CHAPTER

KIMBERLITE-HOSTED DIAMONDS IN FINLAND

4.4

H. O'Brien

ABSTRACT

The levels of brilliance (brightness and contrast), fire (flashes of rainbow color), and scintillation (intense sparkles when moved) of diamonds are unmatched by any other gemstone. Also diamonds of gem size and quality are relatively rare. As a result, gem diamonds are extremely valuable, yet the supply of diamonds is ultimately limited. This reality has pushed diamond exploration and mining into extreme environments, from the far Arctic North to the deserts of southern Africa and onto the ocean bed off the coast of Namibia. About two-thirds of the annual production of diamonds by weight comes from ancient volcanoes that consist of the rock types kimberlite, orangeite, or lamproite. Tracking down the remnants of these small volcanoes requires sophisticated and efficient collection and processing of samples for kimberlite indicator minerals (i.e., peridotite constituent minerals) and evaluation of enormous amounts of mineral data to constrain the diamond prospectivity of a region, cluster of pipes, or particular diatreme. The exploration sampling stage is usually followed by aero- or ground-geophysical measurements, target evaluation, and, finally, drill testing. Diamond exploration is expensive, but the rewards can be great.

Diamond exploration in Finland started in 1985, and has been continuous, albeit with varying levels of activity, since that time. As a result, diamondiferous rocks have been found in three regions—namely, the Kuhmo-Lentiira area hosting a group of 1200 Ma orangeites, the Kuusamo-Hossa area containing several 760 Ma kimberlites, and the Kaavi-Kuopio area with a cluster of ~600 Ma kimberlites. Driven by the needs of these exploration activities, our understanding of the makeup of the Karelian craton, and our understanding of the magmas that have transported diamonds to the surface in this part of the world have benefitted enormously.

Keywords: kimberlite; orangeite; lamproite; diamond; diatreme.

INTRODUCTION

Aside from microdiamonds found in ultrahigh-pressure terranes (e.g., Massonne, 2003) or those associated with astroblemes (e.g., Masaitis, 2013), diamonds do not form in the Earth's crust. Gem-sized diamonds only crystallize at depths of around 140–150 km or greater (depending on the geotherm), where the mantle has been stable over billions of years and there is the right balance of heat, pressure, and low oxygen conditions for carbon to exist as diamond. Complex zoning in diamonds attests to the fluid processes involved as diamond grows in the mantle (Kaminsky and Khachatryan, 2004) and in rare cases encapsulates tiny grains of Mg-rich pyrope, chromite, and sulfide that record the particular types of peridotite and eclogite that host diamond in the mantle (Stachel and Harris, 2008). However, no peridotite or

Mineral Deposits of Finland. http://dx.doi.org/10.1016/B978-0-12-410438-9.00014-5

eclogite massif that has been moved tectonically to the Earth's surface has been found to contain diamond, although rarely, diamond pseudomorphs are known from peridotites (e.g., Beni Bousera; Pearson et al., 1989). Instead, diamonds have been transported to the Earth's surface by rapidly moving magma.

There are only a few magma types that are derived from sufficient depth to pass through mantle where diamond is stable, and that ascend rapidly enough to the surface so that the diamond xenocrysts they entrained are not fully oxidized to graphite on the way up. These magmas are all alkaline in composition, and comprise kimberlites, orangeites, lamproites, and ultramafic lamprophyres (definitions follow). Nearly all hard-rock diamonds mined are found in kimberlites and orangeites, whereas there is currently only one operating mine in lamproite (Argyle in northwestern Australia) and none in ultramafic lamprophyre. Thus, upward of two-thirds of the annual world production of 130 million carats is sourced from kimberlite and orangeites.

This subchapter provides a brief discussion of diamond-bearing rocks in general, and then focuses on diamond exploration and deposits in Finland. Appendix A provides further information about exploration results in the Kaavi-Kuopio area, as well as further data on the Lahtojoki kimberlite, the highest grade kimberlite in Finland.

AGE AND OCCURRENCE

Diamond-bearing igneous bodies have been emplaced from the Holocene (e.g., Igwisi Hills kimberlite volcanoes in Tanzania; Brown et al., 2012) to as far back as the Proterozoic (the Kuruman kimberlites in South Africa erupted ~1.8 Ga; Donnelly et al., 2011). Although examples of diamond mines based on Proterozoic kimberlite (e.g., the Cullinan mine on the 1.2 Ga Premier pipe, South Africa) and olivine lamproite (e.g., the Argyle mine on the 1.2 Ga Argyle pipe, Western Australia) exist, the bulk of the larger diamond mines are built on pipes that are Paleozoic or younger, probably due to the poor preservation of older diatremes (Brown and Valentine, 2013).

Current age data for kimberlite magmatism show that they have been concentrated in "pulses" within the Earth's history, with particularly important intrusion events at around 1100–1200 Ma, 550–650 Ma, 360–380 Ma, 120 Ma, 90 Ma, and 60 Ma. These pulses have been related to periods of supercontinent formation or breakup, while periods with relatively few kimberlites correlate with stable supercontinents (Jelsma et al., 2009). As an example, the Devonian kimberlite event coincides with continent breakup in the Kola and Siberian craton, but a stable Gondwana at that time was almost unaffected by kimberlite magmatism, as described in Jelsma et al.

Kimberlite-related rocks have not been found in oceanic settings, and are not as common in continental areas where the crustal basement rocks are younger than Precambrian. However, this is likely due to the fact that most kimberlites are discovered by exploration companies that focus on cratonic areas understood to be most prospective for diamonds. There are probably more kimberlites in younger terranes, but they are less likely to be found.

Sm-Nd isotope studies of inclusions of Mg-pyrope and diopside (e.g., Richardson, 1986) and Re-Os on sulfide inclusions (e.g., Pearson et al., 1998) have proven that diamonds are generally very old. Some date back to 3.8 Ga, and the vast majority, although not all, are much older than the rocks that contain them. Gurney et al. (2010) reviewed the age information on diamond inclusions (diamonds themselves cannot be dated as they are composed mainly of carbon, and some nitrogen and other impurities) and concluded that there are two main age groups for peridotite-hosted diamonds: 3520–3200 Ma and 2030–1900 Ma. The range of ages for eclogite diamonds is 2900–580 Ma. These ages are older than nearly all of the diamondiferous kimberlites and orangeites in existence, and thus reinforce the fact that diamonds are xenocrysts in these magmas.

DEFINITIONS

Kimberlites are formed from ultramafic, volatile-charged, incompatible element-rich magmas that represent a mixture of small degree partial melts from the mantle, mantle peridotite, and eclogite detritus carried from depth, and typically contain minerals of the megacryst suite such as Ti-pyrope, Mg-ilmenite, and subcalcic clinopyroxene. There are two end-member rocks that have been called kimberlite in the past: Group I has abundant large, rounded grains (macrocrysts) of olivine, in a matrix of subhedral to euhedral olivine, monticellite, perovskite, spinel, mica, calcite, and serpentine, whereas Group II typically has abundant phlogopite ± olivine in a matrix of phlogopite, K-richterite, and other diagnostic minerals.

Due to the lack of evidence for a genetic relationship between these two kimberlite groups, Mitchell (1995) reinstated the name *orangeites,* originally coined by Wagner (1928), for the Group II kimberlites. Mineralogically, the orangeites are more akin to olivine lamproites (except for the lack of carbonate in the latter), and it is now generally agreed that orangeites are the southern African equivalents of lamproites, representing metasomatized lithospheric mantle melts (Mitchell, 2006). The Karelian craton also contains rocks that can be called orangeites, and these are discussed in a later section. The fourth rock type that can contain sufficient diamond to constitute an ore deposit is ultramafic lamprophyre (UML), namely the varieties aillikite and alnöite. However, as mentioned earlier, no lamprophyre is currently mined. The mineralogical differences, noted in the following, between these rock types are summarized in Table 4.4.1:

- Kimberlites and orangeites carry more mantle-derived material than lamproyes and lamprophyres, including xenoliths, xenocrysts, and olivine crystals.
- Phlogopite occurs in all of these rocks, consistent with their alkaline, fluid-rich compositions, but the composition of phlogopite varies significantly between the magma types.
- The CO_2-to-water ratio of the magmas decreases from kimberlite to orangeite to lamproite, with ultramafic lamprophyres showing a wide range of CO_2/H_2O ratios.
- Evolved orangeites and lamproites are mineralogically very similar.

FORM

Kimberlites form dikes, sills, diatremes, and, exclusively in young occurrences, lavas and tuffs (e.g., Igwisi Hills; Brown et al., 2012). The most important kimberlites in terms of volume are those that form diatremes as part of explosive maar-diatreme volcanoes. A diatreme is the carrot-to-cylindrical shaped body that extends downward from the crater (Fig. 4.4.1). It is important to point out that diatremes form from a wide variety of magma types, ranging in composition from alkali basalts to nephelinites to carbonatites to kimberlites. When referring to kimberlites, diatremes are often called "pipes." The exact mechanism by which kimberlite diatremes form is still open to much debate.

Table 4.4.1

		Kimberlites	Orangeites	Lamproites	Ultramafic Lamprophyres
Mantle	*Xenoliths*	common	common	rare	rare
	Xenocrysts	common	common	rare	rare
Olivine	*Macrocrysts*	common	common	rare	rare
	Xenocrysts	common	common	common	common
Mica	*Macrocrysts*	common	common, phlogopite	common, phlogopite to	common
	Phenocrysts	phlogopite		Ti-phlogopite	phlogopite
	Groundmass	common, phlogopite kinoshitalite	common, tetraferriphlogopite	common, Ti-tetraferriphlogopite	common, Al-biotite
Spinels		abundant, Mg-chromite to Mg-ulvöspinel	rare, Mg-chromite to Ti-magnetite	rare, Mg-chromite to Ti-magnetite	common, Mg-chromite to Ti-magnetite
Monticellite		common	--------------	--------------	common
Diopside		--------------	common, Al- + Ti-poor	common, Al- + Ti-poor	common, Al- + Ti-rich
Perovskite		common, Sr- + REE-poor	rare, Sr- + REE-rich	rare, Sr- + REE-rich	common, Sr- + REE-poor
Apatite		common, Sr- + REE-poor	abundant, Sr- + REE-rich	common, Sr- + REE-rich	common, Sr- + REE-poor
Primary Serpentine		abundant	common	--------------	--------------
Calcite		abundant	common	--------------	common
Sanidine		--------------	rare groundmass	common, phenocrysts + groundmass	--------------
K-richterite		--------------	rare groundmass	common, phenocrysts + groundmass	--------------
K-Ba-titanates		very rare	common	common	--------------
Zr-silicates		very rare	common	common	--------------
Mn-ilmenite		rare	common	very rare	rare
Leucite		--------------	rare pseudomorphs	common, phenocrysts	--------------

-------------- = absent | critical characteristic | important characteristic | characteristic of evolved member

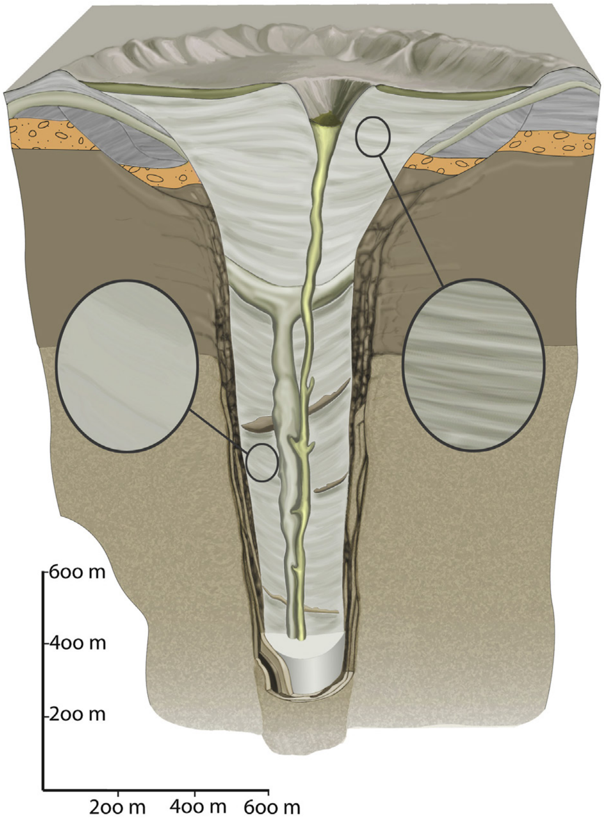


FIGURE 4.4.1 Cross section of a kimberlite diatreme based on the Missouri Breaks diatremes, Montana.

Source: *After* Hearn (1968).

In question is the role of groundwater in kimberlite diatreme formation, with some authors favoring a phreatomagmatic model (Lorenz, 1975; Lorenz and Kurszlaukis, 2007) also used to explain the formation of maar-diatremes of more common, roughly basaltic compositions. Others prefer a purely magmatic gas model wherein intense gas exsolution from uniquely volatile-rich kimberlite magma provides the explosive power to disrupt surrounding country rocks and form the diatreme (e.g., Gernon et al., 2009, 2012). The fragmental rock that fills most kimberlite diatremes in most of the pre-2000 literature was termed *tuffisitic kimberlite breccia* (TKB), but the current term is *volcaniclastic kimberlite* (Scott-Smith et al., 2013).

This fragmental rock represents a mixture of kimberlite and pulverized country rock produced as the diatreme grows downward (Fig. 4.4.1). In well-preserved diatremes, including kimberlite and other magma types, it is common to find the upper diatreme fill showing relatively fine-scale layering, whereas deeper into the diatreme the infill takes on a more massive texture, with only vague large-scale layering developed (see Fig. 4.4.1 and White and Ross, 2013). This, and many other similarities among diatremes of diverse magma types, argues for similarity of processes in their formation.

Most of the diamond mines globally exploit diatremes, as they represent large volumes of diamondiferous rock. However, because the volcaniclastic kimberlite diatreme fill is considerably diluted in mantle-derived material compared to the kimberlite feeder dike magmas, the latter can produce the richer diamond ore. For example, Petra Diamonds' Helam dike has a diamond grade of 2.7 ct/t but only 1.5 Mt of reserves. Nevertheless, such small deposits are economically challenging relative to large diamondiferous pipes. For example, the Orapa mine has a grade of 0.587 ct/t but 146.1 Mt of ore reserves as of December 2012 (DeBeers Annual Report, 2013).

MANTLE ASSIMILATION

As previously described, diamond-bearing alkaline rocks form from volatile-rich potassic magmas that in most cases have incorporated variable amounts of lithospheric mantle-derived peridotite (lherzolite, harzburgite, and dunite) and, in many localities, eclogite. The key to these magmas containing diamond is that as they ascend through the mantle, they fracture and break off meter-sized pieces of the mantle conduit (Fig. 4.4.2). This material disaggregates as the magma ascends, subsequently becoming incorporated and forming a main component of the kimberlite magma.

In some kimberlites, the xenolith material may represent 70% of the magma (Patterson et al., 2009). As a consequence, most of the olivine in kimberlite is xenocrystic and the degree of mantle assimilation is critical in rendering a kimberlite economic because diamond occurs preferentially in harzburgitic peridotite and Mg-poor eclogites. Thus, both mineralogy and lithogeochemistry can provide a measure of the amount of mantle assimilation, which is generally positively correlated with a higher potential for diamond content.

Kimberlite indicator minerals (KIMs) are peridotite and eclogite constituent minerals that are contained in surficial sediments. In exploration samples, the presence of KIMs indicates that mantle-containing

FIGURE 4.4.2 Mantle-derived lherzolite xenolith about 0.75 m in its longest dimension from the Liqhobong mine in Lesotho, southern Africa.

material has been exposed at the surface, and that by erosion of this source material, these grains have been liberated, transported, and deposited by surficial processes. The source is located in the opposite direction of the flow of the transporting medium (e.g., glacial ice or flowing streams). The KIMs comprise mostly olivine, pyrope garnet, chromian diopside, Mg-rich ilmenite (picroilmenite), and chromite; in other words, the constituent minerals of peridotites and eclogites that have been disaggregated and partially assimilated during ascent of the kimberlite magma to the surface.

These minerals have compositions specific to mantle and hence form pathfinders to hidden kimberlite targets. Moreover, the compositions of the KIMs provide substantial information about the type of mantle that was sampled, and allow a rough estimation of the diamond prospectivity of a given region. Several compositional plots for indicator minerals for the Lahtojoki kimberlite (discussed in a later section) are provided as examples in Appendix A.

Chemical compositions of well studied hypabyssal diamondiferous kimberlites, orangeites, and lamproites are plotted on a SiO_2 versus FeO diagram in Fig. 4.4.3. The plots show the geochemical consequences of significant mantle assimilation on kimberlite magma compositions, and they can be used to screen new kimberlite discoveries with regard to their diamond prospectivity. (Note that volcaniclastic diatreme infill as described earlier cannot be plotted due to its large crustal component; see O'Brien and Tyni, 1999, for Finnish examples). Specifically, as the kimberlite whole-rock compositions converge on those of harzburgite—as a direct consequence of having assimilated greater amounts of this material—the probability of containing economic quantities of diamonds increases.

Although there have been many estimates of the so-called protokimberlite melt composition, the composition proposed by Le Roex et al. (2003) has been used here to demonstrate the degree of shift

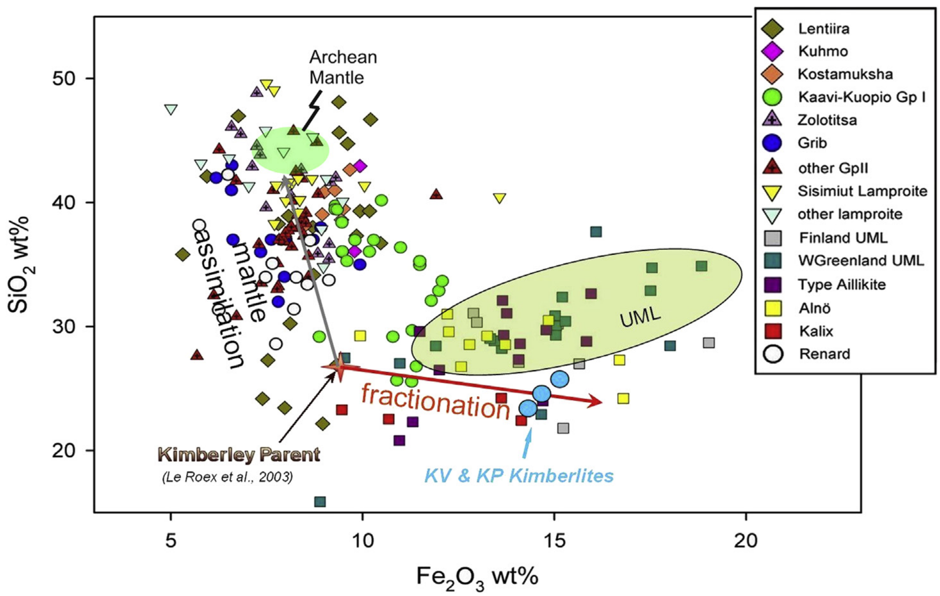


FIGURE 4.4.3 Plot of SiO_2 versus FeO for selected Finnish kimberlites and orangeites.

Shown are a number of well-studied kimberlites, orangeites, and lamproites from around the world and Finland. UML = ultramafic lamprophyre; KV and KP refer to Kuusamo kimberlites.

toward SiO_2-rich compositions that results from significant peridotite assimilation. The general paucity of orthopyroxene xenocrysts in any of the diamond-carrier rocks, and its abundance in peridotites, strongly suggests preferential resorption of this mineral during magma ascent. This model is consistent with the SiO_2-enrichment trend shown in Fig. 4.4.3. It should also be noted that the field that contains the bulk of ultramafic lamprophyre compositions lies at distinctly more Fe-rich compositions than the main cluster of diamondiferous rocks.

DIAMOND EXPLORATION IN FINLAND

As a direct result of the high level of diamond exploration activity in Finland, diamond-bearing rocks have been identified in three different areas of the country: Kaavi-Kuopio, Kuhmo-Lentiira, and Kuusamo-Hossa (see Subchapter 4.1, Fig. 4.1.4; see also locations of individual kimberlites on the GTK map server at http://gtkdata.gtk.fi/mdae/index.html). Each of these regions is described in subsequent sections following a brief review of the diamond exploration activities in Finland that led to the kimberlite discoveries and, consequently, our studies of them.

The first kimberlite in Finland was discovered in 1964 by Malmikaivos Oy, a private prospecting company based in Luikonlahti in eastern Finland. The 1-ha pipe was discovered during a regional ground magnetic survey while prospecting for base metals in the vicinity of Kaavi. Overburden was only 2 m thick and the kimberlite was exposed by trenching and drilling. Since there was no potential for copper ore, the discovery of this pipe was not considered further. However, in the late 1970s, during further base metal prospecting in the area, glacial boulders of well-preserved "almond rocks" were discovered. Samples sent to several diamond companies were identified as kimberlite and proven to contain microdiamonds. By tracing boulders in the up-ice direction, Malmikaivos Oy located a second kimberlite in 1984 under a small swamp and a third ("no. 3") in 1985 under a small lake, only 500 m away from no. 2.

In 1985, Malmikaivos Oy decided to find a partner with diamond exploration expertise, and signed an agreement with Ashton Mining Ltd. Malmikaivos exploration teams subsequently managed to find all but one of the kimberlites now known in the Kaavi-Kuopio area. Till sampling and heavy mineral separation were also used extensively by Dia Met Minerals Ltd. during its four years of exploration for diamonds in Finland from 1996–1999.

Rio Tinto Ltd. (which acquired Ashton Mining in 2000) and Dia Met Minerals relied more heavily on geophysical methods for locating kimberlites including magnetic, electromagnetic, gravimetric, and seismic methods. The success of these various methods was inconsistent and depended on the composition of the pipes (i.e., the pipes did not give equivalent responses to a given geophysical method). For example, in a 1996 helicopter aerogeophysical survey flown for Dia Met, only half of the known bodies were able to be located (Matti Tyni, personal communication, 2012). On the other hand, numerous nonkimberlite anomalies with geophysical responses similar to certain kimberlites (e.g., thick lake-bottom sediments) were found and drill tested. Information on the extent of activities by DeBeers (as Finnsearch Oy) is limited, but it appears the company worked mostly in areas of Finland other than Kaavi-Kuopio.

Near the end of operations by Dia Met and Malmikaivos, the Geological Survey of Finland (GTK) developed new tools for processing till samples for kimberlite indicator minerals (Chernet et al., 1999; Lehtonen et al, 2005). To test this new capability, GTK processed till samples from several sampling lines in the Kuhmo-Lentiira area of eastern Finland, with sufficient positive results that an invitation for tenders was published, and was won by American Mineral Fields. During this same period, Conroy Diamonds and Gold PLC (transferred to its subsidiary Karelian Diamonds Ltd.) was acquiring ground and conducted a successful sampling program in eastern Finland. North Star Diamonds AS, on the other hand, took up activities in the Kaavi-Kuopio area vacated by Ashton/Malmikaivos and Dia Met. The company spent considerable time and effort drilling earlier discoveries but ultimately turned its attention to areas near Ekati Mine in Canada, and left Finland in 2006.

In 2000, European Diamonds was incorporated to explore for diamonds in Finland, and the first target was the area canvassed earlier by American Mineral Fields. Work proceeded for several years in the area, resulting in the discovery of several orangeite dikes and diamonds in till, but the ultimate sources of the main indicator fans were not located. The company also made discoveries in the Kuusamo area, and spent several years (2003–2006) removing overburden, drilling, and sampling for microdiamonds from the Lahtojoki kimberlite in the Kaavi-Kuopio area. It extracted a 2000-ton bulk sample from this pipe and had it processed at GTK Outokumpu for diamonds. Work on this project and others in Finland were, however, rapidly ramped down in 2006 when company resources were directed instead toward developing the Liqhobong mine in Lesotho, southern Africa. Also during the period 2004–2006, Gondwana Investments drilled targets in the Kaavi-Kuopio area and did reconnaissance sampling in other Archean parts of Finland, with some very interesting indicator mineral results that have not yet been followed up.

Mantle Diamonds Ltd. joint-ventured with European Diamonds beginning in 2008 to further the Lahtojoki project. The company moved several million m^3 of overburden and built pads for auger drill sampling of the pipe, but by then a downturn in exploration investment had started and by 2010, further work on this project was halted.

In early 2005, Sunrise Diamonds PLC discovered seven kimberlite bodies in four different localities within a 20-km radius south of Kuusamo, thereby establishing the third kimberlite province in Finland (see later section). The company subsequently broadened its Finnish diamond exploration holdings by being part of the third wave to work on the kimberlites in the Kaavi-Kuopio area (except Lahtojoki) after it agreed on a joint venture with Nordic Diamonds Ltd. (formerly North Star Diamonds) and gained full control of the claims in early 2009. Work included further drilling on several kimberlites, especially no. 17, mostly for microdiamond sampling and additional till sampling in the area. Sunrise Diamonds had several 200–300 kg samples of Kaavi-Kuopio kimberlites processed by Mineral Services in South Africa for microdiamonds and found several macrodiamonds in the process (Table 4.4.2).

DIAMOND REGIONS OF FINLAND

KAAVI-KUOPIO GROUP I KIMBERLITE PROVINCE

The Kaavi-Kuopio kimberlites are found in two fields, located only ~50 and ~30 km inboard from the southwestern margin of the craton, respectively (refer to Fig. 4.1.4 in Subchapter 4.1). The 20 occurrences known are typical Group I kimberlites, with the archetypal suite of mantle-derived peridotite and eclogite xenoliths; disaggregated xenoliths (xenocrysts); and the megacryst suite minerals: Ti-pyrope, Mg-ilmenite, and Cr-diopside. They also commonly contain xenoliths of lower, mid, and upper crustal rocks through which the magmas have traversed (Peltonen et al., 2006).

These kimberlites have abundant large, rounded grains (macrocrysts) of olivine, in a matrix of euhedral olivine, monticellite, perovskite, magnesian ulvöspinel-magnetite, Ba-rich phlogopite-kinoshitalite mica, apatite, calcite, and serpentine. In addition to having typical kimberlite mineralogies, the

Table 4.4.2 Diamond results for Kaavi-Kuopio kimberlites

Claim report	No.	Claim	Latitude			Longitude			Size	micro diamond smp	micro diamond	Macro diamond smp	Result
			deg	min	sec	deg	min	sec	ha	kg	count	tons	ct/100t
No report	1	Koskeniemi	62	54	23.6	28	37	28.7	1.1	107	0[1]	---	
5287/1	2	Niilosuo	63	5	29.8	28	42	13.0	1	172	72	162.8	0.23
5287/1	3	Niilonlampi	63	5	40.9	28	42	3.2	1	---		2.2	0.91
4251/1	4	Karetinsaaret	62	47	49.9	28	44	0.4	1.5	27	18	8.2	0.21
4285/1	5	Kärenpää	63	2	12.5	28	40	1.6	2.2	122	20	185.9	0.6-7.0
4528/1	6	Teeripuro 1	63	0	40.7	28	38	32.7	1	48	18	13.4	6.6
4557/1	7	Lahtojoki	63	1	50.3	28	34	39.2	1.8	59	20	23.3[2]	30.6*
No report	8	Aviolampi	63	3	38.4	28	32	55.5	sill	---		---	
No report	9	Kalajärvi	62	58	10.0	28	31	29.6	0.5	25	0	---	
4937/1	10	Ryönä	62	57	17.8	28	0	51.7	2.2	26	5	13.3	1.8
SD	10									202.76	10		3 macros[3]
5873/1	11	Munakka	62	57	49.1	28	1	41.8	0.3	25	1	---	
4886/1	12	Kotkatniemi	62	56	41.6	27	50	1.6	1.6	161.5	70	9.4	17.11[4]
4988/1	13	Säyneenjärvi	62	58	30.9	27	47	54.1	0.9	48	3	3	14.33
5584/1	14	Kaatronlampi [5]	63	4	2.9	28	25	9.4	0.3	73	1	---	
5175/1	17	Kylmälahti	62	56	44.8	27	54	41.8	2.0	98.7	8	---	
SD	17									134.96	20		5 macros[6]
5584/1	20	Ala-Vehkalahti	63	4	9.4	28	24	39.8	0.3	21	0	---	
5495/1	21	Lapinluhta	62	57	41.8	27	48	59.5	1.6	109	37	16.6	26.65[7]
5495/2	22	Uuhilahti	62	57	28.4	27	47	28.3	0.2	60	22[8]	---	
6058/1	23	Jokiharju	62	43	2.2	27	36	30.4	0.25	154.5	positive	---	
6343/1	25	Viitasalo	63	0	8.3	28	5	56.1	0.2	63.1	5	---	

Notes
SD = Sunrise Diamonds press release
[1]*Sunrise Diamonds also reported no microdiamonds*
[2]*also 1000 ton bulk sample giving 5.68 ct/100 t*
[3]*largest macrodiamond 1.7x0.93x1.57 mm*
[4]*5 Diamonds over 0.4 mm. Macrodiamond content range 12.50-26.06 ct/100t*
[5]*Contains abundant fresh olivine*
[6]*largest macrodiamond 1.02x0.75x0.87 mm*
[7]*4 Diamonds over 0.4 mm. One 1.126 ct diamond Excluding these, diamond content is 19 ct/100t.*
[8]*3 Diamonds over 0.4 mm.*
**see Appendix A for details*

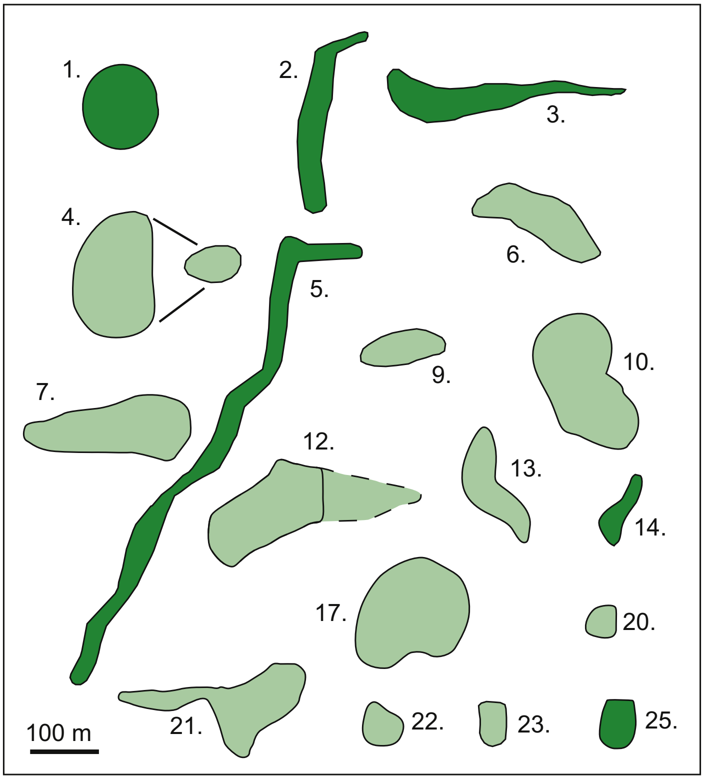


FIGURE 4.4.4 Comparison of kimberlites from the Kaavi-Kuopio area.

Dark green and light green indicate hypabyssal and volcaniclastic kimberlite, respectively. No. 11 is missing because it was not drill-delineated.

Kaavi-Kuopio pipes also have major and trace element and Sr, Nd, and Pb isotopic compositions similar to other Group I kimberlites globally (O'Brien and Tyni, 1999). Age determinations by ion microprobe analyses of U-Pb in perovskites have been made on four of these kimberlites with measured ages ranging from 589–626 Ma (O'Brien et al., 2005), but additional radiometric age dating is ongoing.

The Kaavi-Kuopio kimberlites range from hypabyssal, dike-like bodies (e.g., no. 5), to sheets (e.g., no. 25) to volcaniclastic kimberlite and volcaniclastic kimberlite breccias formed in steep-sided funnel- or carrot-shaped diatremes, as described earlier. Outlines of 19 of the 20 kimberlites from this area are shown in Fig. 4.4.4 (Pipe no. 11 is not included as it was never drill delineated, but its size is estimated at 0.3 ha). As in many kimberlite provinces hosted by crystalline basement, the kimberlites are rather small, ranging in size from narrow dikes <1 m wide to elongate bodies 500 m × 30 m in size to nearly circular diatremes up to 4 ha in size. None of the Kaavi-Kuopio pipes appear to have existing crater-facies materials due to removal of the upper portions of the diatremes by uplift and erosion.

The hypabyssal facies rocks (dark green in Fig. 4.4.4) are hard and compact, with dark gray to black matrices enclosing coarser minerals, particularly olivine, and crustal and mantle xenoliths. Pipe 1 (Fig. 4.4.5(A)) may represent the deepest exposure of root zone material because of its well-developed

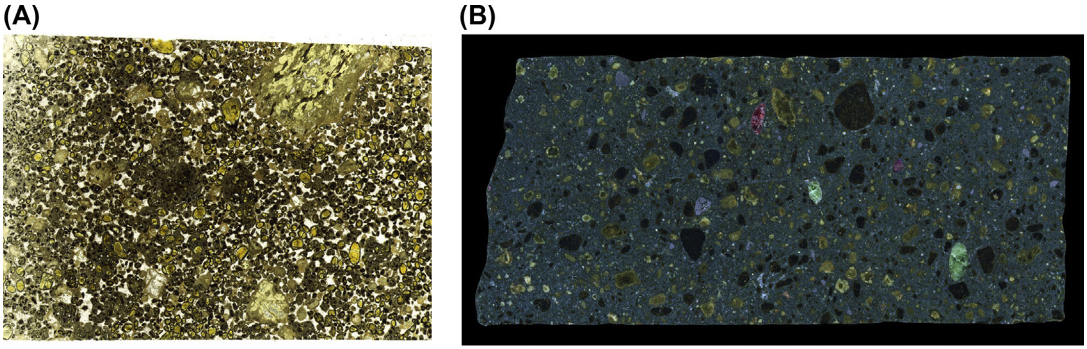


FIGURE 4.4.5 Hypabyssal kimberlites from Kaavi-Kuopio.

(A) Scan of a thin section of the margin of Koskeniemi kimberlite (Pipe no. 1) showing altered olivine xenocrysts and phenocrysts and tiny magmaclasts containing vesicles filled with carbonate, cemented together by carbonate and serpentine matrix. Vertical dimension in image is 3 cm. (B) Hypabyssal kimberlite containing abundant indicator minerals (Malmikaivos Oy, prospect no. 10; Ryönä). The indicator minerals are chrome-rich red pyrope garnet, green diopside, and steel gray magnesian ilmenite. In addition, the sample contains two generations of altered olivine grains. Mantle xenocryst compositions and the existence of diamonds demonstrate that some sampling of the mantle occurred from within the diamond stability field. Core is 3 cm wide.

segregationary texture, which in some samples, particularly near the edge of the intrusion, develops into globular segregations in which late crystallizing serpentine and calcite form irregular pools in a more uniform silicate matrix. A more typical hypabyssal kimberlite from Kaavi-Kuopio is shown in Fig. 4.4.5(B). It displays the classic suite of lithospheric mantle-derived xenocrysts:

1. Mg-ilmenite, which shows complex zoning and resorption features suggesting extensive magma mixing (see O'Brien and Tyni, 1999).
2. Pyrope garnet derived from a range of sources including high Cr, Ca-depleted harzburgite, Ca-saturated lherzolite, Ca-rich wehrlite, Ti-rich megacryst-compositions, and, at lower MgO and higher CaO contents, orange garnets derived from mantle eclogite (Lehtonen et al., 2004).
3. Clinopyroxene comprising lherzolitic, low-Cr megacrystic, and eclogitic subgroups.
4. Spinels from upper mantle spinel lherzolites and rare chromites plotting within the diamond inclusion field.

Quantities and volume ratios of mantle-derived xenocrysts vary considerably among the bodies but, in general, the compositions of these minerals do not show large intrapipe variations. For further details of the Kaavi-Kuopio hypabyssal kimberlite mineralogy, the reader is referred to O'Brien and Tyni (1999) and O'Brien et al. (2005).

The diatreme facies rocks (light green in Fig. 4.4.4) are softer and span the color spectrum from green to gray to brown to dark red. Diagnostic textures of the diatremes facies rock types include rounded pelletal lapilli, in which kernels of small crustal xenoliths or mineral grains, particularly olivine (pseudomorphs), are surrounded by a rim of magma (crystals and melt), later altered to serpentine- and carbonate-rich material. Altered juvenile pyroclasts are also common. The content of crustal material incorporated into the diatreme during formation is large, raising silica contents from original levels of ~30 wt% to ~44 wt% $SiO2$ or more (O'Brien and Tyni, 1999).

Diamond grade results for the 20 known Kaavi-Kuopio kimberlites are summarized earlier in Table 4.4.2. A short discussion for each kimberlite from the area has been extracted from the GTK Research report (Korkeakoski et al., 2004) and compiled in Appendix A. All of the macrodiamond results in the table are based on processing of the kimberlite in the Malmikaivos Oy dense media plant set up in the nearby town of Luikonlahti, except for a few additional data reported by Sunrise Diamonds. Most of the grades are relatively modest, but the value of the diamonds is critical in calculating the value per ton, and none of the kimberlites were sampled adequately to get a representative diamond sample for valuation.

The Lahtojoki Kimberlite (Pipe no. 7) is the best studied of all the kimberlites in the Kaavi-Kuopio area, mostly because it has the most promising diamond content (Table 4.4.2). It is located in the Kaavi district, eastern Finland (63° 1’ 50.3” north latitude, 28° 34’ 39.2” east longitude). The pipe was discovered by Malmikaivos Oy by sampling glaciogenic deposits, which in the Kaavi area consist of an ablation till overlying predominantly a single basal till layer, together forming a till cover rarely more than 3 m in thickness. Basal till samples were processed for kimberlite indicator minerals using the Luikonlahti dense media separation plant and positive samples were followed up the main ice flow direction of 335° until KIM counts dropped drastically (Matti Tyni, personal communication, 2012). At the head of the train, in what turned out to be a deep pocket in the till, a 500 m × 500 m magnetic survey identified a target that was drill tested in October 1989 and proved positive for kimberlite.

A more recent mineralogical study of the glaciogenic deposits in the vicinity of the Lahtojoki pipe designed to investigate in detail the indicator mineral fan in the down-ice direction from Lahtojoki (Lehtonen et al., 2005) concluded the following about the kimberlite indicator minerals in the till:

- Picroilmenite, garnet, and Cr-diopside are the main indicator minerals; chromite is virtually absent.
- Picroilmenite grains are usually covered by leucoxene alteration products and polygranular recrystallization is also a common morphological feature.
- Pyrope garnets are divided into two groups based on color and composition: (a) purple, red, and lilac lherzolitic and harzburgitic Cr-rich pyropes and (b) orange megacryst-composition Ti-pyropes and eclogitic garnets.
- Approximately 20% of the 0.25–2.0 mm pyrope grains are covered by kelyphitic rims, which get more common as the grain size increases and are more common on lherzolitic garnet varieties. Intense alteration and orange-peel resorption surfaces are also abundant in garnets separated from the Lahtojoki kimberlite.
- Cr-diopside grains are mostly angular and corroded.

The Lahtojoki diatreme is suboval in plan, measuring approximately 200 m (east–west) × 100 m (north–south) and is approximately 2 ha in area at the surface. Drill information suggests that at the −100 m contour, the pipe dips 80° toward the south, and is still nearly 2 ha in cross section. A representative sample of the volcaniclastic kimberlite breccia excavated as part of the Malmikaivos/Ashton bulk sample is shown in Fig. 4.4.6. From this image it is clear that at least parts of the bulk sample were quite rich in country rock clasts. Logging of the available Lahtojoki drill core suggests that the bulk of the volcaniclastic diatreme material has much lower country rock dilution.

This difference in wall rock contamination may be the explanation for the large discrepancy between the mini-bulk sampling, which totaled 23.3 t and returned diamond grades ranging from 21 to 45 ct/100 t (cpht), and the bulk sample of 1000 t that returned only 5.7 cpht (see Table 4.4.2 and Appendix A).

FIGURE 4.4.6 Photograph of Lahtojoki bulk sample material tested for diamonds by Malmikaivos Oy.

This volcaniclastic kimberlite material is particularly rich in country rock granite clasts relative to the bulk of the pipe infill based on more recent drilling and core logging.

The exact same processing methods and equipment were used at Malmikaivos Oy for both sampling programs (Matti Tyni, personal communication), so the difference between the two must be related to heterogeneities in the volcaniclastic pipe infill.

The large range in mini-bulk sample results (Appendix A) may be related to the fact that diamonds occur not only as xenocrysts in the kimberlite matrix, but also as a rock-forming mineral in some of the eclogite xenoliths that have been recovered from this pipe (Peltonen et al., 2002, and Fig. 4.4.7(A)). A photograph of the larger diamonds recovered from the Malmikaivos bulk sample of the Lahtojoki kimberlite is shown in Fig. 4.4.7(B).

KUHMO AND LENTIIRA ORANGEITES AND OLIVINE LAMPROITES

Confined to a north–south zone of faults in the of Kuhmo-Lentiira area in eastern Finland (see Subchapter 4.1, Fig. 4.1.4) occurs a series of dikes (less commonly veins or stockworks) 0.5–4 m in thickness and extending up to 450 m in length. The existence of pervasive primary carbonate suggests that these rocks are more akin to orangeites than lamproites (see Table 4.4.1). In a hand specimen, the most distinctive feature of the Kuhmo potassic, ultramafic rocks is their phlogopite-rich nature. Phlogopite occurs rarely as macrocrysts, but is abundant as phenocrysts and microphenocrysts with relatively Ti-rich grain cores that are similar in composition to those of lamproite microphenocrysts, but that are zoned to rims of tetraferriphlogopite, a feature common in orangeites (Mitchell, 1995). The more primitive Kuhmo potassic rocks may also contain large amounts of olivine macrocrysts (Fig. 4.4.8(A)) and in some cases abundant xenocrysts and xenoliths of mantle peridotite.

Additional groundmass minerals include K-richterite, Mn-rich ilmenite, Cr-rich spinel zoned to Ti-magnetite, apatite, and perovskite in a calcite and serpentine matrix. More evolved versions of this rock type contain abundant olivine phenocrysts (rimmed by perovskite; Fig. 4.4.8(B)) rather than olivine

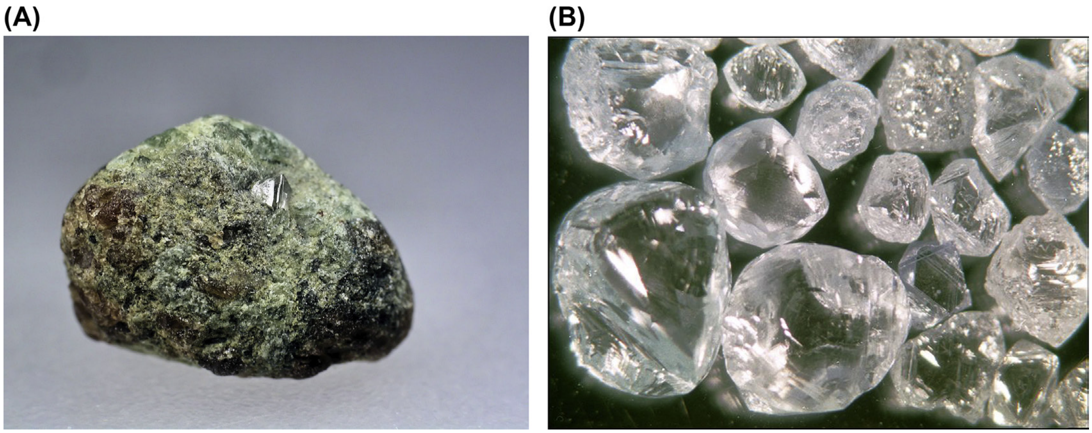


FIGURE 4.4.7 Diamonds occur not only as xenocrysts in the kimberlite matrix but also as rock-forming minerals.

(A) Diamondiferous eclogite xenolith from Lahtojoki kimberlite. Xenolith is 10 mm in the longest dimension. (B) Diamonds from Pipe no. 7, Lahtojoki kimberlite. The largest diamond is about 1 ct and 5 mm in its longest dimension.

Source: *Photograph shown in (A) was taken by Kari Kinnunen, GTK and (B) by Matti Tyni, Malmikaivos Oy.*

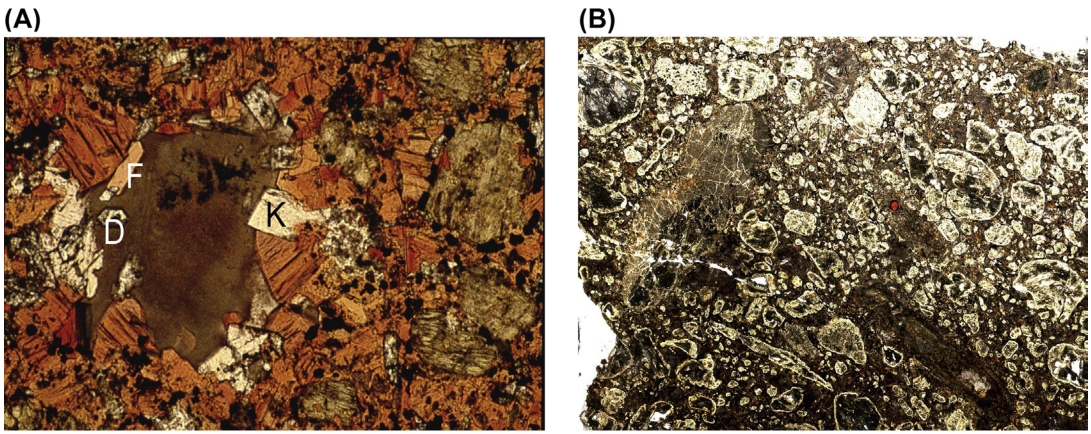


FIGURE 4.4.8 Photomicrographs of Kuhmo-Lentiira orangeites.

(A) Slightly more evolved orangeite from Kuhmo (Seitaperä). Grains surrounding former pool of late-stage liquid include tetraferriphlogopite (F), diopside (D), and K-richterite (K). Olivine pseudomorphs ringed by perovskite in a matrix of phlogopite, apatite, and calcite are also apparent. (B) Primitive olivine macrocryst-rich phlogopite orangite dike rock that also contains abundant euhedral olivine phenocrysts (serpentinized) in a matrix of Ti-rich phlogopite, K-richterite, Mn-rich ilmenite, Cr-rich spinel zoned to Ti-magnetite, apatite, perovskite, calcite, and serpentine (European Diamonds PLC, Lentiira prospect). Both images in plane polarized light; width of field is 2.55 mm (A) and 7.7 mm (B).

macrocrysts, and low-Al clinopyroxene. Mantle-derived xenocrysts are dominantly chrome-spinels zoned to Ti-magnetite, Ti-rich (megacryst-composition) pyropes, less commonly Mg-rich ilmenites and microdiamonds. Notably, mantle-derived Cr-diopside is almost completely absent from the xenocryst suite.

Ar-Ar age dates reported by O'Brien et al. (2007) on a Seitaperä drill core, a pit sample, and a sample 30 km to the north at Lentiira produced ages that are all within error of each other, at 1202 ± 3 Ma (2s), 1199 ± 3 Ma (2s), and 1204 ± 4 Ma (2s), respectively. The consistency of the step-heating results suggests that these ages represent precise determinations of the dike emplacement ages at these localities. The fact that they overlap in time, combined with the mineralogical and geochemical similarities of the dikes, suggest that these dikes represent a cogenetic suite of magmas.

Seitaperä (Pipe no. 16) is the largest of a number of dikes, stockworks, and rare pipes located in the Kuhmo-Lentiira area (see Fig. 4.1.4). It was discovered by Malmikaivos/Ashton using indicator mineral anomaly mapping of the till, followed by noting a small up-ice magnetic anomaly in the regional GTK aeromagnetic survey data. At the time, ground geophysics suggested a body of more than 4 ha in size. As of this writing, Karelian Diamond Resources PLC is the holder of the claims over Seitaperä, and the company has conducted a significant amount of drilling and sampling of the body, producing the geologic map redrafted in Fig. 4.4.9. At this stage of exploration drilling, the area containing massive orangeite and country rocks brecciated by orangeite covers as much as 7 ha. In July 2008, Karelian Diamond Resources reported 61 microdiamonds and 7 macrodiamonds from a 100-kg sample from its Seitaperä drill core, with the largest diamond measured to be 0.63 mm × 0.48 mm × 0.38 mm. More recently reported microdiamond results from other parts of Seitaperä have not been as successful, but the initial results suggest there are zones with potentially higher diamond grades.

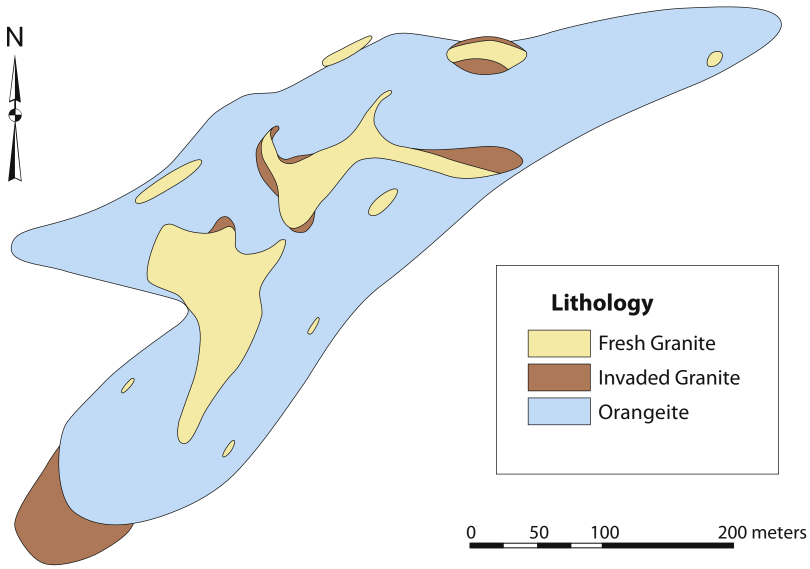


FIGURE 4.4.9 Geological map of Seitaperä based on drilling results from Karelian Diamond Resources.

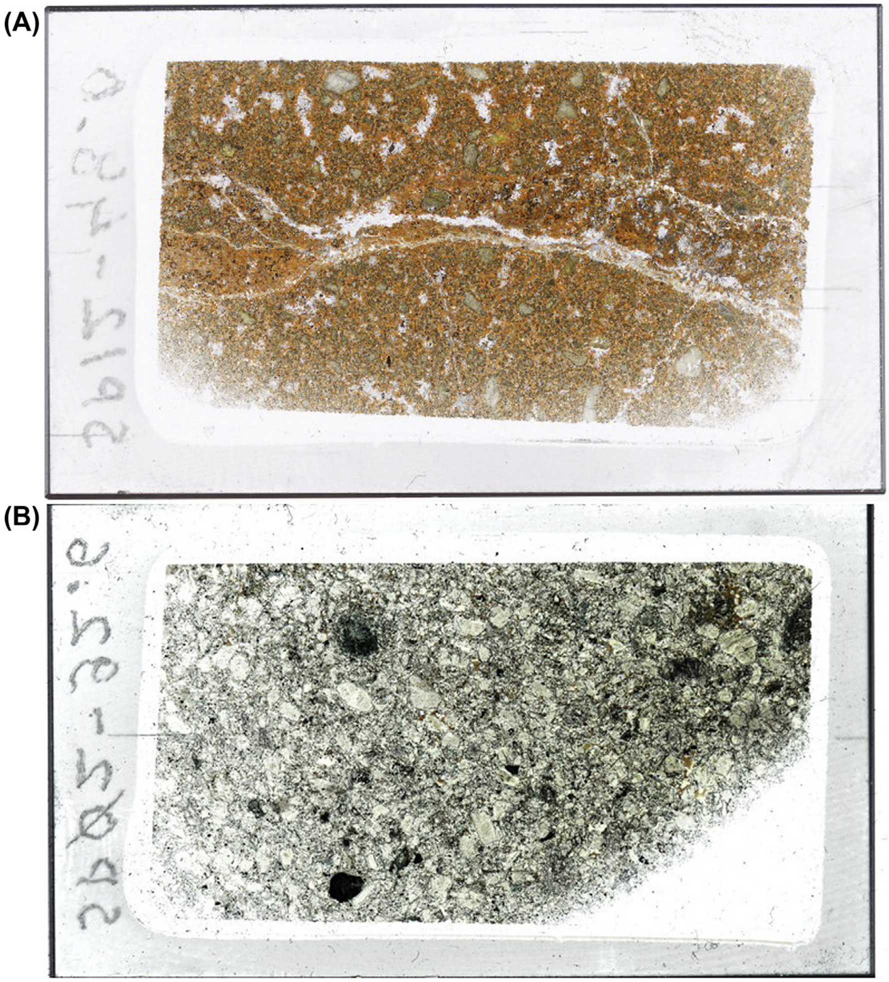


FIGURE 4.4.10 Seitaperä rock types in thin section.

(A) Mica-rich orangeite with carbonate segregations. (B) Olivine-rich orangeite with elongate phlogopite laths in a carbonate-serpentine matrix. Rock slab is 2 cm wide in minimum direction.

Petrographically, the Seitaperä rock types range from hypabyssal orangeite breccias near contacts with the granitic country rock, to porphyritic olivine-rich orangeite without significant crustal contamination. Unusual globular segregation-rich sections mapped in drill core are very similar to those found in some orangeites from southern Africa (e.g., Finsch). Whether these globular structures, many of which are olivine macrocryst or peridotite xenolith-cored, represent coarsened pelletal lapilli (indicating diatreme facies) or some other magmatic separation process (indicating hypabyssal intrusion) remains to be determined.

Although mica-rich orangeites are the most common variety at Seitaperä (Fig. 4.4.10(A)), those dominated by olivine with abundant perovskite in a rhombohedral primary carbonate, apatite, and serpentine (both clear and red-brown Fe-rich types) matrix also occur (Fig. 4.4.10(B)). Fresh samples of the mica-rich variety are golden brown in a hand sample due to the dominance of phlogopite, but more highly serpentinized varieties are thoroughly black in color. Phlogopite compositions from Seitaperä span nearly the entire compositional range of micas known from the KLK magma suite, starting within the lamproite microphenocryst field yet following the orangeite mica evolution trends to extremely low TiO_2 and Al_2O_3 tetraferriphlogopite (Fig. 4.4.11).

Studies of the numerous mantle xenoliths recovered in the Karelian Diamond Resources 2008-2011 drilling program at Seitaperä have provided some sections extremely rich in mantle xenoliths; in places, the xenoliths are tightly packed with little to no intervening magmatic matrix. Study of these xenoliths is ongoing, but preliminary results show that most are garnet-bearing, few have any clinopyroxene, and several examples of highly strained porphyroclastic textured peridotites have been obtained. Garnet in these xenoliths has been preferentially targeted by alteration, with little fresh garnet remaining in the peridotites, explaining the chromite-rich, relatively garnet-depleted mineralogy of the indicator fan down-ice of this intrusion (Lehtonen, 2005).

From 2000–2006, an extensive exploration program was carried out in the Lentiira area, 30 km to the north of Kuhmo, by European Diamonds. Although orangeites were discovered (see Fig. 4.4.8(A))—in some cases with spectacular amounts of mantle material and all with highly prospective indicator mineral compositions—none of the bodies produced significant quantities of microdiamonds. This is despite the fact that macrodiamonds were discovered by till sampling in a number of locations. The exploration possibilities in this area are still intriguing.

In the Kostomuksha region of Russian Karelia, about 40 km northeast of the Kuhmo occurrences, more than 80 dikes and small breccia pipes of similar rocks ranging from leucite lamproite to olivine lamproite to orangeite have been identified and studied (Nikitina, 1999; Kargin et al., 2014). Their age appears to be slightly older than the Kuhmo-Lentiira rocks, with an Rb-Sr mineral isochron age of 1231 ± 8.9 (Belyatskii et al., 1997). The combined Kuhmo-Lentiira-Kostomuksha orangeite region is more than 500 km^2 in size, and undoubtedly contains additional undiscovered intrusions of this rock type.

KUUSAMO KIMBERLITE PROVINCE

The Kuusamo kimberlites mark the third, and most recently discovered, kimberlite region in Finland, located in the northern part of the western terrane of the Karelian craton (refer to Fig. 4.1.4). Six kimberlites occur in two discrete groups. The Kattaisenvaara (KV), Kalettomanpuro (KP), and Lampi hypabyssal kimberlites consist of serpentinized olivine macrocrysts and phenocrysts in a fine-grained matrix composed of microphenocrysts of phlogopite, perovskite, apatite, and spinel with late-stage carbonate and serpentine filling grain interstices (Fig. 4.4.12). The other three kimberlites, named 47, 45, and 45 South, occur close to each other. Pipe no. 45 contains both hypabyssal and diatreme-facies kimberlite, whereas only diatreme material was recovered from Pipe no. 47.

The volcaniclastic kimberlite in these small pipes contains abundant pelletal lapilli. A seventh discovery is a mantle xenocryst-rich orangeite dike intersected at Kalettomanpuro. It appears to be another member of the 1.2 Ga phlogopite-rich dike rocks described from the Lentiira-Kuhmo-Kostomuksha area. Mantle xenocrysts in the kimberlites consist of picroilmenites, pyropes, and chrome diopsides, while chromites appear to be absent. U-Pb analyses of two perovskite fractions from one sample each of the Kattaisenvaara and Kalettomanpuro kimberlites gave weighted mean $^{206}Pb/^{238}U$ ages of 759 ± 15 Ma and 756.8 ± 2.1 Ma, respectively (O'Brien and Bradley, 2008).

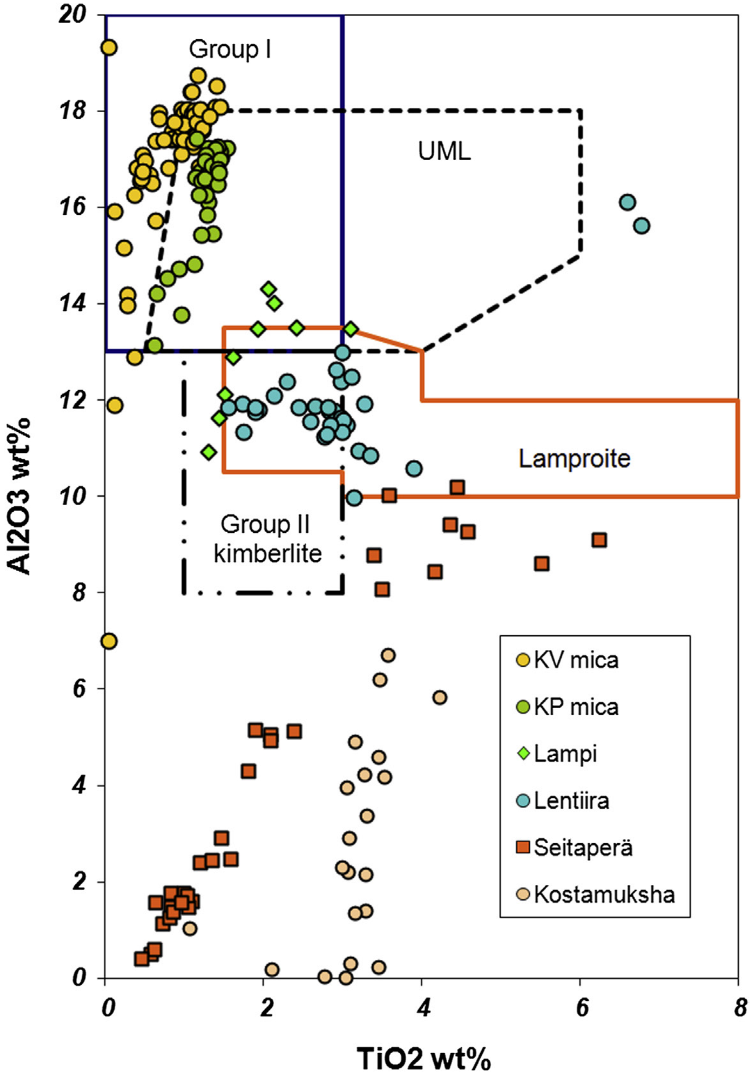


FIGURE 4.4.11 Mica compositions from orangeites.

Mica compositions from Kuhmo, Lentiira Dikes, Seitaperä, and Kostamuksha compared with Kuusamo kimberlites Kalettomanpuro (KP), Kattaisenvaara (KV), and Lampi kimberlite micas plotted in TiO_2 versus Al_2O_3. All of the KP and KV points plot directly in the archetypal kimberlite compositional field, although there is some overlap with the UML field.

Source: *Compositional fields after Mitchell, 1995.*

Mica compositions of the Kattaisenvaara and Kalettomanpuro kimberlites are highly Al- and Ba-enriched kinoshitalites, typical of kimberlite microphenocrysts, with rare tetraferriphlogopite rims detected on some Kattaisenvaara grains. The Lampi kimberlite, on the other hand, has mica that is Ba-rich, yet with only moderate Al_2O_3 and TiO_2 (10–14 wt% and 2–4 wt%, respectively); mica compositions

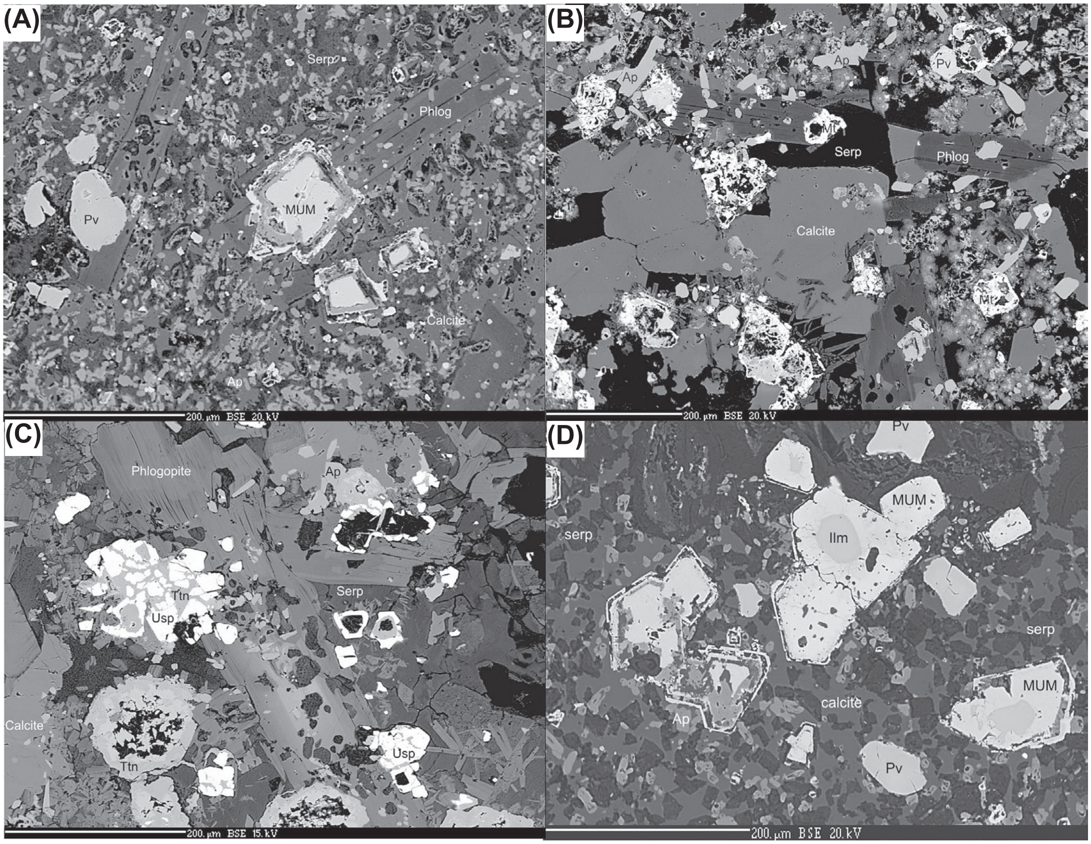


FIGURE 4.4.12 Backscattered electron images of representative samples of Kuusamo kimberlites.

(A) KP: Poikilitic Ba-Al-rich kinoshitalite phlogopite encloses atoll-textured magnesian ulvöspinel-magnetite series (MUM) spinel with late-stage Ti-magnetite rims, apatite, and patches of what are now serpentine. (B) KV: Relatively coarse zone showing highly zoned phlogopite (bottom of image), complex magnetite crystals (Mt), abundant apatite, and late crystals of phlogopite growing within and across calcite-serpentine grain boundaries. (C) Lampi: Strongly zoned Ba-rich poikilitic phlogopites enclose ulvöspine (Usp) and apatite and have abundant embayments filled with serpentine. The development of titanite (Ttn) is thought to be late-stage magmatic and appears to have replaced all original perovskite in this sample. (D) Kasma 45: Atoll structured MUM spinels with partially resorbed, high Mg-Cr picroilmenite cores are common in the Kasma kimberlites. Abundant subhedral to euhedral perovskite is contained in a matrix of subhedral serpentine patches within a carbonate and apatite matrix.

extend from the kimberlite field into the orangeite compositional field. Finally, the zoning patterns from high Al_2O_3 toward lower Al_2O_3 are coupled with decreasing TiO_2 (see Fig. 4.4.11). The KV-KP-Lampi kimberlites are moderately to highly magnetic, and this is directly related to the relatively high modal abundance of magnetite. Mineralogically, the Kasma kimberlites are distinct from KV-KP-Lampi in that they are very perovskite-rich and phlogopite is rare to absent (see Fig. 4.4.12). The Kasma kimberlites, which contain less magnetite, are consequently less magnetic, but nevertheless produce distinct anomalies in a ground magnetic survey against a relatively nonmagnetic baseline.

Major element data confirm the relatively evolved nature of the KV-KP-Lampi kimberlites. Plots such as Fe_2O_3-SiO_2 (refer to Fig. 4.4.3) and CaO-MgO (not shown) indicate that the Kuusamo kimberlites plot slightly outside the field of typical kimberlites, with a vector toward the magnetite and perovskite-enriched partial cumulates from the Benfontein sill where extreme Fe_2O_3 contents reflect accumulation of significant magnetite. Despite their evolved nature, microdiamonds have been recovered from the KV and Lampi kimberlites. Microdiamonds have also been recovered from the Kasma locality (kimberlite 45) but comparative chemical analyses have not been made due to the lack of magmatic kimberlite at this locality.

KARELIAN CRATON MANTLE DIAMOND POTENTIAL

The search for diamonds requires that a considerable amount of information be known about the underlying lithospheric mantle to determine if it has diamond potential. A number of studies (e.g., O'Brien et al., 2003; Lehtonen et al., 2004; Lehtonen, 2005; Lehtonen and O'Brien, 2009) have been made in cooperation with the exploration companies working in the area, to gain a better understanding of the structure and composition of the Karelian cratonic mantle.

Data from xenoliths and xenocrysts from Finnish kimberlites and orangeites and the indicator minerals in exploration till samples allow us to make the following interpretations:

1. P-T data indicate that the mantle root of the Karelian craton varies considerably from margin to core, thickening from about 220 km at Kuopio to nearly 250 km in the Lentiira-Kuhmo-South. Kuusamo section and then thinning again to about 220 km at the North Kuusamo locality.
2. At the craton margin, in the Kuopio and Kaavi area, the mantle is comprised of at least three distinct layers:
   - Layer A—a shallow, 60–110 km, garnet-spinel peridotite layer with high Mg and low Al.
   - Layer B—a variably depleted peridotitic horizon from 110–180 km containing harzburgitic pyropes that represent the diamond window.
   - Layer C—a deep layer, >180 km depth, composed largely of refertilized peridotites. Eclogite and clinopyroxene are common throughout this mantle section.
3. The mantle stratigraphy of the craton core, in the Kuhmo, Lentiira, and Kostomuksha areas, shows less mineralogical variation, with no evidence of Layer A. Layer B begins with the lowest temperature pyropes at an inferred depth of 70 km and continues to a depth of about 250 km, showing a relatively homogenous distribution of harzburgite and lherzolite pyropes throughout, and a high Mg/(Mg + Fe) even compared to global mantle samples. Eclogite and clinopyroxene are rare.
4. The Kuusamo area is located well within the Karelian craton and the composition of mantle xenocrysts derived from this area confirms the existence of depleted mantle underlying the area. Xenocryst pyrope chemistry shows a roughly uniform distribution of lherzolite and harzburgite down to depths of roughly 180 km, and then only lherzolite down to 220 km. The existence of relatively abundant harzburgitic pyrope, some with ultradepleted compositions, throughout most of this mantle section indicates it is similar to that in the Kuhmo region, albeit slightly thinner. Bolstering this interpretation is the paucity of eclogite material in exploration and hard rock samples from the area.

SUMMARY

1. Kimberlites and orangeites are the main source of diamonds, either directly from the igneous rocks themselves, or from the placers derived from these rocks.
2. Diamonds are derived from a specific type of subcontinental lithospheric mantle; it has to be stable and old (Archean), depleted (Mg-rich and harzburgite-bearing), and thick (the diamond window starts at about 140 km depth).
3. This type of mantle has been identified in the Karelian craton, and although varying in detail, appears to be continuous at least over the distance from Kuopio to Kuusamo.
4. Diamond exploration has led to the discovery of more than 30 kimberlites and orangeites in Finland including the 1200 Ma orangeites for the Kuhmo-Lentiira area, the 760 Ma kimberlites from the Kuusamo-Hossa area, and the ~600 Ma kimberlites from Kaavi-Kuopio area. Most of these kimberlites contain at least some diamonds and significant amounts of mantle material.
5. Kimberlite occur as diatremes and dikes in the Kaavi-Kuopio and Kuusamo-Hossa area, whereas the older orangeites from Kuhmo-Lentiira all appear to be more deeply eroded root-zone intrusions.
6. In Finland and globally, knowledge of the geology of the deep lithospheric mantle roots has been advanced immeasurably by collaboration between exploration companies and research institutes.

ACKNOWLEDGMENTS

I would like to thank all of the exploration companies that have worked in Finland and collaborated with our kimberlite and mantle studies at GTK, particularly Malmikaivos Oy/Ashton Mining, whose exploration teams put Finland on the diamond map, and whose director, Matti Tyni, was, from the very early days, very helpful, optimistic, and understanding of the need for scientific cooperation. I would also like to thank Harri Kutvonen for drafting several figures for this section, and W.D. Maier for a thorough review.

REFERENCES

Belyatskii, B.V., Nikitina, L.P., Savva, E.V., Levskii, L.K., 1997. Isotopic signatures of lamproite dikes on the Eastern Baltic Shield. Geochemistry International 35, 575–579.

Brown, R.J., Valentine, G.A., 2013. Physical characteristics of kimberlite and basaltic intraplate volcanism and implications of a biased kimberlite record. Geological Society of America. Bulletin 125, 1224–1238.

Brown, R.J., Manya, S., Buisman, I., et al., 2012. Eruption of kimberlite magmas: physical volcanology, geomorphology and age of the youngest kimberlitic volcanoes known on earth (the Upper Pleistocene/Holocene Igwisi Hills volcanoes, Tanzania). Bulletin of Volcanology 74, 1621–1643.

Chernet, T., Marmo, J., Nissinen, A., 1999. Technical note—Significantly improved recovery of slightly heavy minerals from Quaternary samples using GTK modified 3” Knelson preconcentrator. Minerals Engineering 12, 1521–1526.

Donnelly, C.L., Griffin, W.L., O’Reilly, S.Y., et al., 2011. The Kimberlites and related rocks of the Kuruman Kimberlite Province, Kaapvaal Craton, South Africa,. Contributions to Mineralogy and Petrology 161, 351–371.

Gernon, T.M., Gilbertson, M.A., Sparks, R.S.J., Field, M., 2009. The role of gas-fluidisation in the formation of massive volcaniclastic kimberlite. Lithos 112S, 439–451.

Gernon, T.M., Brown, R.J., Tait, M.A., Hincks, T.K., 2012. The origin of pelletal lapilli in explosive kimberlite eruptions. Nat. Commun 3, 832.

Gurney, J.J., Helmstaedt, H.H., Richardson, S.H., Shirey, S.B., 2010. Diamonds through time. Economic Geology 105, 689–712.

Hearn, B.C., 1968. Diatremes with kimberlitic affinities in North-Central Montana. Science 159, 622–625.

Kaminsky, F.V., Khachatryan, G.K., 2004. The relationship between the distribution of nitrogen impurity centres in diamond crystals and their internal structure and mechanism of growth. Lithos 77, 255–271.

Jelsma, H.J., Barnett, W., Richards, S., Lister, G., 2009. Tectonic setting of kimberlites. Lithos 112S, 155–165.

Kargin, A.V., Nosova, A.A., Larionova, Y.O., et al., 2014. Mesoproterozoic Orangeites (Kimberlites II) of West Karelia: Mineralogy, Geochemistry, and Sr-Nd Isotope Composition. Petrology 22, 151–183.

Korkeakoski, P., O'Brien, H., Lehtonen, M.L., Marmo, J., 2004. Kimberlite/Diamond Claim Reports Kaavi-Kuopio Area—Eastern Finland, Compilation and Review. GTK report 19/3242, 3244, 3331 3333, 4222 4311/2004/1/10.4.

Lehtonen, M.L., 2005. Rare-earth element characteristics of pyrope garnets from the Kaavi-Kuopio kimberlites—implications for mantle metasomatism. Bulletin of the Geological Society of Finland 77, 31–47.

Lehtonen, M., O'Brien, H., Peltonen, P., et al., 2004. Layered mantle at the Karelian Craton margin: P-T of mantle xenocrysts and xenoliths from the Kaavi-Kuopio kimberlites. Finland. Lithos 77, 593–608.

Lehtonen, M.L., Marmo, J.S., Nissinen, A.J., et al., 2005. Glacial dispersal studies using indicator minerals and till geochemistry around two eastern Finland kimberlites. Journal of Geochemical Exploration 87, 19–43.

Lehtonen, M.L., O'Brien, H.E., 2009. Mantle transect of the Karelian Craton from margin to core based on P-T data from garnet and clinopyroxene xenocrysts in kimberlites. Bulletin of the Geological Society of Finland 81, 79–102.

Le Roex, A.P., Bell, D.R., Davis, P., 2003. Petrogenesis of group I kimberlites from Kimberley, South Africa: Evidence from bulk-rock geochemistry. Journal of Petrology 44, 2261–2286.

Lorenz, V., 1975. Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to kimberlite diatremes. Physics and Chemistry of the Earth 9, 17–27.

Lorenz, V., Kurszlaukis, S., 2007. Root zone processes in the phreatomagmatic pipe emplacement model and consequences for the evolution of maar-diatreme volcanoes. Journal of Volcanology and Geothermal Research 159, 4–32.

Massonne, H.J., 2003. A comparison of the evolution of diamondiferous quartz-rich rocks from the Saxonian Erzgebirge and the Kokchetav Massif: are so-called diamondiferous gneisses magmatic rocks? Earth and Planetary Science Letters 216, 347–364.

Masaitis, V.L., 2013. Impact diamonds of the Popigai astrobleme: Main properties and practical use. Geology of Ore Deposits 55, 607–612.

Mitchell, R.H., 1995. Kimberlites, Orangeites, and Related Rocks. Plenum, New York. 410p.

Mitchell, R.H., 2006. Potassic magmas derived from metasomatized lithospheric mantle: Nomenclature and relevance to exploration for diamond-bearing rocks. Journal Geological Society of India.

Nikitina, L.P., Levsky, L.K., Lohkov, K.I., et al., 1999. Proterozoic alkaline-ultramafic magmatism in the eastern part of the Baltic Shield. Petrology 7, 246–266.

O'Brien, H.E., Tyni, M., 1999. Mineralogy and geochemistry of kimberlites and related rocks from Finland. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), Proceedings of the 7th International Kimberlite Conference, pp. 625–636.

O'Brien, H., Lehtonen, M., Spencer, R., Birnie, A., 2003. Lithospheric mantle in eastern Finland: a 250 km 3D transect. In: Extended Abstracts, Proceedings of the Eighth International Kimberlite Conference. Victoria, BC, p. 5. FLA-0261.

O'Brien, H.E., Peltonen, P., Vartianen, H., 2005. Kimberlites, carbonatites, and alkaline rocks. In: Lehtinen, M., et al. (Ed.), Precambrian Geology of Finland—Key to the Evolution of the Fennoscandian Shield. Developments in Precambrian Geology 14. Elsevier, Amsterdam, pp. 605–644.

O'Brien, H., Phillips, D., Spencer, R., 2007. Isotopic ages of Lentiira-Kuhmo-Kostomuksha olivine lamproite—group II, kimberlites. Bulletin of the Geological Society of Finland 79, 203–215.

O'Brien, H., Bradley, J., 2008. New kimberlite discoveries in Kuusamo, northern Finland. In: Extended Abstracts, Proceedings of the 9th International Kimberlite Conference. Frankfurt. 9IKC-A-00346, p. 3.

Patterson, M., Francis, D., McCandless, T., 2009. Kimberlites: Magmas or mixtures? Proceedings of the 9th International Kimberlite Conference 9IKC, 191–200.

Pearson, D.G., Davies, G.R., Nixon, P.H., Milledge, H.J., 1989. Graphitized diamonds from a peridotite massif in Morocco and implications for anomalous diamond occurrences. Nature 335, 60–66.

Pearson, D.G., Shirey, S.B., Harris, J.W., Carlson, R.W., 1998. Sulfide inclusions in diamonds from the Koffiefontein kimberlite, S. Africa: Constraints on diamond ages and mantle Re-Os systematic. Earth and Planetary Science Letters 160, 311–326.

Peltonen, P., Kinnunen, K.A., Huhma, H., 2002. Petrology of two diamondiferous eclogite xenoliths from the Lahtojoki kimberlite pipe, eastern Finland. Lithos 63 (3–4), 151–164.

Peltonen, P., Mänttäri, I., Huhma, H., Whitehouse, M.J., 2006. Multi-stage origin of the lower crust of the Karelian craton from 3.5 to 1.7 Ga based on isotopic ages of kimberlite-derived mafic granulite xenoliths. Precambian Research 147, 107–123.

Richardson, S.H., 1986. Latter-day origin of diamonds of eclogitic paragenesis: Nature 322, 623–626.

Scott-Smith, B.H., Nowicki, T.E., Russell, J.K., et al., 2013. Kimberlite terminology and classification. Proceedings of the 10th International Kimberlite Conference 2, 1–18.

Stachel, T., Harris, J.W., 2008. The origin of cratonic diamonds—Constraints from mineral inclusions. Ore Geology Reviews 34, 5–32.

Wagner, P.A., 1928. The evidence of the kimberlite pipes on the constitution of the outer part of the Earth. South African Journal of Sciences 25, 127–148.

White, J.D.L., Ross, P.-S., 2013. Maar-diatreme volcanoes: A review. Journal of Volcanology and Geothermal Research 201, 1–29.

APPENDIX A. BRIEF SUMMARY OF DIAMOND EXPLORATION RESULTS FROM THE KAAVI-KUOPIO KIMBERLITES

Data extracted from Korkeakoski et al., 2004. Abbreviations used: GT = garnet, PIL = picroilmenite, CP = clinopyroxene, CHR = chromite, DI ## and JÄÄ ## are the registered names given to Dia Met Minerals Ltd. diamond claims.

PIPE 1. KOSKENNIEMI

10 diamond drill holes intersected in total 175m of kimberlite. This extremely fresh and petrologically interesting kimberlite is apparently nondiamondiferous. A 107 kg sample, returned no microdiamonds, and hence no bulk sample was taken for macrodiamond testing. Sunrise Diamonds also reported a negative microdiamond result for this pipe.

PIPE 2. NIILONSUO

44 percussion drill holes and 24 diamond drill holes were used to sample this pipe. Drilling and magnetic measurements revealed a 20 – 30 m wide and 300 m long sill like body. A 172 kg sample from the drill cores yielded 72 microdiamonds. Test quarrying of 162.8 tons for macrodiamond analyses produced a very low grade of 0.23 carats per hundred ton (cpht).

PIPE 3. NIILONLAMPI

A few percussion drill holes and 54 diamond drill holes showed that the body is 10 – 50 m wide and 350 m long. A 2.2 tons sample for macro diamond analyses was obtained by mini bulk sampling but contained only two diamonds, and a calculated grade of 0.91 cpht.

PIPE 4. KARETINSAARET (AKA RIKAVESI)

7 diamond drill holes intersected 163m of kimberlite from this diatreme. Drilling was conducted through winter ice, since the kimberlite is in a lake, at a depth of about 20 m. A 27 kg sample gave 18 microdiamonds. 8.2 tons were processed for macrodiamonds, but provided a very low grade of only 0.21 cpht.

PIPE 5. KÄRENPÄÄ

23 diamond drill holes were drilled, 21 of which reached the kimberlite (combined length 1157.7 m). A 122 kg caustic dissolution sample for microdiamonds was positive. Five mini bulk samples with a total of 15.9 tons and test quarrying of 170 tons of kimberlitic material produced only very low quantities of macro diamonds. Drilling and magnetic surveying revealed an almost vertical sill like body with a width of less than 30 m and a length of approximately 800 m.

PIPE 6. TEERIPURO

30 diamond drill holes were obtained over the magnetic anomaly (combined length 633.2 m) and five mini bulk holes were made into the body. A 48 kg sample from drill core for micro diamonds and a 13.4

ton mini bulk sample for macro diamonds produced only very small quantities of either. The body is elongate, 50 m wide and 200 m long, and oriented almost vertically.

PIPE 7. LAHTOJOKI

17 till samples were collected from various depths for a heavy mineral survey. Geophysical surveys included magnetic, seismic and electric measurements. 39 diamond drill holes (combined length 1747.7 m) were used to delineate the body. These data and geophysical measurements showed the pipe to be pear-shaped, 100 m x 250 m in size. 59 kg of drill core for micro diamonds revealed 20 grains. Eight 200 mm percussion drill holes recovered a 23.3 tons mini bulk sample for macro diamonds giving an average diamond content of 30.6 ct / 100t. A 1600 ton bulk sample, of which 1000 tons was processed yielded an average diamond content of only 5.68 ct/100 t (see table A1).

Table A1 Diamond grade results for lahtojoki kimberlite, Malmikaivos Oy claim reports.

Hole number	collar label	Sample wt (t)	Diamonds >0.8 mm		Diamond total		Largest diamond (mm)	Grade >0.8 mm ct/100t
			count	ct	count	ct		
D4311-116	LU 2-6 LD-11	1.8	69	0.72	179	0.83	2.4	40.00
D4311-115	LU 2-6 LD-12	1.7	34	0.77	91	0.83	4.3	45.29
D4311-114	LU 2-6 LD-13	1.9	75	0.72	148	0.81	2.3	37.89
D4311-155	LU 2-6 LD-36	3.6	101	0.77	324	1.03	2.0	21.39
D4311-154	LU 2-6 LD-37	3.9	119	1.17	380	1.46	2.4	30.00
D4311-163	LU 2-6 LD-39	3.4	52	0.73	183	0.97	3.0	21.47
D4311-162	LU 2-6 LD-40	3.5	51	0.90	238	1.26	2.5	25.71
D4311-161	LU 2-6 LD-41	3.5	86	1.35	313	1.77	3.6	38.57
Bulk Sample		1000	2481	56.85			0.97 ct	5.68

Note that results from more recent work by European Diamonds and Mantle Diamonds on this kimberlite are not available in the public record.

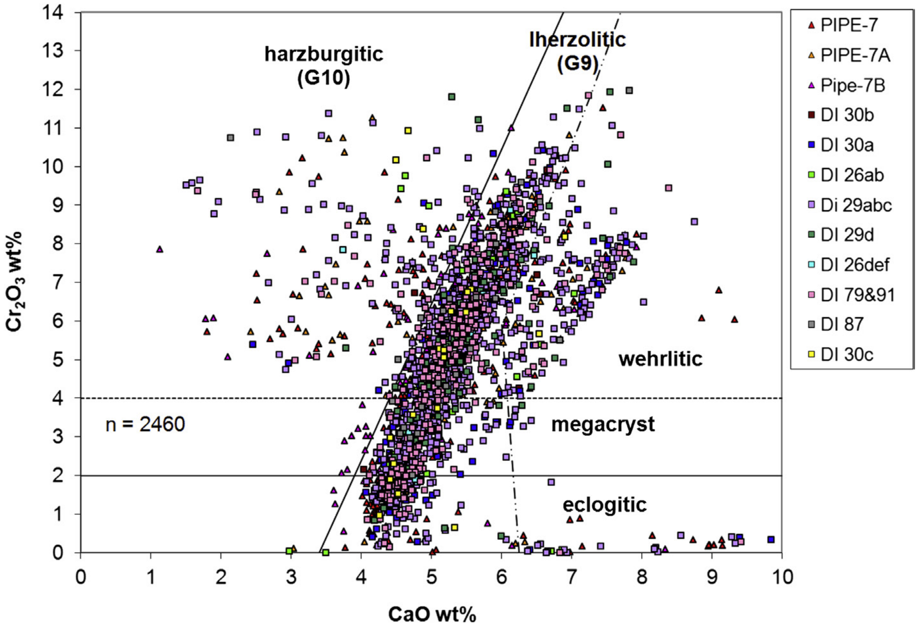
PIPE 8. AVIOLAMPI

On claim DI 82 a heavy mineral survey with seven surface and six basal till samples was done but no significant indicator minerals were found. 20 grains were analysed comprising 6 pyroxenes and 14 chromites. The body is a thin, ~1 m thick sill, but with a large surface exposed due to its sheet-like shape, explaining the large amount of indicator minerals it has shed (M. Tyni, pers. comm.).

There have been five other claims in the ice flow direction SE from the sill (DI 25, DI 50, DI 83, DI 85 and DI 86). 41 surface till samples were collected from these five claims and 43 grains were found and analysed (7 CP, 10 CHR, 20 GT, 5 PIL and 1 OP).

PIPE 9. KALAJÄRVI

5 diamond drill holes hit kimberlite at Kalajärvi, although 1 intersection was thought to be just a large kimberlite boulder (Matti Tyni, pers. comm.). The total intersection of kimberlite was about 91 m. A 25 kg microdiamond sample was negative, and hence no further work was carried out on the pipe.



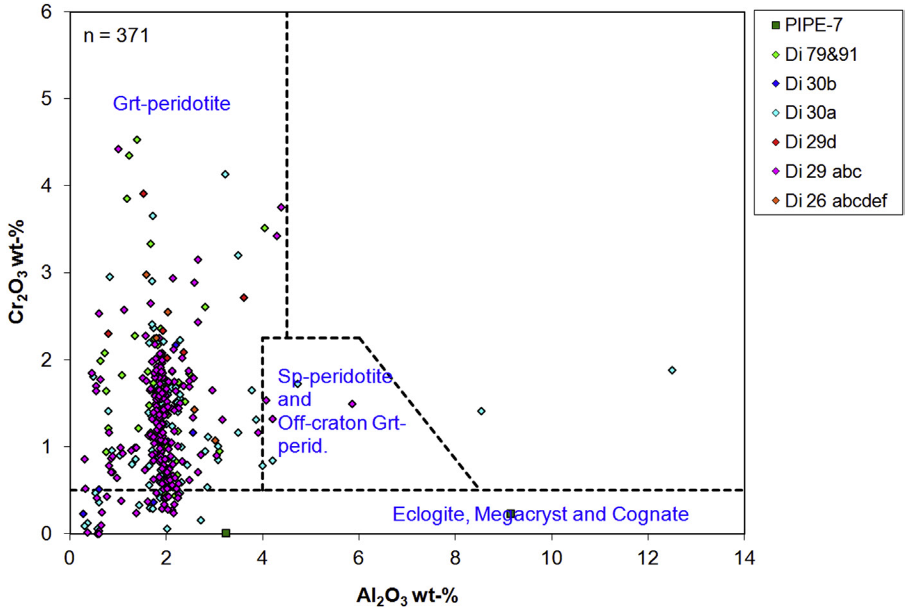
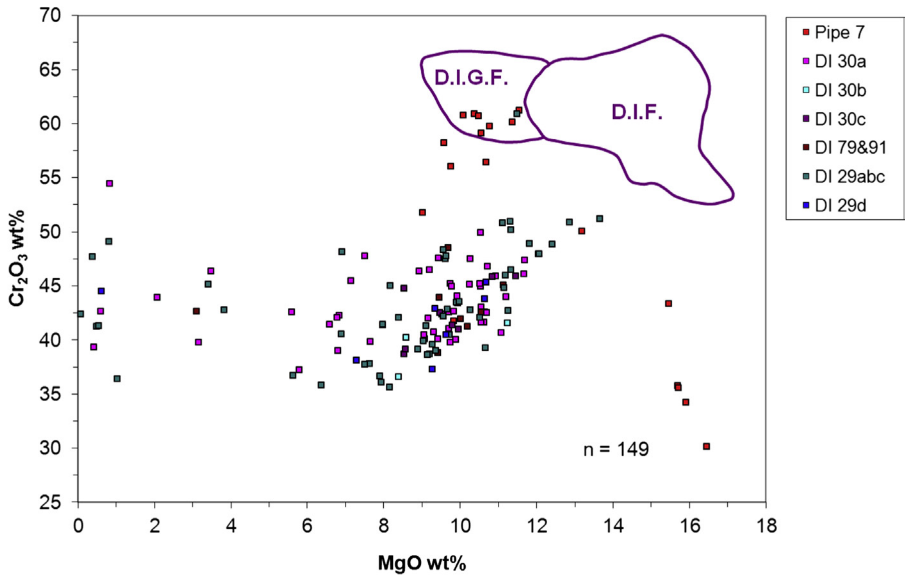


FIGURE 4.4.A1-A4

Xenocryst and kimberlite indicator mineral compositional plots for the Lahtojoki kimberlite and claims in the surrounding areas. A1. Garnet Cr-Ca diagram. A2. Clinopyroxene Cr-Al diagram. A3. Spinel Cr-Mg diagram. A4. Ilmenite Ti-Mg diagram.

Continued



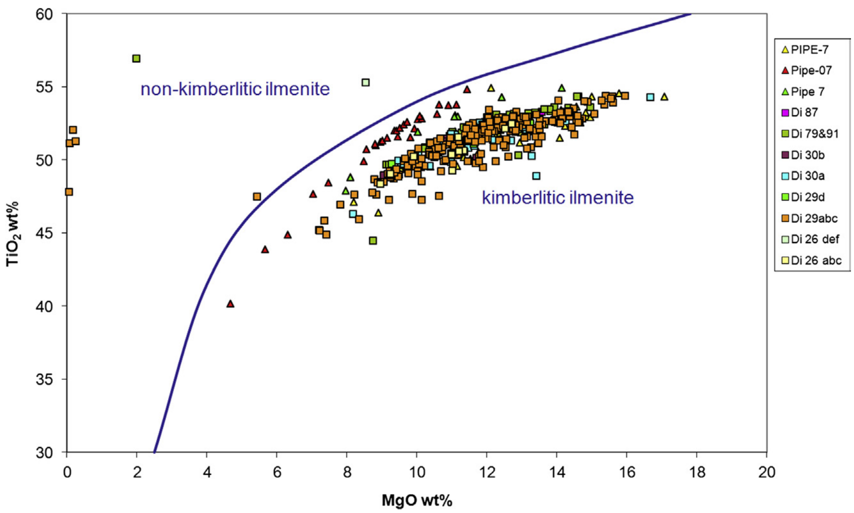


FIGURE 4.4.A1-A4 cont'd

Down-ice, SE from the pipe, there have been two claims. On DI 115, a magnetic survey was conducted, 24 surface till samples were collected and 33 grains were found and analysed (15 GT and 18 PIL). On DI 92, some surface till sampling was done and indicator minerals were found but not analysed or reported. One diamond drill hole to 23.60 m found no kimberlitic material.

PIPE 10. RYÖNÄ 1

To delineate the body, 24 diamond bore holes were drilled (combined length 901.6 m). 26 kg was sampled from the drill core for micro diamond analyses. The body was drilled with four mini bulk holes and 13.3 tons of material were recovered and analysed for macro diamonds. Micro and macro diamond contents of the analysed samples were very low. Drilling and a magnetic survey revealed an oval shaped body with an estimated area of 2.2 hectares.

Seven claims were situated down-ice from the pipe (Jää 61-66 and DI 129). On claim DI 129 a hole was drilled (total length 29.60 m) based solely on an aeromagnetic anomaly. A ground magnetic survey was made on all the JÄÄ 61-66 claims and based on the results four holes were drilled (combined length 180.7 m), one of which did not reach the bedrock.

PIPE 11. MUNAKKA 1

Two diamond drill holes tested the body, a 25 kg drill core sample was analysed for micro diamonds, but only one micro diamond was found. Additionally, the kimberlite is small, only ~0.3 hectares in size.

The single claim near the pipe (DI 103) was only tested by a ground magnetic survey.

PIPE 12. KOTKATNIEMI

19 till samples were collected from the claim area. To delimit the body, magnetic, electric and gravimetric measurements were done giving an estimate of 1.6 ha. 40 diamond drill holes (combined length 1423.4 m) and 161.5 kg of drill core were analysed for microdiamonds. Three large percussion drill holes yielding 9.4 tons of sample material were recovered and processed. 70 microdiamonds were recovered and bulk sample diamond contents ranged from 12.50 – 26.06 ct/100t. 570 microprobe analyses and 20 SEM EDS analyses were done from the pipe material.

One claim (DI 44) was taken down-ice, SE from the pipe and only magnetic measurements were done. Up-ice from the pipe, on two claims (DI 130 and Kotkatniemi 2), magnetic and electric measurements were performed and seven holes were drilled (total length 193.7 m bedrock) but no kimberlitic material was found. Basal till sampling was attempted but no till was found.

PIPE 13. SÄYNEENJÄRVI

32 till samples were collected to better locate the body which has an estimated size of 0.9 ha and is gently dipping to the northeast. Magnetic and electric surveys were conducted and 15 diamond drill holes were completed (combined length 1117 m), 13 of which hit the kimberlite. 48 kg of drill core was analysed for micro diamonds. One mini bulk sample weighting 3 tons was analysed for diamonds. Microdiamond analyses revealed three diamonds and a mini bulk sample contained 14.33 ct/100 t. 441 probe analyses and 20 SEM EDS analyses were done from the pipe minerals.

Five claims were taken near the pipe (DI 31abcd and DI 15). One surface till sample from claim DI 15 was taken, which had indicator minerals that were not analysed. From claims DI 31 a, b, c and d, 48 surface till samples were collected. 25 of these had indicator minerals of which 1001 were analysed

(155 CP, 16 CHR, 739 GT, 82 PIL and 9 Other). Six research pits were dug to investigate the ice flow direction giving reliable results of 310 - 320º. Magnetic and electric surveys were carried out and the resulting anomalies were drill tested with four holes (combined length 479.4 m), none of which hit kimberlitic material.

PIPE 14. KAATRONLAMPI (VEHKALAHTI 1)

To determine the size and shape of the body, six vertical and inclined diamond drill holes were made (combined length 298.7 m). Drillings and a magnetic survey revealed a body with an area of 0.3 ha, 20-35 m wide and 100 m long. A 73 kg sample of drill core produced only 1 micro diamond.

PIPE 17. KYLMÄLAHTI

Geophysical surveys included magnetic and electromagnetic profiles. 21 till samples were taken to investigate the heavy mineral content of the area but only picking results are available. 20 diamond drill holes were drilled to estimate the size and shape of the body. Kimberlitic material occurred in 12 drill holes. The estimated size of the body on the surface is 2.0 ha, but kimberlitic material occurs mainly between large wall rock pieces. A narrow kimberlitic dyke was found 120m east of the main body. Three separate samples were collected for micro diamond analyses (combined weight of 98.7 kg), which produced a total of 8 microdiamonds.

PIPE 20. ALA-VEHKALAHTI (VEHKALAHTI 2)

12 electromagnetic (Slingram) profiles were done in the area, 1 over the body and the rest in an area where abundant indicator minerals occur. An attempt was made to diamond drill the body, but the rock was too soft to recover any drill core. 20 percussion drill holes were done and five of them encountered kimberlite. According to percussion drillings and a gravimetric survey, the body is almost round and 0.3 ha in size. A 21 kg sample taken from the surface of the body produced no micro diamonds.

PIPE 21. LAPINLUHTA

34 till samples were collected to investigate the heavy mineral content in the area. To determine the location and size of the body, magnetic and electric surveys were concluded and showed that the body is 1.6 ha in size and irregular in shape. 62 diamond drill holes were drilled (combined length 1478.5 m). Six percussion drill holes were completed and three separate samples were sent for microdiamond analyses, with a total weight of 109 kg. Six mini-bulk samples were taken and 16.6 tons of material were processed. Microdiamond analyses revealed 37 diamonds, four were +0.4 mm. Mini bulk samples contained 26.65 ct/100t. One stone was 1.126 ct in size. Excluding this stone, the diamond content would be 19 ct/100t. 324 grains were analysed from heavy mineral sampling (259 garnets, 50 ilmenites, 7 chromites and 8 PSBK-F). An age determination gave a K-Ar age of 571 ± 5 Ma.

PIPE 22. UUHILAHTI

14 till samples were collected from the area and 41 garnets were analysed from these. To determine the location and shape of the body 16 drill holes were done. In ten of these, kimberlite was intersected.

Geophysical (magnetic and electromagnetic) measurements were done to better define the extent of the body, which is very small, ca. 0.2 ha. 60 kg of drill core was selected for microdiamond analyses, 22 diamonds were recovered, three of which were +0.4 mm.

PIPE 23. JOKIHARJU

Geophysical measurements in the claim area included magnetic and electromagnetic profiles. The resulting anomaly was drilled with five drill holes (combined length 257.0 m) to define the body, which is oval-shaped with an area of 0.25 ha and has steep, almost vertical contacts. 154.5 kg of drill core selected contained very low contents of micro diamonds.

PIPE 25. VIITASALO (CLAIMS DI 59 & DI 131)

15 till samples (11 from surface till and 4 from basal till) were collected from the area. The samples contained abundant indicator minerals, 343 were analysed (172 GT, 108 PIL, 39 PC, 4 CHR and 22 Other). To locate the source of these minerals, magnetic and electric surveys were concluded. Anomalies were drilled with 17 diamond drill holes (combined length 1208 m). From these drill cores 647 heavy mineral grains were analyzed (413 GT, 200 PIL, 19 CP and 25 Other). A 63.1 kg sample was analysed for micro diamonds, five were found. The kimberlite is estimated to be small and is under a lake.