. Pressure and temperature (P - T) data from peridotite xenoliths and xenocrysts from the Arkhangelskaya and Grib kimberlites. For Arkhangelskaya clinopyroxene, P - T was calculated using Nimis and Taylor (2000), using data from Lehtonen et al. (2009). For Grib peridotite, P - T was calculated using Taylor (1998) and Nickel and Green (1985) using data from Shchukina et al. (2012) and other studies. Gray dashed lines are model P - T paths for the mantle known as “geotherms” for different thermal conditions, so cooler (35 mW/m^2) and warmer (50 mW/m^2) regions can easily be compared (from Hasterok and Chapman, 2011). The graphite-diamond transition, from Day (2012), defines the higher P and T conditions where diamond is expected to crystallize based on experimental studies of graphite transforming to diamond. The P - T arrays for both kimberlites are essentially similar and indicate that below the Arkhangelsk kimberlite province, diamonds are stable below 110–120 km depth. Extending the P - T trend to the temperature of the convecting mantle (or mantle adiabat) shows that the lithospheric keel is more than 220 km deep under both kimberlites. While this data is useful for comparison between these two kimberlites’ diamond favorability, it can also be applied in pre-mining studies to any kimberlite to see if it is sampling mantle that is diamond-stable.

Mantle Parageneses. Diamonds are metasomatic minerals that form when carbon-bearing fluids or melts infiltrate into either peridotite (depleted harzburgite + fertile lherzolite) or eclogite; carbon isotopic compositions of diamond can be used to distinguish its mantle paragenesis. Carbon isotopic composition is expressed in delta notation, $\delta^{13}\text{C}$, where two isotopes of carbon, ^{13}C and ^{12}C , are referenced to a standard and expressed in ‰. The mantle has an average $\delta^{13}\text{C}$ value of -5‰ but can extend down to around -9‰ . Peridotitic diamonds typically have $\delta^{13}\text{C}$ values similar to those of the mantle. Eclogitic diamonds can similarly have so-called mantle values, but also have $\delta^{13}\text{C}$ values that extend down to -41‰ . These extremely negative $\delta^{13}\text{C}$ values reflect carbon input from crustal reservoirs that likely were recycled into the lithospheric mantle through subduction (De Stefano et al., 2009; Smart et al., 2011). Grib diamonds have a narrow range of $\delta^{13}\text{C}$ values between -10 and -3‰ that likely reflects their peridotitic nature (Rubanova et al., 2009). Most Lomonosov diamonds have a similar $\delta^{13}\text{C}$ range, but a few diamonds have values down to -22.2‰ (Galimov et al., 1994), suggesting mixed peridotitic and eclogitic parageneses.

Mineral inclusions in diamonds can provide information (temperature, depth, and compositional paragenesis) about the environment in which diamonds grew. As suggested from the predominantly mantle-like carbon isotopic compositions (Rubanova et al., 2009), Grib diamonds are predominantly peridotitic and contain both chromite and olivine inclusions. Olivine from Grib has Mg# (calculated as $\text{Mg}/(\text{Mg}+\text{Fe}) \times 100$) between 92 and 94 (Malkovets et al., 2011), indicating its derivation from depleted harzburgitic to dunitic peridotite (i.e., not fertile lherzolite, which would have lower Mg# around 89–91). Grib also has a minor eclogitic diamond population containing typical orange eclogitic garnet inclusions. There have not been many studies on the mineral inclusions from Lomonosov diamonds, so a full comparison of the inclusion characteristics of these two mines is not possible. Interestingly, one study by Sobolev et al. (1997) reported a majoritic garnet inclusion (garnet with excess Si) in a diamond from Lomonosov's Pomorskaya kimberlite. These majoritic garnets are only stable at depths greater than 250 km (Stachel et al., 2005), significantly deeper than the majority of lithospheric diamonds that are derived from depths between 120 and 220 km.

Color and Morphology. Lomonosov produces few very large diamonds. The largest was a 106 ct gray indus-

trial diamond found in February 2011. Between the two kimberlite pipes being mined at Lomonosov, 82% of the diamonds are gem or near-gem quality, which is higher than the global average of 50–60% (Bain & Company, 2013). Diamonds examined by Galimov et al. (1994) and Kudryavtseva et al. (2001), as well as those on display during the authors' visit (figure 7), were predominantly resorbed dodecahedra with only minor octahedral diamonds. Approximately 0.04% of diamond production from the two pipes is fancy color, such as purple, pink, violet, green, yellow, and brown (figures 7–9). For comparison, Argyle produces around 72% brown, 27% colorless to yellow, and $<<1\%$ pink-red diamonds (Shigley et al., 2001).

Fancy colors are due to different impurities and defects in the diamond lattice and can be used to understand the geological history of the diamonds. Most near-colorless and yellow diamonds from Lomonosov would be referred to in the gem trade as "cape" diamonds (Garanin et al., 1994). These cape diamonds obtain their color from the N3 defect (three nitrogens and a vacancy; van Wyk, 1982) that forms as a byproduct during the A to B aggregation. By definition, then, all cape diamonds are type IaAB, consistent with FTIR results indicating that Lomonosov diamonds are predominantly type IaAB that have resided at temperatures around $1100 \pm 50^\circ\text{C}$ (Khachatryan and Kaminsky, 2003).

From visual color observations, there appear to be two different kinds of green diamonds, similar to Grib (Rubanova et al., 2009), with color originating from both GR1 (neutral vacancy— V^0 ; Clark and Walker, 1973) and H3 defects (NVN^0 ; Davies and Summersgill, 1973; Clark and Davey, 1984). GR1 forms through natural and artificial irradiation and also during deformation. Although GR1 occurs in all natural diamonds, the concentration of GR1 is typically too low to detect with visible/near-infrared (Vis-NIR) spectroscopy and therefore does not influence the bodycolor.

GR1 formation related to irradiation is typically imparted relatively late in the diamond's history, when it resides in crust with high concentrations of radioactive minerals. Irradiation sources for natural diamond include radioactive grains such as uraninite, zircon, monazite, and pyrochlore that may be present in either the Archean crust and its sediments or the host kimberlite. However, diamonds can also be irradiated in the lithospheric mantle when radioactive minerals such as monazite and titanite, as well as rare loparite and chevkinite, are trapped in the diamond during growth (Kopylova et al., 1997; Smith and Wong, 2016).



Figure 7. A selection of diamonds from two weeks' production, put on display during the visit to Severalmaz's sorting facility in Arkhangelsk. Diamonds from the Lomonosov deposit are predominantly re-sorbed dodecahedra, and only a few primary octahedral diamonds were seen. Around 0.04% of the diamond production consists of fancy colors such as yellow, green, purple, pink, and brown. Also on display were gray industrial diamonds. Photos by Karen Smit.

Vacancies are not exclusively related to irradiation. They can also form due to deformation during diamond's residence at high pressures and temperatures in the mantle. H3 normally forms during heating (annealing) of diamonds, which facilitates vacancy migration and trapping at A centers. These vacancies could be from GR1 or vacancy clusters that are normally associated with deformation glide planes in the diamond. A spectroscopic study of Lomonosov green diamonds would be necessary to determine if these particular H3 green diamonds underwent high amounts of deformation.

Although the pink, purple, and brown diamonds from Lomonosov have not been spectroscopically studied, a broad band centered around 550–560 nm is typically responsible for such colors (Raal, 1958; Collins, 1982). The defect structure of the 550 nm

band is unknown but generally understood to be related to deformation, since the pink and brown colors are normally concentrated along deformation glide planes in diamonds (Titkov et al., 2008; Gaillou et al., 2010; Howell et al., 2015). For example, the pink and brown Argyle diamonds occur in a Proterozoic orogenic setting along the margin of the Kimberley craton. Their residence at high temperatures in the high deformation zone near the base of the lithosphere (Stachel et al., 2017) resulted in deformation glide planes and the 550 nm band that imparts the pink and brown colors distinctive of Argyle. The Lomonosov diamonds also occur in an area of Proterozoic mountain building (the Lapland-Kola orogen noted above), and it is very likely that these pink and brown diamonds have a color origin similar to the Argyle diamonds that occur in the Proterozoic Halls Creek



Figure 8. Two yellow cuboctahedral diamonds separated during recovery sorting in the processing plant at the Lomonosov mine. Photo by Karen Smit.



Figure 9. A purple-pink Lomonosov diamond weighing approximately 0.4 ct. It was mined in early 2015 and sold for more than US\$1.6 million per carat at the Hong Kong tender sale in September of that year. Photo by Russell Shor.

orogen (1.8 Ga; Tyler and Page, 1996). It is remarkable that basic mineralogical and geological research now allows us to understand the geological conditions that create specific color centers in these diamonds.

DEVELOPMENT AND MINING OF THE LOMONOSOV DEPOSIT

Location and Development. The Lomonosov deposit is about 110 km from the White Sea port of Arkhangelsk, which was for centuries Russia's primary deepwater seaport. The deposit is located at around 65°N, a latitude similar to that of the Arctic diamond mining operations in Siberia and northern Canada. Its proximity to the White Sea greatly moderates the climate; the average winter low is -13°C (8°F), compared to -32°C (-25°F) at the Canadian and Siberian mines. Instead of barren tundra, the area hosts dense woods that have served as a source of Russian timber for several centuries.

Mining in the extreme cold of northern Canada and Siberia presents formidable logistical and operational difficulties, as detailed by Shigley et al. (2016), but Lomonosov poses challenges of its own. First, part of the site was built on a partial wetland and groundwater that had softened the soil and rock. This required Severalmaz to truck in tons of hard gravel to shore up the roads leading into the mining pits so they could withstand the weight of the large hauling trucks (Serdyukova, 2013). Then, 63 wells had to be drilled and maintained to continually pump out groundwater at more than 5100 cubic meters per hour (each well pumps nearly 70–80 cubic meters per hour), which is then fed into a canal system surrounding the mining area.

Initial development costs totaled US\$385 million, which included a processing plant with an annual capacity of 1 million metric tons of ore (Serdyukova, 2013). Production at Lomonosov started with the Arkhangelskaya pipe in 2005 (figure 10), since it had the largest reserves and the least amount of overburden—about 30 m, compared to the much larger Lomonosovskaya pipe, which was 45 m underground. Production at a second kimberlite pipe—Karpinskogo I—began nine years later in 2014. This was in tandem with the opening of a second plant capable of processing 3 million tons of ore per year.

Mining. Severalmaz employs 1,600 workers. Only the Arkhangelskaya and Karpinskogo I kimberlite pipes are currently being mined (figures 10 and 11), leaving Pionerskaya and Lomonosovskaya in reserve and Karpinskogo II and Pomorskaya under evaluation. Both kimberlite pits are mined using only excavators, without blasting. A fleet of 25 hauling trucks with 35 to 90 metric ton capacity carry the kimberlite ore from each pipe to separate stockpiles. On average, 14 million cubic tons of rock are mined per year, of which only 2 million cubic tons are kimberlite.

The shapes of the Arkhangelskaya, Karpinskogo I, and Karpinskogo II kimberlites and the diamond grade variations are given in figure 11. Current resource estimates show that Karpinskogo I has a grade of 0.6 carats per ton in the upper eruptive levels of the pipe (crater facies), improving to 1.4 carats per ton in the lower non-eruptive or magmatic section (diatreme facies). The Arkhangelskaya kimberlite has a similar resource, with current estimates of 0.5 carats



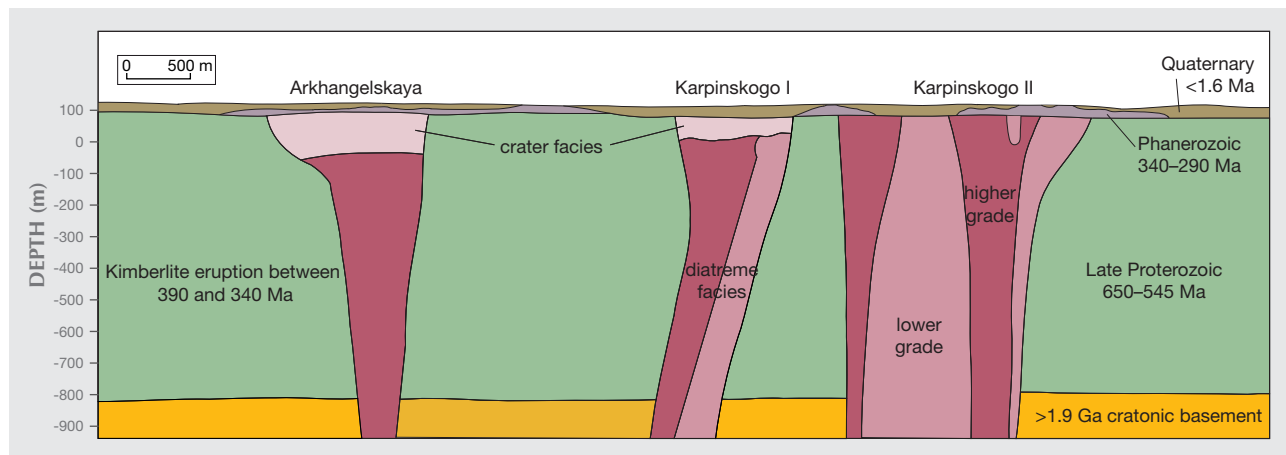
Figure 10. Open pit of the Arkhangelskaya kimberlite in August 2016, which at the time spanned 1.1 km. Arkhangelskaya was the first of the six kimberlites at Lomonosov to be developed since it had the least overburden and the largest diamond reserve. Photo by Karen Smit.

per ton in the crater facies and 1.06 carats per ton in the diatreme facies. By comparison, the Jwaneng operation in Botswana, the world's richest diamond mine by value, averages between 1.2 and 1.4 carats per ton. Russia's largest mine, Udachnaya, averages 1.3 carats per ton (Serdyukova, 2014).

Severalmaz geologists aim to maximize yield by continually sampling kimberlite sections being mined down to 2 m spacing (figure 12), updating diamond grade statistics as they go. This detailed sampling helps them identify high-grade areas in the kimberlite where diamonds are more highly concentrated. The lowest grade that Severalmaz will consider mining is 0.166 carats per ton. The total reserve estimates from all six pipes in the Lomonosov deposit are approximately 167 million carats.

Mining of crater facies kimberlite for the Karpinskogo I and Arkhangelskaya pipes will be completed in December 2017. Severalmaz expects annual production to more than double to approximately 4.6 million carats after 2017 as operations move into the richer diatreme facies and the existing processing plants are expanded. Reserves for both pipes have been determined down to 460 m, yet Severalmaz's current plan is to complete open-pit mining on them by about 2026, when Arkhangelskaya is down to 324 m (currently at 154 m) and Karpinskogo I down to 260 m (currently at 105 m). A decision will then be made about whether it is more profitable to continue mining deeper or to mine one of the other pipes such as Pionerskaya. The predicted grade for Pionerskaya is lower than for Arkhangelskaya and Karpinskogo I,

Figure 11. Geological cross-sections of the Arkhangelskaya, Karpinskogo I, and Karpinskogo II kimberlites. Modified from Severalmaz source material.



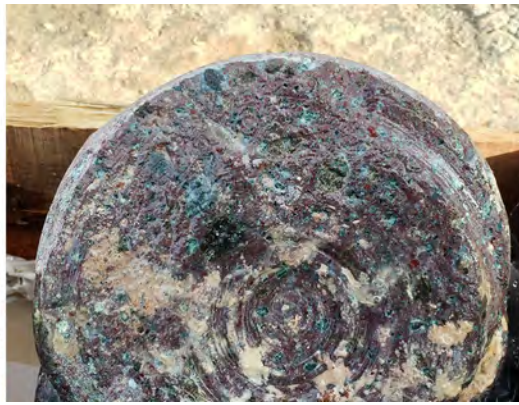


Figure 12. Large-diameter drill core samples of kimberlite from Karpinskogo I, examined by the authors. The fine-grained kimberlite contains highly altered country rock fragments, altered olivine and clinopyroxene macrocrysts, and small mantle xenoliths. Severalmaz continually examines core samples during mining to improve diamond grade estimations. Photos by Karen Smit.

but the diamonds are expected to be of better quality. During the authors' visit, Severalmaz officials said that no decisions had been made about developing the remaining pipes, though a 2017 report to shareholders said that such development was very likely.

RECOVERY AND SORTING OF LOMONOSOV DIAMONDS

Processing Plant. After mining, nearly all of the kimberlite from each pipe is stockpiled for several months in two areas located several hundred meters from mining operations. The weathering of the kimberlite, especially over winter, softens the material, making it much easier to liberate diamonds and reducing the risk of breaking or damaging larger crystals. This weathering technique is as old as systematic diamond mining and was used extensively in the early 1900s in South Africa. While the production profile is different for each pipe, the ore from both pipes is mixed together during processing to obtain uniform grades.

The initial processing phase tumbles the kimberlite in a large rotating mill that breaks the material into smaller pieces measuring about 120 × 25 mm while mixing this material with water (figure 13). This autogenous method of using the kimberlite to crush against itself instead of employing jaw crushers is less damaging to larger diamonds. The maximum size allowed through the mill was determined after a geological study showed that diamonds larger than 120 × 25 mm would likely occur only once every 30 years.

After milling, material is dispatched to hydraulic separators that segregate likely ore material from waste material based on density. The largest pieces out of the hydraulic separators go directly to units that use X-ray fluorescence and X-ray luminescence to identify diamonds. Air jets triggered by the X-ray signals deflect the diamonds into a collector box. The medium-sized pieces are first directed to density separators and

then into a thin stream through to the X-ray units, which separate diamonds down to 1.25 mm (sieve size 2, or 0.008 per carat). Material under 1 mm never makes it to the X-ray units and is sent directly to the tailings. Alrosa is developing X-ray transmission technology to identify large diamonds in kimberlite before they undergo recrushing (Alrosa Annual Report 2015).

The waste material is continually sampled for diamonds the recovery process may have missed. During GIA's visit to the processing plant in August 2016, monitors in the recovery control room continually updated the recovery rate, which remained between 97% and 99%. Between 2014 and 2016, mining of the additional kimberlite pipe (Karpinskogo I) and the comple-

Figure 13. During the initial stage of processing, the ore material is sent through a large rotating mill that breaks the material into smaller pieces through autogenous grinding while mixing it with water. This method is designed to minimize the breakage to larger diamonds that often occurs with high-pressure crushing. Photo by Karen Smit.



tion of the new \$325 million processing plant increased annual diamond production at Lomonosov from approximately 500,000 to 2 million carats (Serdyukova, 2013; Miller, 2014). Production is expected to increase to 5 million carats after the Pionerskaya and Lomonosovskaya pipes are developed (“Severalmaz recovers first 10 million carats...,” 2017).

Diamond Sorting. Every two weeks, diamonds recovered from the Arkhangelskaya and Karponskogo I kimberlite pipes are dispatched to a preliminary sorting facility in the city of Arkhangelsk. Two weeks’ production from these two kimberlites averages between 65,000 and 70,000 carats. In the Arkhangelsk sorting facility—overseen by Pavel Grib, the son of the geologist who discovered the Grib kimberlite—the diamonds are sorted manually by weight, color, shape, and clarity. Severalmaz then performs a preliminary valuation for each weight and quality category (for insurance purposes) before shipping the rough diamonds to Alrosa’s United Selling Organisation (USO) in Moscow.

At the USO, all incoming rough diamonds from Alrosa’s various Russian mines are first weighed and compared against the weights noted from each production region. Diamonds from these different production regions are then sorted by carat, color, shape, and clarity into about 8,000 subcategories of selling lots (Alrosa Annual Report 2015). Sorting is done through a combination of manual and automated operations, though development is continually underway to automate this process as much as possible (Alrosa Annual Report 2015; O. Petrov, pers. comm., 2016).

Diamonds from each production region (including Severalmaz) are kept separate throughout the sorting and sales process and are always sold in separate lots. Severalmaz determines pricing by offering small lots of diamonds, including fancy colors, at tender auctions through Alrosa sales offices. While Severalmaz is generally regarded as an Alrosa subsidiary, unspecified outside owners hold a 0.04% share in the company, necessitating the separate accounting (www.eng.alrosa.ru).

MANUFACTURING OF ALROSA DIAMONDS

Alrosa reserves 5% to 8% of its total diamond production, including Lomonosov goods, for domestic polishing. The vast majority of these are sent to Kristall, its diamond cutting operation, and marketed through the company’s polished diamond sales division, which maintains offices in Moscow, Antwerp, New York, and Hong Kong (Alrosa Annual Report 2015).

The first Russian diamond manufacturing unit was founded in 1963 in the city of Smolensk, about 400 km southwest of Moscow. By the 1970s, six additional units had been established in different cities throughout the Soviet Union (www.kristallsmolensk.com/about/history). During that period, the Soviet government earmarked as much as 20% of Russian production to be cut locally and sold primarily through offices in Antwerp, Geneva, and London (“Soviet discounts irk diamond cutters,” 1984). While officials never disclosed the exact percentage of diamonds being cut and sold, this polished production (estimated between \$230 and \$270 million yearly) was sufficient to have a strong effect on world markets by the 1980s (Thompson, 1982).

After the end of the Soviet regime, the government kept control of the operations within Russia proper. This included Kristall Smolensk, which became a sightholder in the mid-1990s after formalizing relations with De Beers. The government also invited foreign diamond manufacturers to open factories in the country. The state-owned Smolensk facility has remained the largest operation, with 2,500 workers producing 600,000 carats yearly by its fiftieth anniversary (Almor, 2013).

Russia’s 20 diamond polishing operations produced approximately 300,000 carats worth US\$670–\$680 million in 2014, the most recent year for which complete figures are available (Leikin, 2016). Three of the operations—including Smolensk, which accounts for 40% of the total polished production—are in the Kristall network. International diamond companies or independent ventures operate the remaining 17 cutting plants. The vast majority of these factories produce smaller sizes ranging from 0.2 to 0.3 carats (Leikin, 2016). As with rough diamonds, the polished goods from Severalmaz and other Alrosa subsidiaries are kept separate through the cutting process and sold separately to diamond wholesalers and large retail chains.

MARKETING AND PRICING OF ALROSA DIAMONDS

In 2015, Alrosa’s various operations produced a total of 38.4 million carats, with Severalmaz accounting for about 5%. By volume, Alrosa was responsible for 30% of world production in 2015, compared to De Beers’ 22%. It sold 30.1 million carats of rough that year for US\$3.55 billion, an average price of just over \$103 per carat. This price is relatively low, but at the same time Alrosa’s minimum recovery size is much smaller than that of other producers (Leikin, 2016).

The remaining 2015 production was either stockpiled by Alrosa or sold to Gokhran, the Russian government bureau that oversees the country's reserves of precious materials (Alrosa Annual Report 2015). In difficult economic times when demand from Alrosa's clients falls short of production, Gokhran buys the excess and stocks it until the market improves. Indeed, during the 2008–2009 financial crisis, Russia's diamond mines maintained full production, selling as much as US\$2 billion to the government bureau, while De Beers and others sharply curtailed their mining output (Shor, 2009).

Between 66% and 70% of the United Selling Organisation's rough sales are sold through a structure similar to De Beers' sight system. A set list of 54 contracted clients, called the Alrosa Alliance, buys rough at monthly sales events in Moscow during the three-year contract life. In 2016, Severalmaz goods were offered every other month in lots separate from Siberian rough. According to Alrosa, these 54 firms represent a sustainable client base of major diamond manufacturers and jewelry retailers. About half of the current Alliance members are Antwerp dealers and manufacturers (figure 14), with most of the remainder from Israel and India. They also include eight Russian manufacturers and three large retailers, Chow Tai Fook (Hong Kong), Signet Group (United States and United Kingdom), and Tiffany & Co. through its Laurelton subsidiary (<http://eng.alrosa.ru/operations/sales-policy/>).

Alrosa allocates diamonds to each client based on requested size, quality, and rough shape parameters. Its stated policy is to provide long-term contracts to guarantee monthly supply of goods in pre-agreed volumes and assortments, as well as an option to purchase an extra range of goods. This policy is designed to provide stable supplies of rough diamonds and a hedge against diamond price volatility. While Alrosa aims to fully supply requested goods, each contract does contain a provision that there may be periods when it cannot deliver entire allocations of certain types of goods (<http://eng.alrosa.ru/operations/sales-policy/>).

An additional 25% of Alrosa production, including all rough larger than 10.8 ct and all fancy colors, are sold through tender auctions termed "competitive sales" (Shor, 2014). These are conducted in Alrosa's sales offices (operating as Arcos) in New York, Tel Aviv, Dubai, Antwerp, Hong Kong, and Moscow. Buyers include members of its Alliance or companies from the industry at large that have been vetted. The auctions use electronic bidding confirmed by hard copy, with the lots going to the highest bidders, as-



Figure 14. Pink Lomonosov diamonds obtained from Diarough, an Antwerp-based diamond manufacturer. Photo by Kevin Schumacher.

suming their offers meet the reserve prices. Most other diamond producers employ more complex bidding systems that average out the top bids (O. Petrov, pers. comm., 2016). For more information on the bidding process, see Shor (2014).

Although Alrosa generally has autonomy over its diamond pricing, the Russian Ministry of Finance remains the final authority (Alrosa Annual Report 2015). Alrosa's management sets rough prices based on market information gleaned from De Beers and Rio Tinto diamond sales, results of other producers' various tender auctions, and the company's own tender auction results. The company takes a very conservative approach and tries to minimize month-to-month price volatility in favor of stability (O. Petrov, pers. comm., 2016). During the second half of 2015, however, the diamond manufacturing industry faced a crisis due to a combination of unsustainably high rough prices, low polished prices, rising

inventories, and declining bank credit. In response, the company reduced its average prices by 15% (Alrosa Annual Report 2015).

In 2016, the company reduced its output by 2% to 37.4 million carats but sold 40.1 million carats (for US\$4.3 billion), the difference coming from the 22 million carat stockpile it had accumulated during previous periods of slow demand (“Alrosa caps 2016 output to reduce stocks,” 2017). Demand for small diamonds fell sharply at the end of 2016 because of a currency crisis in India. Early in 2017, however, India adjusted to this event, and between January and April 2017, Alrosa sold 16.9 million carats of rough and polished diamonds. These sales figures were up more than 7% compared to the first quarter of 2016. By value, however, sales declined 12.5% to US\$1.7 billion as dealers wanted primarily smaller stones (“Alrosa reports sales results...,” 2017).

SUMMARY AND CONCLUSIONS

In contrast to many diamond mines in South Africa, Canada, and Siberia, the Lomonosov deposit does not occur within a setting that was stabilized in the Archean. Rather, the kimberlites at Lomonosov erupted within a Proterozoic terrane that records both splitting of the continent and subsequent collision of older Archean terranes. The thick lithospheric keel below this region—a requirement for diamond formation—was either inherited from these Archean subterranean or reestablished during Proterozoic craton assembly. Proterozoic mountain-building in this diamond-producing region of the Baltic shield is seemingly at odds with Clifford’s Rule, which states that diamond deposits are found in old cratonic regions that have been stable for at least 2.5 bil-

lion years. However, the emerging pattern in many diamond-producing regions is that these Proterozoic terranes can yield economic quantities of diamonds.

Lomonosov produces many fancy-color diamonds, including yellow, brown, pink, violet, and green, and these can be related to the diamonds’ geological history, specifically their residence in a lithospheric keel that likely experienced high amounts of deformation related to Proterozoic tectonic processes. Pink-brown diamonds typically result from deformation, either during residency at the base of the lithospheric keel approximately 200 km in the mantle (e.g., Argyle) or possibly during kimberlite eruption. It is hard not to draw parallels between Argyle and Lomonosov, since both localities occur in areas that experienced Proterozoic continental assembly and produce pink, purple, and brown diamonds.

Yellow “cape” diamonds from Lomonosov result from aggregation of nitrogen impurities in the diamonds during what appears to have been a billion-year residency at temperatures above 1100°C in the lithospheric mantle. Green diamonds are likely related to irradiation and annealing, probably late in their history during kimberlite eruption or residence at the earth’s surface.

The Lomonosov deposit is the first diamond development in the Baltic shield. Although it is in the early stages of development and only two of six potentially economic kimberlites are being mined, it is already an important source for fancy-color and colorless gem-quality diamonds. While Alrosa’s plans to develop the additional kimberlites have not been finalized, Lomonosov will likely remain a significant source of colored and gem-quality diamonds in the coming decades.

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