PART

1

A HISTORY OF EXPLORATION FOR AND DISCOVERY OF FINLAND'S ORE DEPOSITS

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ABSTRACT

Historically documented mining in Finland started in the 1530s when the area formed part of Sweden. The post of commissioner of mines was founded in 1638. The Swedish government activated mineral exploration in Finland in the seventeenth century and, during the Age of Utility, in the eighteenth century. Numerous small iron, copper, and lead occurrences were found, as well as the larger Orijärvi copper deposit. During 1809-1917 when Finland was a Grand Duchy within the Russian Empire, exploration was reorganized and strengthened. New, generally small iron deposits were discovered to supply iron works. Deposits found in the Pitkäranta area were mined for copper, tin, zinc, and iron. The Geological Survey of Finland was established in 1885. The large and rich Outokumpu copper deposit was discovered in 1910 as a result of scientific exploration by Otto Trüstedt of the Geological Survey. Since then, boulder tracing (later also till geochemistry), geophysical measurements, and diamond drilling have been the standard exploration methods. After Finland declared independence in 1917, mineral exploration was considered important for the development of domestic industry. In 1921 the Geological Survey discovered the nickel–copper ore field of Petsamo, and by the end of the 1930s, several other deposits, including the Otanmäki iron–titanium–vanadium deposit, were discovered. After the Second World War, the Geological Survey was reorganized and strengthened, and in the following decades it discovered numerous important ore deposits, including the Vihanti zinc–copper deposit (1951) and the Kemi chromium deposit (1960). The state-owned mining companies Outokumpu Oy and Rautaruukki Oy established their own exploration departments in the 1950s. Outokumpu Oy discovered the Kotalahti (1956), Vammala, and Kylmäkoski nickel–copper deposits, the Pyhäsalmi copper-zinc deposit (1958), the Vuonos (1965) and Kylylahti (1984) Outokumpu-type deposits, and several gold deposits. Otanmäki Oy/Rautaruukki Oy discovered several iron deposits in Lapland, as well as the large apatite-rich Sokli carbonatite complex. Rautaruukki Oy terminated their exploration activities in 1985 and

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Outokumpu Oy in 2003. Finnish private companies also carried out successful mineral exploration. After becoming a member of the European Union in 1995, the role of international mining and exploration companies has strongly increased in Finland, the main interest being in precious metal deposits.

Keywords: exploration; Finland; history; ore deposits; Geological Survey of Finland; Outokumpu Oy; Rautaruukki Oy.

INTRODUCTION

The activity and success of exploration for mineral deposits in Finland has, over the centuries, varied markedly depending on the political, cultural, and economic situation, as well as on the more or less fortuitous availability of persons capable to plan, lead, and carry out prospecting and exploitation of deposits. A major historical background is provided by the changes in the form of government. The eastern part of Norden (or geographic Fennoscandia) now known as Finland was gradually incorporated into the kingdom of Sweden during the twelfth and thirteenth centuries. Over the subsequent five centuries, the eastern border of Sweden shifted several times as a result of wars between Sweden and Novgorod/Russia, until 1809 when Finland was ceded to Russia. Since December 1917 Finland has been an independent state.

Several extensive volumes have been published on the history of the mining industry and exploration in Finland. The first that should be mentioned is the work of Tekla Hultin, which deals with the evolution of the mining industry and exploration during the time of Swedish rule (Hultin, 1896, 1897). The exploration and mining industry during the period of the Russian rule has been documented in detail by Dr. Eevert Laine (e.g., Laine, 1950, 1952). A comprehensive account of the mining industry in Finland from 1530–2001 was recently published by Kauko Puustinen (1997, 2003). Hyvärinen and Eskola (1986) published a chapter on mineral exploration in Finland, including selected case histories of discoveries. A shorter article, "One hundred years of ore exploration in Finland," by one of the current authors (Papunen, 1986), has been an important source, for the present review.

TIME OF SWEDISH RULE

The skill to collect limonitic bog and lake iron ore nodules and produce iron from it in simple furnaces was known in Finnish villages in ancient times, and such iron occurrences were still harvested in small quantities at the end of the nineteenth century. Some lake ore deposits south of Iisalmi in eastern Finland were still studied as possible manganese ores in 1940s and 1950s.

During the reign of King Gustaf I Vasa (1496–1560), the crown supported exploration and mining in the eastern part of Sweden as well. The first clearly documented mine in Finland was the Ojamo skarn-type iron deposit in Karjaa, southern Finland. The deposit was mined in the 1530s by Erik Fleming, the councilor of southern Finland, although it was not until 1542 that King Gustaf I awarded him the formal privilege to exploit the deposits (Puustinen, 1997, 2010). The ore was first worked up in Siuntio, and later in the nearby Mustio ironworks. After Fleming's time mining slowed down. Under the reign of Gustaf I some other minor deposits (e.g., copper ore of Remojärvi in Juva in eastern Finland and iron ore in Siuntio) were exploited. How the deposits were discovered is not known.

In the seventeenth century, under the reign of Gustaf II Adolf Vasa (1594–1632) the mining industry rose to a new level, driven by mercantilism and wars in central Europe, especially the Thirty Years' War in 1618–1648. One reason for the success of the Swedish army in this war was the large and rich Dannemora iron and the Falun copper mines. Gustaf II Adolf had a keen interest in ores and mining. As the crown prince, he had stayed in Finland in 1611 and collected ore specimens that he brought to Stockholm for closer studies (Salokorpi, 1999). As king he traveled in Finland during 1614–1616 and gave personal orders to open or reopen mines and to establish new ironworks (Hultin, 1896, 1897). He had an optimistic view of Finland's ore potential. After his death in the battle of Lützen in 1632 mining policies were continued by his successors. The Board of Mines was established in Stockholm in 1637, and Finland received a permanent post of commissioner of mines in 1638. Finland's first university, Academia Aboensis (Academy of Turku), was founded in 1640 in Turku.

The mining and manufacturing of the large ore deposits in central Sweden seriously depleted Swedish forests. As Finland contained huge tracts of virgin forest that could be exploited for the production of charcoal, as well as rivers for transport and rapids to run furnaces and hammers, experts were sent to Finland to explore for ore deposits and set up metal works in suitable places. Clergymen and other officials were urged to assist in these efforts. The Ojamo mine was reopened and several new ironworks were established: Mustio or Svartå in Karjaa (1550–1901); Antskog (1630–1880), Billnäs (1641–1905), and Fiskars (1649–1904) in Pohja; Fagervik in Inkoo (1646–1904); Orisberg in Isokyrö (1676–1900); Skogby in Tammisaari (1682–1908); and Tykö in Perniö (1686–1908). As raw material, these ironworks mainly used ore or raw iron from the Utö deposits in the Stockholm archipelago. If possible, hard-rock iron deposits from Finland were used, including Ojamo (exploited periodically in 1533–1863), Vittinki in Ylistaro (1563–1920), Sådö (1610–1863) and Långvik (1662–1863) in Inkoo, Juvakaisenmaa in Kolari (1662–1917), Morbacka in Lohja (1668–1873), Malmberg in Kisko (1670–1866), Vihiniemi in Perniö (1690–1865), and Kelkkala in Tammisaari (1690–1900), as well as many other relatively small deposits. In some cases, Finnish lake and bog iron ores were used. The copper and lead occurrences found in the seventeenth century were generally relatively small (Puustinen, 2003).

The beginning of the eighteenth century was overshadowed by the Great Nordic War (1702–1721) as a result of which Sweden lost parts of eastern Finland to Russia. In order to strengthen the Swedish and Finnish mining industry after the war, a royal statute of 1723 promised significant rewards for discovery of ore deposits and benefits for their exploitation.

The Board of Mines sent geological experts to work in Finland, including Daniel Tilas (1712–1772) and Magnus Linder (1709–1799). In the report of his travel to Finland in 1737–1738, Tilas described the bedrock and mineral occurrences of southern Finland. His visits to larger villages were announced in churches, and people were urged to report their findings. Tilas himself carried out exploration for ore deposits at several sites, including the newly discovered Ansomäki iron deposit near **Haveri** in Viljakkala (Puustinen, 2006). In Tammela he visited a site where in 1733 a farmer had found a large boulder containing high-grade copper ore. Tilas had recognized that erratic boulders are generally situated southeast of their sources, which enabled him to find chalcopyrite-bearing veins in outcrops at Hopiavuori (later known as Tilasinvuori). The deposit was mined in 1740–1749 (Puustinen, 2014). This is the first time that "boulder tracing" was successfully applied to the exploration of ore deposits, long before the theory of the great Nordic continental glaciation (Ice Age) was presented.

Tilas' colleague Magnus Linder was appointed to the post of deputy commissioner of mines in Finland in 1741, but because of renewed war with Russia he could not travel to Finland until 1744. He held the permanent post of commissioner of mines in 1747–1787. When Linder started his work, the few existing mines and ironworks were stagnant and the mining administration was thoroughly decayed. Linder set about reorganizing the mining industry. In 1744 he discovered the skarn-type Sillböle iron deposit in Helsinki, which was in production in 1744–1770 and 1823–1866. In the same limestone-skarn horizon, a few kilometers west of Sillböle, other skarn iron deposits were found in Hämeenkylä and Jupperi, and they were mined periodically from 1786 to 1860 (Saltikoff et al., 1994). In 1757 the owner of the **Orijärvi** estate found metallic ore minerals in a rock outcrop in his back forest, and the rock turned out to be good copper ore. The deposit was mined with some interruptions from 1758 to 1954, and during the last 30 years zinc and lead were also produced (Nikander, 1929; Turunen, 1957; Poutanen, 1996). Orijärvi was the first significant copper deposit found in Finland (Figs. 1.1 and 1.2).

PERIOD OF RUSSIAN RULE

ORGANIZATION OF GEOLOGICAL RESEARCH AND MAIN RESULTS OF MINERAL EXPLORATION

During the Napoleonic wars the Russian army occupied Finland in 1808–1809. Russia annexed Finland and conveyed it the status of a Grand Duchy. Because of the war, mining and exploration had largely ceased. The only significant discovery was that of the Kulonsuonmäki titaniferous iron deposit near Karkkila. It was mined in 1817–1888, and the Högfors ironworks was built to process the ore. The office of the commissioner of mines was weak, but the situation improved when General Count Fabian Steinheil was appointed Governor General in 1810. Steinheil, who himself was a skillful mineralogist, wanted to promote geological research, exploration, and the mining industry in Finland. On his recommendation, the young lawyer and mineralogist Nils Gustaf Nordenskiöld (1792–1866) was appointed at commissioner of mines in 1818. Nordenskiöld had studied law and chemistry under Johan Gadolin in the Academy of Turku as well as science of mining and metallurgy in Uppsala, and he was familiar with the ore deposits of central Sweden. Steinheil arranged financing for a three-year expedition to central and western Europe, during which time Nordenskiold got acquainted with mineral exploration and its organization as well as other branches of the mining industry. The office of commissioner of mines was rearranged in 1821. The leader of the office became superintendent, and the staff was increased. Nils Gustaf Nordenskiöld was appointed the first superintendent in 1823, a post he retained until 1855. In 1858 the office was reorganized and became the Board of Mines.

Nordenskiöld reorganized the mineral exploration and the training of his staff. He gave prospectors detailed directions on how to compile geological maps and collect samples. All known ore fields were restudied and some of them were mined. Numerous new ore deposits, mainly iron deposits, were found, and the mining compass came into use. The remarkable **Jussarö** iron ore field in the archipelago near Tammisaari was discovered in 1834, and the deposit was mined in 1834–1861. Most of the other occurrences were quite small and were mined only briefly. A few deposits, such as Haukia (exploited 1839–1864) and Pahalahti (1826–1854) in Kisko, and Väsby in Korppoo (1839–1864) produced thousands of tons of iron ore. The old deposits of Ojamo, Sillböle, Hämevaara, Malmberg,

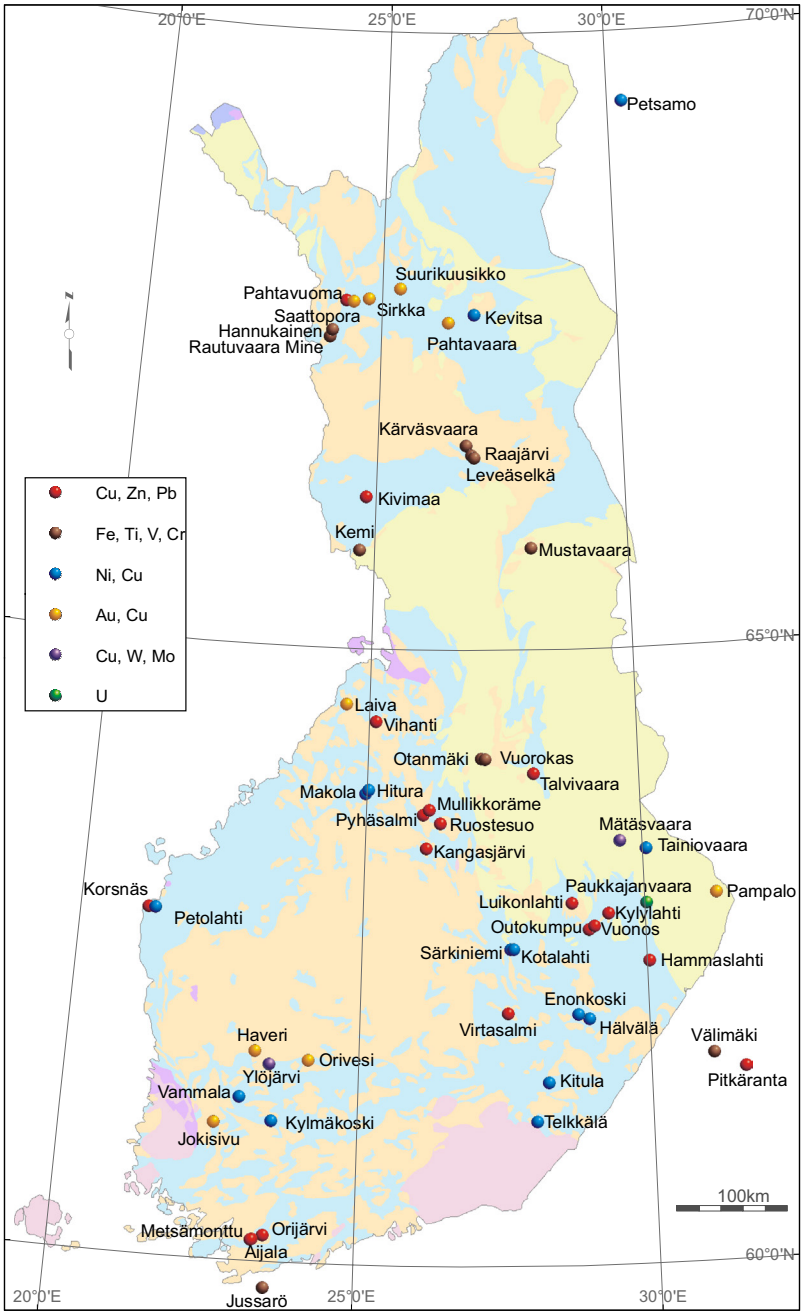

FIGURE 1.1 Location of the metallic ore deposits mined in Finland in 1900–2013.

Source: *Data are from Puustinen (2002), from later ore data files of the Geological Survey of Finland, and from the publications cited in the text.*

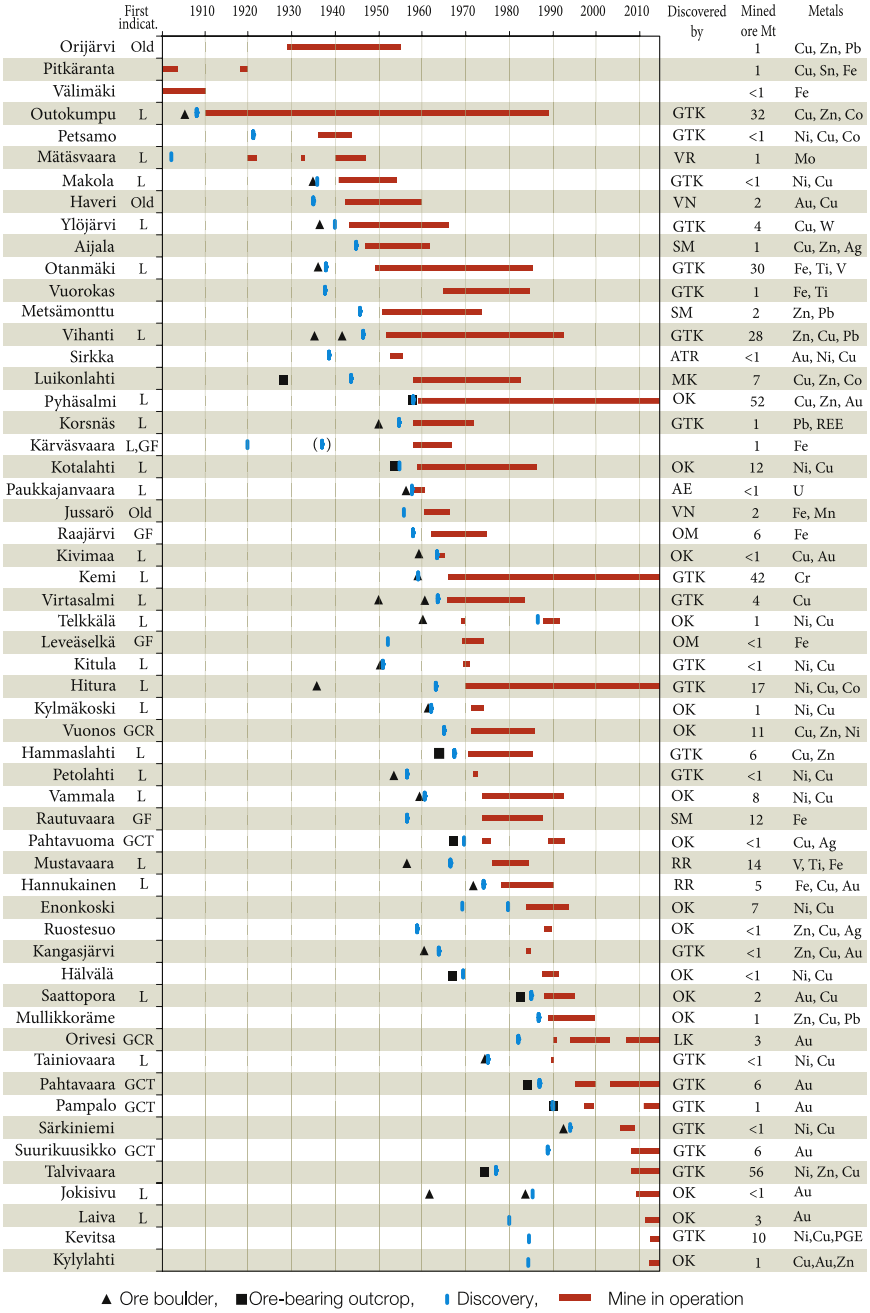

FIGURE 1.2 The life span of the metallic ore mines in Finland, 1900–2013, from exploration to exploitation.

Explanations: First indication of the deposit: GF, geophysical anomaly (airborne or ground); GCR, rock geochemistry; GCT, till or stream sediment geochemistry; L, layman-sent sample; Old, old mine. Discovered by: AE, Atomienergia Oy; ATR, Atri Oy; GTK, Geological Survey of Finland; LK, Oy Lohja Ab; MK, Malmikaivos Oy; OK, Outokumpu Oy; OM, Otanmäki Oy; SM, Suomen Malmi Oy; VN, Oy Vuoksenniska Ab; VR, Oy Värtsilä Ab.

Source: *Data from same references as in Fig. 1.1.*

and Vihiniemi were again mined, and special attention was paid to the deposits of Haveri and Juvakaisenmaa. The aim was to make Finland self-sufficient with respect to iron, but this goal was not attained. Iron ore and raw iron were imported from the Utö mines in Sweden to the ironworks of southern and western Finland. When large limonitic lakes and bog ores were found in central and eastern Finland, a number of ironworks were established in those areas to work the lake ores. The Juantehdas (Strömsdal) ironworks in Juankoski, founded in 1746, was in operation until 1911. Of the ironworks established in eastern Finland during the nineteenth century, those of particular importance included Möhkö in Ilomantsi (in operation 1837–1907), Värtsilä in Tohmajärvi (1851–1920), Varkaus (1815–1908), and Annantehdas in Suojärvi (1809–1905). In the nineteenth century, exploitation of the lake ores was less expensive than mining of hard rock ores of similar iron contents, but their utilization was hampered by high phosphorus contents. Many ironworks in eastern Finland developed into large enterprises, which sold their products mainly to St. Petersburg (Laine, 1952). The smelting of lake and bog ores reached a peak in the 1860s and 70s. Subsequent international development of iron metallurgy decreased the profitability of the production of iron from lake and bog ores, and mining ceased in the 1920s.

In 1810, copper showings and remnants of earlier mining attempts were found in the Pitkäranta area by Russian mining officer Anton Furman on the northeastern side of Lake Ladoga, and later cassiterite was also identified (Laine, 1952). The deposits represent skarn-type occurrences at the margin of the Salmi rapakivi granite batholith. The deposits were mined, mainly by Russian enterprises, for copper, tin, and iron in 1842–1904. The geology and ore deposits of the Pitkäranta area were studied in detail by Trüstedt (1907) (see Chapter 8).

In 1837, gold-bearing boulders were found near the mouth of the Kemijoki River, and Nordenskiöld enthusiastically began systematic exploration. Prospecting was continued for several years, first in the Kemi, Tornio, and Rovaniemi areas, and then, in 1847–1848, in Kuusamo under the leadership of Henrik Holmberg. Minor amounts of gold were obtained by panning in several places in Kuusamo, but not enough to continue the extensive prospecting. When rumors of the California gold discoveries reached Finland in 1849, Holmberg left in autumn 1849 for America to continue gold prospecting in California and Alaska. The disappointing results of gold prospecting in Lapland inspired Finland's national poet Johan Ludvig Runeberg to his well-known words in the Finnish national anthem (presented for the first time in 1848): *Our land is poor, and so shall be to him who gold will crave*. It took more than 100 years to realize that Runeberg's views were overly pessimistic.

From the modest success of exploration, Nordenskiöld concluded that to improve the efficiency of prospecting the whole country should be mapped geologically. On his suggestion, geological mapping was started in southern Finland in 1860s, but it was interrupted because of new placer-type gold findings in Lapland.

In 1867 and 1868, mining engineer Tellef Dahll from the Geological Survey of Norway had found gold flakes by panning in the Tana (Teno) and Enare (Inari) rivers. These rivers mark the international boundary between Norway and Finland, and gold was found on both sides of the boundary. In 1868, a Finnish expedition led by mining engineer Konrad Lihr was sent to study the gold potential on the Finnish side the Tana River. The occurrences proved to be uneconomic. On their return to Rovaniemi the group performed test panning at various sites, and a promising gold occurrence was found on the banks of the Ivalojoki River.

During the following summer, two sailors, Jakob Ervast and Nils Lepistö, panned within one month 2 kg gold at Saariporttikoski in the Ivalojoki River. This discovery led to a gold rush to Ivalojoki. A "crown station" was constructed at Ivalojoki River in 1870, and it became the center for the gold diggers—in 1871 up to 500 men—who worked there. The staff of the Board of Mines superintended the mining. Geologist A.M. Jernström prepared a geological map of the area at the scale of 1:800 000. The amount of gold produced was highest in 1871 and 1872, about 56 and 53 kg, respectively, but then the results declined and the crown station was closed in 1890. Prospecting and washing for gold moved to the tributaries of Palsinoja and Sotajoki, then at the beginning of the twentieth century to the Laanila area, and to Lemmenjoki River in 1945. Gold washing has continued to a minor degree. Attempts to find economic primary gold deposits in the Laanila area in early twentieth century failed (Stigzelius, 1986).

In 1877, a geological office was founded under the Board of Mines with the aim of producing geological maps of the whole country, and financing was arranged for 10 years. The mapping that had been started in 1865 in southern Finland could now be continued. In 1885, the responsibilities of the geological office were transformed to a new government agency within the Ministry of Industry, the Geological Commission, later known as the Geological Survey.

Of the ore deposits found in the nineteenth century, the **Välimäki** titaniferous iron ore on the northeastern side of Lake Ladoga (Blankett, 1896) was of note. Indications of the ore, ore boulders, and a magnetic anomaly were detected already in 1855 during H.J. Holmberg's research trip to the area, but the actual ore body was not found until 1889, by prospectors of a Russian company. The deposit was mined in 1889–1910 and contained about 0.35 Mt of ore with 32% Fe and 5.5% Ti (Figs. 1.1 and 1.2). The iron ore was transported to the Vitele ironworks in Aunus.

In connection with a railway construction, a low-grade molybdenite deposit was discovered in 1902 at **Mätäsvaara** in Lieksa, eastern Finland, at the contact between Archean granitoid gneiss and Svecofennidic potassium granite. After several attempts to exploit the deposit, it was effectively mined by Oy Vuoksenniska Ab in 1940–1947, producing 1.15 million tons of ore with 0.14% MoS_2 (Kranck, 1945; Zeidler, 1949).

DISCOVERY OF THE OUTOKUMPU (KERETTI) COPPER DEPOSIT

The discovery of the Outokumpu copper ore in North Karelia was an epoch-making achievement in the history of the Finnish mining industry. The story of the discovery has been described in numerous articles in Finland and abroad. The short review presented here is based mainly on Saksela (1948).

In March 1908, a large (approximately 5 m^3) boulder containing ore minerals was found at three meters depth in soil when dredging the Kivisalmi canal in Rääkkylä, eastern Finland. The discoverers, building engineer Montin and machine operators Eskelinen and Asplund, thought that the boulder could be a meteorite; at the turn of the century, three meteorites had fallen down in Finland, including the famous Bjurböle stone meteorite that fell in 1899 between Porvoo and Helsinki. They sent a sample of the boulder to the Geological Survey, where it was identified as a high-grade copper ore that contained the minerals pyrite, pyrrhotite, and chalcopyrite. Otto Trüstedt, a mining engineer and geologist who then worked for the Survey, visited the site of discovery. He observed that the quartzitic ore boulder, which was blasted into several pieces, had been rounded at the edges and situated in a till bed. No other ore boulders were discovered at the locality.

At that time, the approximate movements of the continental ice sheet were already known from the directions of glacial striations on outcrops. In North Karelia, there existed two directions: 105–113°

and 165–177°. Trüstedt decided not to continue prospecting solely on the basis of glacial striations. At the beginning of the twentieth century, the fieldwork for the geological mapping at a scale of 1:400,000 had largely been completed in southeastern Finland, and some results had been published. The geologists who had conducted the mapping, B. Frosterus and W.W. Wilkman, were of the opinion that the quartzite of the boulder could only be the so-called "Kalevian quartzite," that was found in several places in North Karelia. Trüstedt studied in detail the Kalevian quartzite formations in Liperi and Rääkkylä, north and northwest of Kivisalmi. In some cases the rock contained a little pyrite and pyrrhotite, but no chalcopyrite was found.

Trüstedt now returned to the site of the Kivisalmi ore boulder and carefully studied the composition of the gravel associated with the ore boulder during dredging of the canal. His aim was to find some clue to characterize the source locality. He found several boulders containing tremolite fels (skarn) and black, sulfide- and graphite-rich schist. Trüstedt returned to the Geological Office and showed the samples to Frosterus and Wilkman. Frosterus remembered that in 1899 they had seen and studied similar rocks near Outokumpu Hill in Kuusjärvi, notably a hundreds-of-meters-wide mica-bearing quartzite schist that contained intercalations of talc and tremolite schists, carbonate rock, and skarn, as well as lenses of serpentinized dunite. Wilkman had written in his diary that the northern slope of Outokumpu Hill contains "banded, ore-bearing quartzite."

In the autumn of 1908, exploration moved to Kuusjärvi. Numerous chalcopyrite-bearing ore boulders were found in the Outokumpu area. Some ore boulders also contained uvarovite and other chrome silicates. The area was poorly exposed, but systematic magnetic measurements revealed an anomalous, northeast-trending zone near the assumed contact between the mica schist and quartzite schist. In March 1909, the Senate of Finland approved 8000 marks to continue and intensify exploration.

In the summer of 1909 several test pits were dug, first at Sänkivaara and the Outokumpu hills and then to the eastern side of Outokumpu. No bedrock hosted ore was found, but rocks of the quartzite-carbonate rock association, and some copper ore boulders. Trüstedt concluded that the ore must be situated in quartzite between the northernmost ore boulders and the assumed northern contact of the quartzite against the mica schist. Because of the thick overburden, he decided to use the remaining funds for diamond drilling. The first two drill holes did not hit ore, so Trüstedt paid for the third hole from his own pocket. On March 16, 1910, the drill penetrated 9 m of high-grade copper ore containing approximately 6% Cu. The Outokumpu deposit was discovered, about 50 km north-northwest of the original Kivisalmi boulder. Nearly simultaneously, on March 18, the Senate appropriated 2000 marks to continue drilling.

After the discovery of the ore it was necessary to continue exploration to determine the size, shape, and grade of the deposits utilizing geological and geophysical (magnetic and electrical equipotential) methods and diamond drilling. The work was financed by the State (the finder) and Hackman & Co. (the land owner). It was soon ascertained that the ore body was at least 1400 m long. The State and Hackman & Co. formed a general partnership named "Outokumpu Kopparverk" to exploit the deposit. Pilot mining was carried out in 1910–1912, and more effective mining was started in late 1913. In 1917 the mine was lent to a Norwegian-Finnish mining company Ab Outokumpu Oy, but in 1921 the State of Finland bought up the shares of the Norwegian partner and in 1924 also the shares of Hackman & Co. Under the leadership of Eero Mäkinen, mining became productive. Later on, new mines were opened paving the way for Outokumpu Oy to become a significant internationally operating mining company.

EARLY YEARS OF INDEPENDENCE: 1917–1944

The discovery of the Outokumpu copper deposit in 1910 had to some extent changed the generally pessimistic view about the possibilities of finding economic mineral deposits in Finland. The discovery had also shown the usefulness of new exploration methods, boulder tracing, geophysical measurements, and diamond drilling. Further optimism resulted from the discovery of some minor sulfide ore deposits in eastern Finland, including the pyrite deposits of Otravaara in Eno and Tipasjärvi in Sotkamo. The Otravaara pyrite ore body was discovered in 1918 on the basis of an ore boulder sent to Suomen Malmitutkimus Oy (Finnish Ore Exploration Co.) in Helsinki. Aarne Laitakari, the director of the company, found more ore boulders, had small trenches dug through the till cover near the boulders and across the strike of foliation, and found the ore body hosted by sericite quartzite (Saxen, 1923). The deposit was exploited in 1919–1924 by Suomen Mineraali Oy. The important nickel–copper deposits of Petsamo were discovered a few years later (1921).

To promote exploration for mineral deposits, Pentti Eskola, Eero Mäkinen, and some other geologists from the Geological Survey wrote in Finnish and Swedish articles and booklets on Finnish mineral deposits and their exploration, as well as possibilities for evolution of the mining industry.

DISCOVERY OF THE PETSAMO (PECHENGA) NICKEL–COPPER ORE DEPOSITS

In 1920, in the Peace Treaty of Tartu, Petsamo (Pechenga), a strip of the Arctic coast between the Soviet Union and Norway, was incorporated into the new Republic of Finland. In spring 1921 the Geological Survey of Finland sent two students, Alppi Talvia and Hugo Törnqvist, to study if the banded iron formations of Sydvaranger in Norway continue across the border to Petsamo. No extension of the iron ores could be found, and the group moved from Salmijärvi east to the fells of Petsamo. In Kotseljoki, on the western end of Kammikivitunturi, Törnqvist found a rusty sulfide-bearing rock that could be followed on the ground as a magnetic anomaly. Later the rock was identified by the Geological Survey as nickel–copper ore. In 1922 the studies were led by Dr. Hans Hausen, an experienced geologist, and Törnqvist was his assistant. During the short Arctic summer they succeeded in establishing the main geological frameworks of the nickel ore. Nickel occurrences were found in an 80-km-long bent schist belt (greenstone belt) that extended from the Norwegian border across Petsamo to the border with the Soviet Union. The belt included mafic–ultramafic metavolcanic and intrusive rocks and metasediments. The Kotseljoki Ni-Cu occurrence was interpreted to be hosted by a dike, whereas the other occurrences were disseminations in ultramafic rocks (Hausen, 1926).

The next expedition took place in 1924 under the leadership of Dr. Väinö Tanner; other members were Hans Hausen, H. Törnqvist, and J.N. Soikero. Tanner also led the annual field campaigns during the following years until 1931, followed by Dr. Heikki Väyrynen until 1934. During these years, the exploration comprised detailed research in the long but narrow ore-bearing zone characterized by phyllites or black schists and mafic–ultramafic (ferropicritic) volcanic and plutonic rocks (Väyrynen, 1938). Magnetic, electric equipotential, and, since 1927, electromagnetic geophysical techniques were used along with geological mapping. Diamond drilling was carried out at selected localities. Due to the lack of local roads, the research equipment had to be carried to the fells by men or reindeers. For several years the researchers also had to prepare basic maps. The work became much easier in the early 1930s when airborne photographs became available.

When the Geological Survey finished exploration in Petsamo in 1934, more than 10 ore deposits had been found, including the Kaulatunturi, Kammikivitunturi, Onkitunturi, Ortoaivitunturi, and Pilgujärvi deposits. The ore resources of the Kaulatunturi deposit were estimated to be at least 5 million tons (Haapala, 1945).

By 1933 it had become clear that mining would be profitable at the Kaulatunturi deposit. At the time, Outokumpu Oy, the country's only company mining metallic ore, did not have the financial resources to found a new mine in the wilds of Lapland. Under these circumstances, it was logical to seek a foreign partner. After long and thorough negotiations, in the summer of 1934 the Government of Finland concluded an agreement with the Mond Nickel Company (London), a subsidiary of the Canadian International Nickel Company (INCO), for exploitation of the ore. For operations in Finland, Mond Nickel Company established the company Petsamon Nikkeli Oy. Exploration continued under the leadership of Dr. Paavo Haapala, and construction for mining of the Kaulatunturi deposit began. From autumn 1940 to autumn 1944 Petsamon Nikkeli Oy was in partnership with the German company I.G. Farbenindustrie AG, and after the Second World War the district of Petsamo was incorporated into the Soviet Union (Autere and Liede, 1989; Vuorisjärvi, 1989).

OTHER EXPLORATION FOR ORE DEPOSITS

In the mid-1930s, when Finland's economy slowly started to recover from the global economic depression, the government aimed to support mineral exploration in order to find new ore deposits and thereby strengthen economic development. The Geological Survey received new statutes in 1936, which, without neglecting basic research, emphasized the role of practical geology. Three research fields were defined: ore geology, bedrock geology (petrology, Precambrian geology), and geology of surficial deposits (Quaternary geology). The number of staff was increased. The new director, Aarne Laitakari, supported public enlightenment on geology by giving lectures and writing newspaper articles and books directed to a broad audience. University professors Pentti Eskola and Matti Sauramo wrote popular textbooks and in their presentations highlighted geology as an important future field of science. The number of geology students increased, and many of them found their places in ore exploration and the mineral industry.

Outokumpu Oy carried out exploration for ore deposits in North Karelia in 1935–1939 under the project named Suuri Malminuotta (the Great Ore Seine Operation). A number of students from the University of Helsinki participated in the program under the leadership of Paavo Haapala. The students received both theoretical and practical training in exploration, and many of them were subsequently employed by Outokumpu Oy or the Geological Survey.

In 1935, a new company, Suomen Malmi Oy, was established to carry out ore exploration, including geological and geophysical methods and deep drillings. In the 1930s, the company participated in exploration in the Pitkäranta ore field and several other areas (e.g., the iron ore fields of Porkonen-Pahtavaara, Misi, and **Kärväsvaara** in Lapland). Local villagers had already discovered the Kärväsvaara occurrence in 1921 on the basis of magnetic anomalies and digging. In 1937–1938, Suomen Malmi carried out geological mapping, magnetometric measurements, and diamond drilling at the locality, and sank a 20-m-deep shaft into the ore. Although the iron content was reasonably high (≥50% Fe), the locally high sulfide content and scattered distribution of iron decreased the quality of the magnetite ore. When negotiations of the mining rights failed, Suomen Malmi Oy stopped exploration at Kärväsvaara (Olson, 1937).

In the second half of the 1930s, the Geological Survey received two important ore boulder specimens from local farmers. In 1936, Kusti Ainasoja sent rusty, sulfide-bearing samples from Hosionperä in Järvikylä, Nivala, which caused a short visit to the locality to obtain unaltered samples. An analysis of an unaltered sample from the original serpentinite boulder showed 0.63% Ni and 1.7% Cu. The area was poor in outcrops and no serpentinite rocks were known to exist in Nivala. The succeeding field studies in 1936 and 1937 revealed a narrow, several kilometers long ore boulder fan in the area. Magnetic and electromagnetic measurements showed anomalies near the northwest end of the boulder fan, and soon thereafter the **Makola** nickel deposit was found by diamond drilling. In 1939 biogeochemical studies— based on the ash of birch leaves—showed anomalous Ni contents in the same area. The ore was exploited by Outokumpu Oy from 1941–1954.

In 1937, Kalle Leppänen sent a pyrite-rich boulder specimen from a Järvenpää farm in **Ylöjärvi**, about 20 km northwest of Tampere. State geologist Martti Saksela became interested in the sample: it contained abundant pyrite in a sericite schist and resembled the ores of Otravaara and Karhunsaari that he had studied earlier. He visited the locality and recognized in the schist a zone of sericite-quartzite (metasomatic "ore quartzite") that contained small amounts of pyrite. A prospecting team was moved to the area. Numerous boulders containing sulfides in sericite schist were found, and a 2-km-long sericite schist zone was outlined. About 5 km south of the Järvenpää farm, the team found several breccia boulders, which contained fragments of mafic metavolcanic rocks in a matrix composed of tourmaline, quartz, chalcopyrite, and arsenopyrite.

The boulder fan guided prospectors to the shore of the small Paronen Lake where tourmaline breccia was found in outcrop, but without chalcopyrite. Field studies, including magnetic surveys and diggings, were continued in summer 1938 under the leadership of Dr. Erkki Mikkola, and the Ylöjärvi or Paronen copper deposit was found near the southern end of the lake. Diamond drilling was started at the end of 1938, and in spring 1940 the research material was assigned to Outokumpu Oy. Mining of the copper ore started in 1942. In 1945, a mineral resembling quartz was found in the ore and identified as scheelite, and after this discovery tungsten became an important by-product. In 1942–1966, about 4 million tons of ore with 0.76% Cu were mined, producing 28,000 tons Cu, 427 tons W, 49 tons Ag, and 270 kg Au (Himmi et al., 1979).

In 1937, two summer assistants of the Geological Survey found two high-grade Fe-Ti ore boulders near the Sukeva prison in the municipality of Sonkajarvi, between Iisalmi and Kajaani. The following summer, detailed studies began to find the source of the boulders. Neither new ore boulders nor ore-bearing outcrops were found. At the same time, Quaternary geologists were mapping surficial deposits in Vuolijoki, some 30 km northwest of Sukeva, and they observed strong compass disturbances in a place called **Otanmäki**. When the explorer group, led by Veikko Pääkkönen, heard of this, they moved from Sukeva to Otanmäki, and soon found strong magnetic anomalies and iron ore outcrops (Pääkkönen, 1952). The ore consisted of similar titaniferous magnetite ore as the Sukeva boulders. In the next few years, the area was surveyed in detail. Several Fe-Ti-V ore bodies were located in a gabbro-anorthosite complex, and diamond drilling verified the economic significance of the deposit. Because of metamorphic recrystallization, magnetite and ilmenite occurred as separate grains, which was an advantage in processing the ore (Pääkkönen, 1956). The Otanmäki and adjacent **Vuorokas** deposits were mined in 1953–1985, first by Otanmäki Oy and, since 1968, by Rautaruukki Oy. Altogether, approximately 31 Mt of Fe-Ti-V ore was mined, and significant resources still remained.

In addition to the activities described, two private companies, Atri Oy and Oy Vuoksenniska Ab, prospected for ore deposits in the 1930s and 40s. Atri Oy was especially active in Lapland, where the

most important occurrence was the **Sirkka** gold prospect ("Sirkka mine") in Kittilä. The Sirkka prospect was composed of hydrothermal gold and sulfide-bearing veinlets in the greenschist facies rocks of the greenstone belt of central Lapland. After Atri Oy, the prospect was studied intensely by Oy Vuoksenniska Ab, Outokumpu Oy, and the Geological Survey (Eilu et al., 2007). Vuoksenniska studied the Mo deposit of Mätäsvaara and the old **Haveri** iron deposit. During a visit to the old Haveri iron mine in 1935, Professor Hans Hausen from Åbo Akademi University and mining counselor Bengt Grönblom from Oy Vuoksenniska Ab took specimens from the mining waste. Analyses showed that the specimens contained considerable contents of copper and a few grams of gold per ton. This led to intense new geological and geophysical studies with diggings, diamond drilling, and to sinking of an exploratory shaft in the iron ore at Kruuvanmäki, under the leadership of Kurt Lupander. Vuoksenniska started mining in 1942, and when the mine was closed in 1960 it had produced about 1.5 Mt of ore at 2.8 ppm Au and 0.37% Cu.

The prospecting company Malmikaivos Oy was founded in 1941. It was first a subsidiary of Yhtyneet Paperitehtaat Oy (the United Paper Mills Company) and later of Myllykoski Oy. Dr. Martti Saksela was appointed the director and Dr. Erkki Aurola the chief geologist of the new company. They placed extensive advertisements in newspapers requesting ore samples from laypersons, and the company soon received abundant specimens. The **Luikonlahti** copper occurrence in Kaavi became the main exploration target. The prospect had been studied since 1910 by Hackman & Co., the Geological Survey, Outokumpu Oy, and Ruskealan Marmori Oy, before Malmikaivos Oy started long-lasting detailed research in early 1940s.

THE YEARS 1945–2013

After the two lost wars, the Winter War in 1939–1944 and the Continuation War in 1941–1944, Finland was smaller and poorer than before, and heavy war reparations had to be paid to the Soviet Union. Without copper production from the Outokumpu mines, the metal industry of Finland would not have been able to fulfill the reparation contracts (Kuisma, 1985, p. 235). There was a global shortage of raw materials, and Finland needed metals for industry and foreign currency. In this difficult situation the government wanted to support and strengthen the mineral industry and ore exploration, which turned out to be a far-sighted decision.

EXPLORATION BY THE GEOLOGICAL SURVEY

Evolution of the exploration organization

The Geological Survey got new statutes in 1946. The Survey was divided into four departments: Exploration Geology (headed by Dr. Aarno Kahma), Petrology (headed by Dr. Ahti Simonen), Quaternary Geology (headed by Dr. Esa Hyyppä), and Chemistry (headed by Lauri Lokka). The number of staff was increased from 14 in 1935 to 143 at the end of 1959, reaching the maximum 944 persons in 1988 (Kauranne, 2010). The Exploration Department, had a central position in the Survey, but all departments had good collaboration. For example, the Petrologic Department selected the areas for the geological mapping on a scale of 1:100,000 partly on the basis of ore-geological aspects. Kahma and geophysicist Mauno Puranen developed and applied airborne geophysical and ground geophysical methods for exploration.

Airborne magnetic mapping from the flight altitude of 150 m was started in 1951, electromagnetic mapping in 1954, and radiometric mapping in 1956. Since 1972, airborne geophysical mapping has also been conducted from the altitude of 30 m. The airborne maps have been useful in mineral exploration and bedrock mapping. The airborne geophysical surveys were started by the Exploration Department, but in 1972 a new Geophysical Department was established for these and related surveys. Maunu Puranen was appointed the head of the new department. The first geochemical studies for local ore exploration were conducted in the late 1930s, and in the 1950s till geochemical studies became a part of the exploration program. A separate unit, the Geochemical Department, was established in 1973 to carry out systematic geochemical mapping, and Professor Kalevi Kauranne was appointed as the first head. In the mid-1970s, in keeping with the national decentralization program, the Geological Survey established offices for fieldwork in different parts of the country. In the late 1970s, they were grouped into three regional offices, one in Rovaniemi for Northern Finland, one in Kuopio for Mid-Finland, and one (with headquarters) in Espoo for Southern Finland. In 2004 the fourth regional office was established in Kokkola for Western Finland. Aarno Kahma was succeeded as the head of the Exploration Department by Dr. Lauri Hyvärinen in 1979–1981, Dr. Jouko Talvitie in 1982–1995, and Dr. Pekka Nurmi in 1995–1998.

Ore Exploration

The reorganized Geological Survey had considerable exploration success. A number of deposits were discovered during the time Aarno Kahma acted as the department head in 1946–1977: the Vihanti Zn-Cu deposit, the Korsnäs Pb deposit, the Petolahti Ni-Cu deposit, the Kemi Cr deposit, the Hitura Ni-Cu deposit, the Virtasalmi Cu-deposit, the Pyhäselkä (Hammaslahti) Cu deposit, and the Talvivaara Ni-Cu-Zn deposit.

In 1936, the Geological Survey received several sulfide ore samples from the Alpua village in **Vihanti**, sent by Juho and Atte Lumiaho and Jaakko Salo. Dr. Sampo Kilpi's team carried out boulder tracing and geological mapping in the area. The new Zn-rich boulder sample sent in 1939 by Edvard Kesäläinen from Törmäperä and the pyrite ore samples sent in 1941 by Atte Lumiaho from silty basal till in Rantala reactivated the research. Because of the glacial overburden, the exploration was started with detailed Quaternary geological studies led by Simo Kaitaro and Esa Hyyppä. The studies indicated that the glacial transport had been from west-northwest to east-southeast and that the boulders had not traveled long distance from their sources (Hyyppä, 1948). The prospecting continued in 1945–1949 in the possible source area (ca. 18 km^2) with magnetic, electromagnetic, and gravimetric surveys led by Drs. Paavo Haapala, Aarno Kahma, and Aimo Mikkola. Diamond drilling in 1947–1950 into geophysically promising sites led to the finding of an important Zn-Cu deposit at Lampinsaari. Outokumpu Oy exploited the Vihanti deposit in 1954–1992, and the total production of zinc ore was 27.9 Mt.

Exploration in **Korsnäs** was started in 1951 on the basis of the galena-rich carbonate rock specimen that Gottfrid Pistol had found in 1950 from the bank of Poickelbäck creek. The exploration was led first by Max Kulonpalo and later by Dr. Oke Vaasjoki. Again, the studies were started with boulder tracing and other geological observations. This resulted in a collection of different types of carbonate rock boulders in a wide area where the prevailing rocks were mica gneiss and mica schist. Lauri Hyvärinen was able to construct from mutually similar carbonate rock boulders four different, narrow boulder fans, which had the axial direction of approximately 165°, corresponding to the youngest of the three glacial striae directions known from the Vaasa region. Systematic geochemical studies of till were started in 1953. They showed four lead anomaly fans that coincided well with the boulder fans (Hyvärinen, 1958).

Diamond drilling was started in 1953 after magnetic, electromagnetic, and gravimetric measurements. The so-called Häppelträsk lead ore body was discovered in 1955 at the tip of the strongest till

anomaly, and the Poickelbäck prospect was founded in 1956 at the tip of the most well-defined boulder and lead anomaly fan. The Häppelträsk deposit was a galena-bearing calcite and pegmatite vein complex in a shear zone. It was estimated to contain at least 0.7 Mt of ore with 3.5–5.5% Pb. The deposit was mined in 1957–1972 by Outokumpu Oy. A by-product, apatite concentrate, was obtained for separation of lanthanides (Himmi, 1975). The small **Petolahti** nickel–copper deposit in Maalahti was discovered in 1958 on the basis of a boulder sample found by G. Pistol. It was a small deposit in a differentiated Subjotnian diabase dike (Ervamaa, 1962). The deposit was exploited by Outokumpu Oy in 1972–1973.

In 1953, Jopi Malinen sent to the Geological Survey a boulder sample containing native antimony as large, cm-sized crystals and disseminations in silicified rock, discovered in Törnävä, Seinäjoki. Various geological, geophysical, and geochemical methods, as well as excavations and diamond drilling, were applied in search for the source, under the direction of Veikko Pääkkönen. As a result of the studies in 1953–1958, two ore zones, about 50 m apart, were found in schists, totaling about 0.5 Mt of ore with 0.51–1.37% Sb and variable Au contents (Pääkkönen, 1966). During renewed exploration led by Veijo Yletyinen in the 1970s, another deposit with about 0.4 Mt of ore averaging 0.7% Sb was discovered, as well as a cassiterite-bearing pegmatite lens with 0.14 Mt of rock containing 0.3% Sn. The prospects of Törnävä have not been mined.

An important chain of events in the mineral history of Finland took place in spring 1959 when a diver and amateur prospector Martti Matikainen sent a pyrite- and magnetite-bearing specimen from **Kemi** to the Geological Survey. When geologist Pentti Ervamaa visited Kemi, Matikainen showed him other specimens he had collected from a new freshwater canal in Elijärvi, near the city of Kemi. A heavy ultramafic rock sample turned out to represent chromium ore. Exploration was started under the leadership of Valto Veltheim, and soon a chromite-rich layer was discovered in an altered ultramafic rock. In the winter of 1959–1960, all available working resources of the Geological Survey were concentrated on this research area; by the end of May 1960, 29 holes had been drilled into the prospect. It was calculated that the deposit contained at least 7.6 Mt of ore with more than 30% Cr_2O_3, situated in a layered mafic–ultramafic intrusion (Kahma et al., 1962). The results were passed to Outokumpu Oy in May 1963 (Alapieti et al., 1989). After follow-up studies and process development, the decision was made to open a mine in 1964, and the production started in 1969. By 2010, approximately 37 Mt of ore had been mined, and the mining operations continue.

In connection with the exploration around the Makola deposit in Nivala in late 1930s, a low-grade Ni-Cu dissemination was found in serpentinite about 5 km northeast of the Makola deposit. In the 1960s, the Geological Survey returned to the **Hitura** locality. Airborne geophysical surveys indicated that the Hitura ultramafic intrusion is more extensive than previously supposed. After detailed ground magnetic and electromagnetic surveys, diamond drilling was started at the northern margin of the serpentinite intrusion, and a new semicircular Ni-Cu deposit following the margins of the serpentinite body was found in 1963. The deposit was estimated to contain 5 Mt of ore with 0.75% Ni and 0.28% Cu. The exploration at Hitura was led by Veijo Yletyinen. The prospect was handed over to Outokumpu Oy in 1964. After continued drilling, underground test mining at the 205 m level with related concentration tests, and feasibility studies, mining was started in 1970 (Papunen et al., 1997).

In the 1960s, the Geological Survey carried out extensive exploration, led by Lauri Hyvärinen, in the Juva-Virtasalmi area in eastern Finland to find the source of the numerous copper ore boulders found in this area. The chalcopyrite-bearing skarn boulders contained reddish-brown garnet of similar composition, suggesting that they all were of the same source. The prospecting was directed to the northeastern end of the long boulder fan. A chalcopyrite-bearing skarn outcrop was discovered in 1964 at Hällinmäki, a hamlet of Narila in the municipality of Virtasalmi, and in 1965–1966 87 holes were

drilled in the occurrence. The deposit was estimated to contain at least 2 Mt of ore with 0.5% Cu (Hyvärinen, 1969). The **Hällinmäki (Virtasalmi)** deposit was handed over to Outokumpu Oy in 1966. The deposit was mined from the end of 1966 until 1984 producing 4.18 Mt ore averaging 0.78% Cu.

A chalcopyrite-bearing ore boulder discovered in 1960 at Petäjävesi in the municipality of Pihtipudas, led to systematic exploration. Magnetic and electromagnetic anomalies in the Murtoselkä area in the Säviä schist sequence, in the municipality of Pielavesi, led to drilling in 1966–1967 and the discovery of the Säviä Zn-Cu deposit. The estimated ore reserves are about 4 Mt of copper ore with 1.1% Cu and zinc-bearing pyrite ore with 2% Zn and 33% S. Because the deposit is located beneath a lake, it has not been exploited, but it is a future reserve. Aatto Laitakari was in charge of the exploration.

In connection with geological bedrock mapping, in 1966 Osmo Nykänen from the Petrology Department of the Geological Survey detected chalcopyrite in graywacke schist at **Hammaslahti** in the municipality of Pyhäselkä, and he informed the Exploration Department of the matter. Detailed exploration, including geological and geophysical studies, was undertaken under the leadership of Lauri Hyvärinen in 1967–1968 in the locality. It was observed that the Cu-mineralized rock was situated in an electromagnetic anomaly zone. The first drill holes immediately below and on the sides of the first chalcopyrite showing yielded hardly any copper or contained only iron sulfides. Before finishing the exploration, it was decided to drill one more hole, which should meet the possible continuation of the chalcopyrite-bearing zone at a depth of 50–60 m. This "last" hole penetrated better quality chalcopyrite dissemination than the surface samples, and the deep drilling was continued. The deposit was investigated by 88 drill holes, and the estimated resources amounted to 3 Mt of ore containing on average 1.2% Cu. Besides chalcopyrite, the deposit contained pyrrhotite, pyrite, and sphalerite. The deposit was exploited by Outokumpu Oy in 1973–1986.

In 1968 the Geological Survey received an albite-rich sample with 3.8% Cu, sent by Matti Vänni and taken from an outcrop at Riikonkoski in the municipality of Kittilä, within the greenstone belt of central Lapland. Geological mapping and ground geophysical survey were carried out the following year, and on the basis of received information, 33 holes were drilled in 1970. It was estimated that the so-called eastern ore contained about 2.5 Mt of rock with 0.68% Cu, and the western ore about 6.5 Mt of rock with 0.41% Cu. The prospect has not been exploited.

In 1969, the Geological Survey started systematic exploration in the areas of differentiated mafic intrusions in Lapland. The first targets were the Koitelainen and Akanvaara intrusions that, according to recent age determinations, are 2.45 Ga old, and the 2.05-Ga-old Kevitsa (Keivitsa) ultramafic intrusion, all in the Neoarchean–Palaeoproterozoic volcanic-sedimentary greenstone belt of central Lapland, in the municipality of Sodankylä. A number of researchers participated in the studies, but the main merits of the geological achievements go to Tapani Mutanen.

The exploration in the Koitelainen area was initiated by the discovery of a Ni-anomalous weathered ultramafic rock in spring 1969 in Rookkijärvi, in the western part of the Koitelainen intrusive complex. The exploration work continued with varying intensity and different targets for more than 20 years. In 1969, the main interest was in the Pd-anomalous rocks in the lower parts of the intrusion. In 1973–1977, the roughly 20 × 27 km intrusion was mapped geologically, and showings of different ore types were discovered, including magnetite- and ilmenite-rich ultramafic pegmatoid pipes and V-rich magnetite gabbros enriched in platinum-group elements (PGE). The magnetite gabbro also contained a 2-m-thick layer with 2–2.5 ppm Au. A low-altitude airborne magnetic survey and ground geophysical measurements were used in the exploration. The most interesting discovery was in 1977 when the last two of the 24 drill holes planned for the Koitelainen intrusion intersected a chromitite layer (UC) in the northeastern

part of the intrusion. In 1978–1982, the UC chromitite layer was drilled in different parts of the intrusion. Chromitite layers (LC) were found also in pyroxenite near the base of the Koitelainen intrusion. In 1983–1985, Mutanen continued the geological mapping. In 1985–1989, the main interest was in the exploration and study of the PGE showings in different parts of the intrusion.

Mutanen (1997) identified three main zones in the layered mafic–ultramafic series of the Koitelainen intrusive complex: the ultramafic Lower Zone (LZ; dunites, peridotites, pyroxenites), the mafic Main Zone (MZ; gabbros, norites), and the Upper Zone (UZ; gabbros, anorthosites, magnetite gabbros). Above the layered series is granophyre. The total thickness of the intrusive complex is 3.2 km. Of the different ore types of the Koitelainen intrusion, the upper chromitite layer (UC) appears to be the most promising. It extends along a strike 56 km, is 1.2–1.3 m wide, and its average Cr_2O_3 content is about 20%, with 1.1 ppm PGE. It may be regarded as a future reserve.

The Akanvaara layered mafic intrusion is located about 80 km southeast of Koitelainen. It is 15 km × 7 km in size and resembles the Koitelainen intrusion in occurrence and layered structure. Lower and upper chromitite layers and local PGE enrichments were found there.

The exploration of the **Kevitsa** (Keivitsa) ultramafic–mafic complex was prompted by the glacial erratics of ultramafic rocks with disseminated Cu-Ni—sulfides that Mutanen discovered in 1973. The first diamond drill holes in 1984 intersected several meters of sulfide-rich rock at the basal contact of the complex, but it proved to be "false ore," pyrrhotite-rich sulfides with low base and precious metal values. Outokumpu Oy's exploration department had previously studied this occurrence with similar negative results. Systematic ground magnetic and electromagnetic surveys and geochemical sampling of the basal till in 1984–1987 gave anomalies that were drilled in 1987. The two last of the planned 24 drill holes intersected 22–24 m of disseminated ore with 0.36% Ni, 0.40% Cu, and 1–1.4 ppm PGE + Au. Subsequent drilling programs at Kevitsa in 1990 and 1992–1995 delineated a large low-grade Cu-Ni-PGE-Au deposit. The deposit was composed of three main types: the irregular ore that makes up the main ore and typically contains 0.4–0.6% Cu, 0.2–0.4% Ni, and 0.015% Co, as well as 0.6–1.0 ppm Pt + Pd + Au; the false ore that contains >5% S but generally <0.1% Ni; and the Ni-PGE ore that occurs as pipe-like bodies and contains >0.5% Ni and 1–27 ppm PGE (Mutanen, 1997; Törmänen and Iljina, 2007).

After the Geological Survey left the final research report to the Ministry of Trade and Industry in 1994, the rights to the Kevitsa deposit were sold to Outokumpu Oy. Outokumpu made follow-up and feasibility studies in 1995–1998, but resigned the rights to the large but low-grade deposit. Scandinavian Gold Prospecting AB (later Scandinavian Minerals Ltd.) claimed the deposit in 2000 and planned to open the Kevitsa multimetal mine. First Quantum Minerals Ltd. (FQM) bought Scandinavian Minerals Ltd. in 2008, and started production in 2012. In December 2012, the FQM Kevitsa Mine published the proven and probable mineral resources as 157 Mt, with Ni 0.31% and Cu 0.41%, and precious metals Pd 0.18, Pt 0.24, and Au 0.12 ppm.

The black schists or graphite-bearing phyllites of the **Talvivaara** area in the municipality of Sotkamo have been known for their high sulfide contents since regional geological mapping began in 1902–1926. They were explored briefly by Oy Prospector Ab and the Geological Survey in 1930s, and in more detail by Suomen Malmi Oy in 1961–1962, paying special attention to their high contents of Cu, Ni, and Zn. More serious exploration was carried out by the Geological Survey in 1977–1984 to decipher the ore potential of the metal-bearing black schist. The leader of the exploration team was Dr. Pentti Ervamaa. Two test holes drilled in 1977 showed promising and uniformly distributed Cu, Ni, and Zn contents in the black schist, and in the following years an extensive exploration program was carried out. The exploration comprised, besides geological field and laboratory studies, geophysical (magnetic,

electromagnetic, gravimetric) measurements and lithogeochemical studies. Altogether, 95 holes were drilled in the anomalous black schist, mainly with 170–200 m profile distances. Of the geophysical methods used, only the multifrequency slingram measurements could be applied to outline the mineralized zones from barren black schist.

The main ore minerals were pyrite, pyrrhotite, sphalerite, chalcopyrite, pentlandite, galena, alabandite, ullmannite, stannite, and molybdenite. Scintillometric measurements of the drill cores indicated relatively low uranium contents. For the main mineralized zones of the Talvivaara area, Kolmisoppi and Kuusilampi, the following estimates were reported in 1980 and 1986: Kolmisoppi, 81 Mt of rock averaging Cu 0.14%, Ni 0.27%, Zn 0.54%, Co 0.02%, Mn 0.32%, S 10.37%, C 7.1%, V 657 ppm, and Mo 103 ppm; and Kuusilampi, 221.4 Mt rock with Cu 0.14%, Ni 0.26%, Zn 0.54%, Co 0.02%, Mn 0.36%, S 8.54%, C 7.8%, V 614 ppm, and Mo 101 ppm. The geochemistry of the black schist has been studied by Loukola-Ruskeeniemi (1991).

In 1986, Outokumpu Oy received the mining rights to the Talvivaara deposits. Diamond drilling was continued and extensive feasibility studies were carried out. Although the deposit was large, it was considered too low grade for conventional technologies. Outokumpu tested and developed bioheap leaching technology to extract nickel and other metals. Outokumpu sold the mining rights and research results at a formal price to Pekka Perä, a former Outokumpu employee, and the Talvivaara Mining Company was established in 2004. After the permits to commence mining were obtained and necessary constructions were made, metal production was started in 2008 utilizing the bioheap leaching technology. Since 2012 the company has had serious problems, mainly because of environmental accidents and unfavorable metal price evolution.

In the late 1970s, the Geochemical Department of the Geological Survey carried out regional geochemical till sampling (1 composited sample / 16 km^2) in the area of the Archean Hattu schist (greenstone) belt in eastern Finland. Emphasis was on base metals, but no significant occurrences were found. Reanalysis of the finest faction (grain size < 0.06 mm) of the till samples in 1982 revealed distinct W and Mo anomalies in the southern part of the Hattu belt, and scheelite grains were observed in the heavy mineral fractions of the corresponding samples. A more detailed geochemical sampling focused on a promising anomaly in the Kuittila area. Subsequent excavations and deep drillings resulted in the discovery of tonalite-hosted quartz veins carrying scheelite and molybdenite, and soon also gold disseminations were found in the quartz and sericite-rich shear zones (Nurmi et al., 1993). There was additional interest in the area from 1985 to 1987 when Outokumpu discovered a promising gold occurrence in a shear zone at Rämepuro, approximately 15 km north of Kuittila, on the basis of a copper- and gold-bearing sample taken by an amateur prospector from a small creek bank outcrop. The geochemical till anomalies and gold discoveries indicated gold potential of the Kuittila sub-belt and the whole Hattu schist belt.

In 1986–1992, the Geological Survey carried out the extensive and successful Ilomantsi Gold Project, which covered large parts of the Hattu schist belt and comprised detailed geological-petrological studies (geological mapping, geochemical and isotopic studies) and ore exploration (till and rock geochemical studies, geophysical exploration, mineralogical, isotopic and fluid inclusion studies). Till geochemistry turned out to be a very effective method in prospecting for gold. Regional-scale sampling (1 composite sample / 16 km^2) was sufficient for finding gold provinces; sampling density of 16 bottom till samples / km^2 was suitable for delineating gold-bearing zones; and for prospect-scale exploration, sampling of bottom till and underlying rock specimens at 10 m intervals along traverses 100–300 m apart was needed (Hartikainen and Nurmi, 1993). A number of significant

gold deposits, prospects, and showings were found along the >40-km-long Au-anomalous zone, the Karelian Gold Line, in the Hattu schist (greenstone) belt. Of the nine gold prospects (Kuittila, Kelokorpi, Korvilansuo, Kivisuo, Elinsuo, Muurinsuo, Rämepuro, Ward, and Korpilampi) described by Nurmi et al. (1993), all but the Rämepuro prospect were found from sites indicated by till geochemistry. The Ilomantsi Gold Project was coordinated by Pekka Nurmi, while practical exploration was managed by Martti Damsten and Aimo Hartikainen. The research results of the project were published in a volume of 15 articles, edited by Nurmi and Sorjonen-Ward (1993).

After the end of the Ilomantsi Gold Project, the so-called Ward prospect was exploited under the name **Pampalo** Mine by Outokumpu Mining in 1996–1999, producing 0.114 Mt of ore at 15.3 ppm Au. When Outokumpu withdrew from mining activities, the rights to the deposit were sold in 1994 to Polar Mining Oy, a Finnish subsidiary of Australian mining company Dragon Mining, and two years later the rights were transformed to Endomines Oy. Endomines has constructed the necessary ore processing plants and continued inventory of the deposits. Plans exist to continue mining at Pampalo and start exploitation of some other deposits in the Hattu schist belt.

In the 1970s, the Geochemical Department carried out regional geochemical mapping along lines ("line geochemistry") in the Central Lapland Greenstone Belt. The concentration of Si, Al, Fe, Mg, Ca, Na, K, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Pb, and Ag were analyzed. The area of the Sattasvaara komatiite complex was characterized by elevated contents of Mg, Cr, Ni, and Co, and several local Cu anomalies appeared in the monotonous komatiitic environment indicating sulfide mineralization. Additional geochemical till sampling was carried out with a grid of 50 × 100 m in the winter of 1984–1985 to check the Cu anomalies, and also Au was analyzed. A distinct Au anomaly was found in **Pahtavaara**, and follow-up studies, including sampling of the bedrock surface by percussion drilling and excavated trenches, unearthed an altered zone containing visible gold in 1985 between komatiitic lavas and tuffites (Pulkkinen et al., 1986; Korkiakoski, 1992). The exploration was continued with diamond drilling and geophysical measurements to delineate the occurrence. The deposit was mined by Terra Mining in 1996–2000 and by Scan Mining in 2003–2014. The ore resourced were estimated by Scan Mining in 2005 as 3 Mt at 3.2 ppm Au.

The Geological Survey launched a new project in 1986, led by Ilkka Härkönen, to work up the gold potential of the Palaeoproterozoic greenstone belt of central Lapland. On the basis of low-altitude airborne surveys and geochemical sampling, four targets were selected for detailed studies in the Kittilä area: Soretiavuoma, Suurikuusikko, Kuotko, and Petäjäselkä. Soon a small pocket containing visible gold in a quartz-carbonate vein was discovered in a road cut about 4 km south-southwest of Suurikuusikko, which gave an additional impetus to the project. Ground geophysical (magnetic, electromagnetic, gravimetric) and geochemical sampling carried out in the selected areas indicated that the target areas of Soretiavuoma, Suurikuusikko, and Kuotko were all located in the same, north-trending Kiistala shear zone. Diamond drilling across this shear zone was started in 1987 at **Suurikuusikko**, and the first drill hole penetrated the silicified and albitized shear and breccia zone, which contained pyrite and arsenopyrite as well as 6.8 ppm Au / 8 m (Härkönen and Keinänen, 1989). Exploration and drilling continued in 1998, but were interrupted after 21 drill holes. The deposit appeared to be very scattered, and most of the gold ore was refractory. Gold occurred mainly in the lattices of arsenopyrite and pyrite (Kojonen and Johanson, 1999). After finding a suitable bioleaching processing method for the refractory gold ore, the drilling program was continued in 1995. By the end of 1996, a total of 77 holes had been drilled outlining a resource of 1.5 Mt with an average grade of 5.9 ppm Au and cutoff value of 1 ppm (Patison et al., 2007 and references therein). After an international tendering process, the deposit was sold in 1998 to Riddarhyttan Resources AB, which continued exploration and feasibility studies. In 2005 Agnico-Eagle acquired

Riddarhyttan, and the mine was opened in 2006 as the Kittilä Gold Mine. At that time, the probable reserves were estimated at 2.4 Mt averaging 5.16 ppm Au, but in the course of the mining the reserves have increased so that at the end of 2011, when 3.05 Mt of ore had been mined, the combined reserves and resources were estimated to be 55 Mt at 4.13 ppm Au (Geological Survey of Finland, Kittilä Mine database).

The Geological Survey started exploration for sulfide ores in Kuusamo in 1983, when an Au-bearing Co-Cu occurrence was found in Kouvervaara in connection with uranium prospecting. Because the occurrence was visible in new high- and low-altitude airborne magnetic and electromagnetic maps, a systematic survey of electromagnetic and magnetic anomalies in the sericite quartzite formation was started. During the first stage, 30 anomalies corresponding to that of Kouvervaara were selected for closer exploration. After ground geophysical studies, 15 anomalies were selected for follow-up studies. The Juomasuo Au deposit was discovered by diamond drilling in 1985 of a geophysical anomaly about 25 km NE from Kouvervaara (Pankka et al., 1991). The deposit is situated in a shear zone hosted by an altered sericite quartzite formation. Altogether, 44 holes were drilled into the Juomasuo deposit in 1985–1989. The main gold deposit was estimated to contain about 0.7 Mt of ore grading 5–6 ppm Au, or, if Co is emphasized, 1.8 Mt of rock with 0.2% Co and 3 ppm Au. In the immediate surroundings of the main deposit were six smaller satellite ore bodies. When elevated contents of uranium were observed to be present in the Juomasuo deposit, radiometric measurements were also applied in the prospecting. The Geological Survey discovered more than 20 Au-bearing sulfidic ore occurrences in the Kuusamo area, the most promising being Juomasuo, Sivakkaharju, Hangaslampi, Pohjasvaara, and Meurastuksenaho (Vanhanen, 2001).

In 1990, Outokumpu Oy acquired the exploration rights over the area encompassing those five gold deposits and continued exploration and feasibility studies, including test mining, until 2004. Exploration activities have been continued since 2010 by Dragon Mining Oy. A continued drilling program has increased the ore resources (at the end of 2012 the inferred resource estimate for the five Kuusamo gold deposits was 3.4 Mt grading 4.2 ppm Au), and plans have been made for opening of mines.

Systematic up-to-date exploration carried out in the Leppävirta-Juva area since the 1990s brought to light several Ni occurrences in association with the 1.9 Ga mafic–ultramafic intrusions, including the **Särkiniemi** (discovered 1994) and Rytky (2000) deposits in Leppävirta, near the Kotalahti mine (Mäkinen and Makkonen, 2004). The Särkiniemi deposit was estimated to contain 0.29 Mt of ore with 0.91% Ni and 0.53% Cu (Geological Survey of Finland, Särkiniemi–nickel database), and the Rytky deposit 0.90 Mt ore with 0.75% Ni and 0.47% Cu (Geological Survey of Finland, Rytky nickel database). Suomen Nikkeli Oy (Finn Nickel Oy) mined the Särkiniemi deposit in 2007–2008.

In 1979, low-altitude airborne geophysical mapping showed a strong radiometric anomaly at Lake Palmottu in the municipality of Nummi-Pusula. Field studies and diamond drillings from 1980–1984 unearthed 1–30-m-wide dikes of uraninite-bearing pegmatite and sheared granite that cut the migmatites of the area and contain 0.1–0.2% U. It was estimated that the prospect contains 1 Mt of rock with 0.11% U to the depth of about 250 m (Geological Survey of Finland, Palmottu–uranium database).

Since the 1980s, the search for gold has been the focus of the Survey's exploration programs. A large number of gold occurrences have been discovered in the Central Lapland Greenstone Belt (Korkalo, 2006; Eilu and Nykänen, 2011; Nykänen et al., 2011), but also in the Palaeoproterozoic Svecofennian schist belts in central and southern Finland (Grönholm and Kärkkäinen, 2012; Eilu, 2012).

ACTIVITIES OF SUOMEN MALMI OY

The exploration company Suomen Malmi Oy undertook exploration in 1945 in the leptite zone of southwestern Finland, which, in view of the previously known prospects and old, shut-down mines, was thought to contain still exploitable ore deposits. First, three areas were selected for investigation—the surroundings of the Orijärvi and old Aijala mines and Lohjansaari—but by 1950, the region under exploration had expanded from the eastern side of Lohjansaari all the way to the village of Perniö, an area of no less than 500 km^2. The project was the first systematic regional exploration program conducted in Finland on such a wide scale. The operations included geological bedrock mapping on a scale of 1:4000 on the basis of airborne photographs and a network of staked-out lines, magnetic and electromagnetic surveying, as well as diamond drilling of observed geophysical ore indicators. The procedure of investigation was believed to be suitable for exploration of every type of ore.

In the very first year of operations, interesting geophysical anomalies were detected on the area of the old Aijala silver mine and closer investigation of the eastern extension of the geophysical anomaly led to the discovery of the **Aijala** copper ore (Turunen, 1953). The deposit was estimated to contain 0.815 Mt of ore at 2.13% Cu, and in 1948 it was sold to Outokumpu Oy, which exploited the deposit in 1949–1958 with total production of 0.835 Mt of ore averaging Cu 1.59%, Zn 0.7%, Au 0.7 ppm, and Ag 14 ppm.

In the spring of 1946, a hole was drilled into the western extension of the electromagnetic anomaly of Aijala, and a sulfide-bearing zone was observed to exist also there. The **Metsämonttu** deposit was estimated to contain 0.600 Mt of ore at 4.6% Zn extending down to the 150 m level (Turunen, 1953). The deposit was likewise passed on to Outokumpu Oy. The mine was worked in two stages, 1952–1958 and 1964–1974, and it yielded a total of 1.5 Mt of ore with Zn 3.5%, Cu 0.3%, Pb 0.8%, Au 1.43 ppm, and Ag 25 ppm.

Several other ore prospects and showings were discovered in the leptite belt, but they proved to be of no economic significance. It became obvious that the leptite belt in Finland had only a few significant ore deposits compared to the Bergslagen Province in Sweden, although the belts displayed many geological similarities.

In the 1950s, Suomen Malmi Oy's main prospecting targets were the iron ores of the Misi and Kolari districts in northern Finland. In the 1960s, Suomen Malmi turned its attention to the Kuusamo district, where, among other prospects, the Au-Cu occurrence of Apajalahti was explored in the shore zone of Yli-Kitkajärvi. In the 1970s, Outokumpu Oy, and in the 1980s, the Geological Survey studied the same ore province. In 1960–1962 the company analyzed and mapped the Talvivaara sulfide occurrence in black schist and recognized the high nickel concentrations in the sulfides. The deep extension of the deposit was confirmed with two diamond drill holes. In 1962–1963 Suomen Malmi conducted regional exploration in the Archean Kuhmo greenstone belt, and in 1963 they investigated with geological mapping, geophysical surveys, and diamond drilling the Arola nickel occurrence discovered earlier by Outokumpu Oy. The deposit was transferred in 1972 to Malmikaivos Oy, which extended the studies and finally estimated the deposit to contain 1.52 Mt of mineralized rock at 0.56% Ni. Hekki Tuominen was the chief geologist of Suomen Malmi Oy in 1945-1957, and Toivo Mikkola in 1957-1966.

In 1966, the Ministry of Trade and Industry, which was in charge of the state-owned company, decided that Suomen Malmi Oy had to terminate the geological investigations. After that the company continued as a contractor for ore exploration and mining. One of its most important tasks was to carry out airborne geophysical surveys for the Outokumpu Oy and Rautaruukki Oy. In 1990, the Ministry sold the shares of the company to a private entrepreneur. The exploration data file with reports, maps, and analyses were transferred to the Geological Survey where they are available for review.

EXPLORATION BY OUTOKUMPU OY

Evolution of the organization

The shortage of metals and raw materials was a great challenge for the Finnish heavy industry after the Second World War. The opening of the Otanmäki mine in 1950 came at the right time to improve the iron supply of the domestic steel industry. At the end of the 1940s, the governmental authorities encouraged Outokumpu Oy to take a major economic responsibility of ore exploration and development of new metal mining. After protracted discussions between the Ministry of Trade and Industry and the Director General Dr. Eero Mäkinen, the Outokumpu Company finally decided to establish its own exploration department in 1951.

At its founding stage Mäkinen invited Veikko Vähätalo, an experienced economic geologist, to take charge of the exploration operations. In 1951, the team in the newly established exploration department gained its first members when Olavi Helovuori and Olavi Kouvo were hired as company geologists. The personnel were enlarged in succeeding years, when Matti Laurila joined as geophysicist and Erkki Viluksela and Aarto and Maija Huhma came on board as geologists. Dr. Paavo Haapala was appointed the chief geologist and member of the board of directors of the company in 1954.

Dr. Veikko Vähätalo was the head of the exploration department until 1965, followed by Pauli Isokangas until 1975, Dr. Pentti Rouhunkoski until 1984, and then Dr. Matti Ketola. Since 1990, the responsibility of exploration in Finland and Nordic countries was transferred to Outokumpu Finnmines Oy, an affiliated company of Outokumpu Oyj, with Matti Ketola as the head. Dr. Juhani Nuutilainen was the head of exploration in 1990–1992, followed by Tuomo Korkalo until 2002.

In the 1970s the permanent staff numbered 210–250, with an additional 30 summer assistants in the field. A total of 55 geologists and geophysicists were engaged in exploration. In the early years of the 1980s, international mining and exploration operations took the main role in Outokumpu Oy, but at the same time, the domestic exploration activity and personnel gradually decreased. In 2002, the Outokumpu Company left the mining business, with the exception of the Kemi chromite mine, and concentrated on developing stainless steel production. The ore exploration data files with reports, maps and analyses, were transferred to the Archives of the Geological Survey, where they are available for review.

Exploration operations

The first deposit discovered was at **Kotalahti** in the municipality of Leppävirta. Sulfide-bearing black schist samples sent in for inspection in 1954 caused Olavi Helovuori to visit the site. The samples proved to have no significance, but he observed an interesting mafic rock type on the shore of the small Lake Huuhtijärvi. Field assistant Jouko Talvitie, then a student of geology, was sent to study the area in more detail. In a newly constructed road cut of highway NR 5, he found a sulfide-bearing ultramafic rock, which was found to contain considerable concentrations of nickel and copper. A follow-up geophysical survey revealed an electromagnetic anomaly caused by a sulfide-bearing mafic–ultramafic intrusion. After a period of intensive diamond drilling, the ore body was delineated and mining operations were started in 1959.

The **Pyhäsalmi** deposit was discovered in 1958. That year, August was very dry, and a farmer named Erkki Ruotanen attempted to deepen his well through the glacial till. However, underneath the till he intersected bedrock composed of massive pyrite ore. The samples sent to Outokumpu Oy contained considerable concentrations of copper and zinc. The operations to open a mine started the

following summer, and production from an open pit got under way in 1962. The deposit has now been exploited for more than 50 years.

Following the discovery of Pyhäsalmi, Outokumpu Oy conducted airborne geophysical surveys over an extensive area around the deposit, and a number of interesting anomalies were registered. Many of them contained zinc and copper-bearing sulfides, and a few proved to be mineable deposits, such as **Ruostesuo** and **Kangasjärvi**.

In the postwar period, the role of ore samples sent by laymen to exploration organizations was of great significance in bringing to light new prospective areas. A good example is the location of a zone with potential for nickel ores in southwestern Finland, from where Outokumpu Oy received, since 1960, a number of nickel sulfide samples in the area extending from Ahlainen in the west to Vammala and Kylmäkoski in the southeast. With the accumulation of findings, the zone as a whole appeared to hold potential for nickel ores in mafic and ultramafic intrusive rocks, and it became a target of continuous attention with field studies and geophysical and geochemical surveys (Papunen, 1976). Intensive exploration initiated by boulder tracing led to the discovery of the Kovero-oja deposit in **Vammala**, Taipale in **Kylmäkoski**, and finally the "deep orebody" of the Stormi intrusion in Vammala, which all led to mining activity. In all, about a dozen deposits were unearthed, but most of them were small in tonnage or of too low grade to be mined.

The **Vuonos** ore body in the Outokumpu area has a different story of discovery. While analyzing trace element contents in the rocks around the Keretti ore body, Maija and Aarto Huhma observed that the ore proper and its extensions along the ore horizon were characterized by Co/Ni > 1, whereas in all other rock types of the Outokumpu association the concentrations of Co were much less than those of Ni. This knowledge was confirmed by checking the analyzed drill cores of the Outokumpu association (serpentinite, carbonate rocks, tremolite/diopside skarn, sulfide ore), and in the area of Vuonos, roughly 6 km northeast of the Keretti deposit, anomalously high Co/Ni values were registered in a drilled section. A new test hole drilled in this section penetrated a massive Outokumpu-type Cu-Co-Zn ore, mined from 1972 to 1985.

The belt was a target of intense exploration from 1979 to 1985. Dr. Markku Mäkelä initiated and led the program in the first years and Jyry Saastamoinen was the leader in the last years. A notable result of this project was the discovery of the **Kylylahti** deposit in Polvijärvi in 1984. Outokumpu continued exploration, but did not decide to start mining. The Australian company Vulcan Resources Ltd. bought the deposit in 2004. In 2010 the rights were transferred to Altona Mining Ltd., which immediately started sinking an inclined shaft, inventory drilling, and feasibility studies, and opened the Kylylahti mine in 2012. The probable reserves were at that time estimated as 4.34 Mt of ore with 1.56% Cu, 0.29% Co, 0.17% Ni, 0.58% Zn, and 0.65 ppm Au (Geological Survey of Finland, Kylylahti–Copper Database). In 2014 the mine was sold to Boliden Ab.

Besides the discovery of Vuonos, basic geochemical research led in the 1960s also to some other practical applications in the ore prospecting of Outokumpu Oy. An analytical and research laboratory was founded by the exploration department in 1960, and three years later the leader of the laboratory, Dr. T.A. Häkli, published a basic study on the distribution of nickel between coexisting silicates and sulfides (Häkli, 1963). The work relied on the geochemical and mineralogical data collected from a number of Finnish ore-bearing and barren mafic and ultramafic intrusions, and it was concluded that the nickel concentrations of coexisting silicate minerals can be applied in the classification of ore potential of the intrusion even if sulfide-bearing samples were not available.

Based on this conclusion, a program was organized to collect representative samples of all the known mafic and ultramafic intrusions in Finland. The samples were analyzed for sulfur and sulfide-bound Fe, Ni, Cu, Co, and Zn, as well as for the Fe and Ni contents in mafic silicates. Since nickel tenors of sulfides and silicates were proven to be in equilibrium, it was possible to predict, on the basis of the nickel content of the silicates, the composition of any undiscovered sulfide. The studies indicated that it is possible to delineate areas likely to contain nickel ore (Häkli, 1970, 1971). The method was applied at Outokumpu exploration for a long time, and it was instrumental in the location of numerous minor nickel sulfide occurrences and the mineable deposit of Laukunkangas (Grundstrom, 1980). Lamberg (2005) published the summary of the collected comprehensive data and presented the scientific basis for the computerized programs for the calculations of nickel ore potential.

In 1962, Nickel-bearing boulder samples were obtained from Laukunkangas, in the municipality of **Enonkoski**, but no ore outcrops were found at that time. In connection with the regional nickel program in 1969, the Laukunkangas mafic intrusion was found to be sulfide-bearing. The intrusion was exposed and mapped in detail as well as drilled to ascertain the nature of deeper portions. On the basis of the findings, the intrusion was estimated to contain 4.5 Mt of rock with 0.33% Ni and 0.10% Cu. At that time these contents were too low for mining operations.

At the end of the 1970s, Leo Grundstrom studied the Laukunkangas occurrence for his academic thesis. In the course of the work, it became clear that the small ultramafic rock unit, penetrated in the drilling of the eastern part of the intrusion, contained a noticeably higher grade of nickeliferous sulfides than the gabbroic rocks that predominated in the occurrence. In follow-up work, the holes drilled into the eastern part of the occurrence led to the discovery of the ultramafic portion of the intrusion and a high-grade Ni-Cu ore body associated with it. By 1983, the ore deposit had been proven by drillings to be promising enough to warrant sinking an inclined shaft for further investigation underground. The decision to start mining was made in 1984, and it was based on the amount of 4.3 Mt of ore at 1.1% Ni and 0.29% Cu. In the mining period 1984–1994 the total amount of ore including the low-grade disseminated ore was calculated to be 7.9 Mt at 0.72% Ni and 0.20% Cu of which 6.7 Mt at 0.87% Ni and 0.22% Cu was exploited.

The bedrock mapping in 1962 revealed nickel-bearing sulfides in a mafic intrusion in Makkola, some 10 km southeast of Laukunkangas. The drillings in 1970–1972 showed that the host noritic intrusion contains disseminated sulfides. Massive sulfides were discovered in the drilling of the Hälvälä intrusion nearby. The **Hälvälä** occurrence was estimated to contain 0.448 Mt of ore at 1.5% Ni and 0.36% Cu, and it was exploited in 1988–1992 as a satellite mine of Laukunkangas. In 1989 Outokumpu mined selected parts of the small **Tainiovaara** nickel deposit, hosted by serpentinized komatiite and found in 1975 by the Geological Survey.

Outokumpu Oy started exploration in central Lapland in 1960. The greenstone belt of Kittilä was one of the early targets of field studies and geophysical surveys, and also soil and stream-sediment geochemistry were applied in 1966. Tracking down geochemical copper anomalies, a prospecting team led by Tuomo Korkalo discovered in the fall of 1970 an occurrence of chalcopyrite in bedrock at the edge of a mire called Pahtavuoma in the municipality of Kittilä. A detailed study of the occurrence was undertaken using geological mapping, geophysics, and drilling. In addition to the Cu and Cu-Zn mineralizations, the drillings also brought to light a uranium mineralization within the same rock assemblage. The Pahtavuoma ores were investigated underground in 1974–1976, when an inclined shaft and drifts were made for a total length of nearly 1.5 km. The deposit was estimated to contain more than 4 Mt of ore at 1% Cu and ~20 g/ton Ag.

In Outokumpu's stream-sediment study the **Saattopora** area also proved anomalous. The presence of sulfides was established in the bedrock in follow-up investigations in 1965–1967, but the prospect was not then regarded worth drilling. After the discovery of the **Pahtavuoma** deposit, the area attracted renewed attention and in drillings in 1972 a schist zone containing chalcopyrite was penetrated. The amount of ore was estimated to be some 7.4 Mt at 0.69% Cu and 0.10% Ni. Later in the mid-1980s, Tuomo Korkalo observed high gold values in the ore, and after drilling a resource estimate in 1988–1989 indicated 0.68 Mt of ore at 3.6 g/t Au and 0.3% Cu. The ore was mined in 1989 - 1995 and a total of 6277 kg gold and 5177 t copper was produced.

Saattopora was the first gold discovery in the Kittilä greenstone belt that led to mining. Erkki Ilvonen from Outokumpu exploration discovered in the 1980s several other gold indications in the area, which led to regional studies by the Geological Survey of the Sirkka gold line that indicated the great gold ore potential of central Lapland. In 1965, Outokumpu discovered the small **Kivimaa** Cu-Au deposit in a quartz-carbonate vein system cutting metavolcanics in Tervola, and mined it in 1969 (Rouhunkoski and Isokoski, 1974).

Exploration for gold ore at **Jokisivu** in the municipality of Huittinen started in 1985 on the basis of two gold-bearing boulder samples received in 1964 and 1984. The exploration included detailed geological mapping, geochemical till investigations, rock sampling along profiles by drilling and blasting, geophysical measurements, and diamond drilling. The Jokisivu deposit was located with drilling in 1985. It comprised gold-bearing sulfide mineralization in sheared and quartz-veined zones hosted by metamorphosed diorite (Luukkonen, 1994). Outokumpu continued studies in several phases until 2003, after which Dragon Mining Oy (earlier Polar Mining Oy) continued with extensive drilling, feasibility studies, and exploitation. The resource estimate was in 2005 1.47 Mt grading 6.8 ppm Au (Grönholm, 2006). The mining was commenced in 2009.

Since the late 1950s, Outokumpu Oy explored for uranium, focusing on the areas of Palaeoproterozoic quartzites in eastern and northern Finland. Several occurrences were discovered, including the Nuottijärvi prospect in the municipality of Paltamo (discovered 1959) and the Kesänkitunturi prospect in Kolari (1965). The Nuottijärvi prospect is a mineralized breccia in a carbonate-apatite zone between the Jatulian quartzite and overlying Kalevian mica schists, and contains 1–2.5 Mt rock with 0.04% U (Sarikkola, 1979; Geological Survey of Finland, Nuottijärvi–Uranium Database), the Kesänki prospect consists of uraninite-bearing zones (with 0.06% U) in the quartzite (Sarikkola, 1979).

In the 1970s, Outokumpu also carried out follow-up studies of the porphyry-type Mo-Cu and Au occurrences of Pohjanmaa, including the known Mo-Cu prospects of Rautio (Kalajoki) and the Au-deposit of Kopsa (Haapavesi) (Gaál and Isohanni, 1979). The **Laivakangas** (or **Laiva**) Au-deposit near Raahe was discovered as a result of detailed exploration based on a boulder sample that was sent to Outokumpu in 1980. Nordic Mines Ab started to mine the deposit in 2011.

In addition to its own ore prospecting in the 1960s, the geological staff of Outokumpu Oy carried out feasibility studies and mining plans for numerous deposits handed over to the company by the Geological Survey. The most laborious and time-consuming of these tasks was the investigation of the technical properties involved in the mining of the Hitura deposit, which finally led to the opening of the nickel mine in 1970. A positive result was achieved also with the Hammaslahti copper occurrence discovered by the survey in 1966. Outokumpu started the feasibility study in 1971 and the mine was active in 1973–1986, and 5.59 Mt of ore at 1.11% Cu and 1.26% Zn was then mined.

The discovery of the Laukunkangas deposit was the only one of economic value made in Finland for a long time, and it maintained faith in the productivity of exploration. In the mining industry,

however, the costs of ore exploration were included in expenditures of research and development (RD), and the exploration was considered to take a disproportionately large portion of the funds of RD in the whole production chain from ores to metals. As a consequence, it was decided in the mid-1980s to cut down substantially the costs spent in ore exploration. Exploration continued, but the responsibility shifted to the Geological Survey to a greater extent than ever.

In order to cut exploration costs the state-owned companies Outokumpu and Rautaruukki joined forces in Lapland at the beginning of 1982 by establishing a joint venture named Lapin Malmi. Up to the mid-1980s, the most important of its projects was the investigation of the Pd-Pt occurrences discovered in the layered intrusions of Kemi-Penikat-Suhanko. Jarmo Lahtinen of Outokumpu exploration and Tuomo Alapieti from Oulu University identified numerous Pd-Pt occurrences of different types (e.g., Alapieti and Lahtineni, 1989; Alapieti and Kärki, 2005). During the International Platinum Symposia organized in Finland in 1989 and 2005, the occurrences became known to specialists around the world, and after Finland joined the EU in 1995 and the mining rights became open for international exploration companies, the Pd-Pt occurrences have been targets for extensive exploration studies.

The Pd-Pt-Ni-Cu-Au occurences in the Suhanko intrusion, at Konttijarvi and Ahmavaara, had already been discovered by Outokumpu Oy in 1964. The exploration continued periodically until the 1980s with Konttijärvi as the main target (161 drill holes) and showed that pyrrhotite-chalcopyrite-pentlandite-PGE mineralization existed in the basal part (marginal series) of the layered intrusion, some also as offshoots in the basement rocks near the basal contact of the intrusion (Alapieti et al., 1989). The exploration and feasibility studies were continued in 2000–2003 by Arctic Platinum Partnership, a joint venture of Gold Fields Finland Oy and Outokumpu Mining Oy. When Outokumpu withdrew from the partnership, Gold Fields Arctic Platinum Oy continued as a subsidiary of the South African company Gold Fields Ltd. Exploitation of the Suhanko deposits was not considered profitable in the 2000s due to low metal prices and problems in processing (flotation), but in the 2010s a massive drilling program increased the ore resources and the development of a suitable hydrometallurgical Platsol method for processing the ore have led to a more positive outlook.

International activities were the main focus of Outokumpu's exploration from the mid-1980s (Kuisma 1985), and domestic exploration was targeted to massive sulfide deposits and nickel to guarantee the raw materials for the steel works. Besides extensive studies of layered mafic intrusions and their PGE potential, also basic geochemical and volcanological studies were undertaken on ultramafic rocks with komatiitic affinities in the Archean provinces of eastern and northern Finland. The nickel discoveries of Arola in Kuhmo and Vaara in the Suomussalmi greenstone belts as well as Ruossakero and Sarvisoaivi in the Enontekiö Archean greenstone belts, and several occurrences of nickel sulfides at the Proterozoic Pulju greenstone belt in Kittilä were surveyed in detail, but the resources were not regarded economic for mining.

The most notable event in the exploration of the 1990s was the discovery of the deep extension of the Pyhäsalmi sulfide deposit. In 1996 the known ore reserves of the Pyhäsalmi mine were so small that the mine was facing termination of its operations in the next few years. However, in December 1996, deep drilling instigated by mine geologist Timo Mäki intersected a considerable thickness of massive sulfides, and the inventory work following this discovery increased the life of the mine by more than 20 years. The Pyhäsalmi deep extension, together with the discoveries of the Vuonos, Laukunkangas, and Saattopora deposits, were all good examples of successful innovative actions in the history of the Outokumpu exploration department.

EXPLORATION ACTIVITIES OF OTANMÄKI OY/RAUTARUUKKI OY

When mining operations in Otanmäki began in 1952, the ore proved to be more heterogeneous than the experts had predicted. Instead of a large, uniform ore body that was indicated in early reports, the deposit more resembled a school of herrings, with hundreds of small, separate ore pockets. In the first estimate of the ore reserves made on the basis of mining technology, the actual amount of ore fell well below original expectations. The ore grade confronted the geologists with challenging problems, and many novel geophysical measuring methods and apparatus were developed to determine the economic limits of the Otanmäki ore deposit.

In the 1950s, the establishment of ironworks was planned using the titanium-bearing magnetite concentrate as a raw material. The Otanmäki ore grade was not suitable as such for the blast furnace, and the company turned to the Geological Survey and Suomen Malmi Oy with an appeal for the intensification of iron ore prospecting in northern Finland. However, the level of planned activities did not satisfy Otanmäki Oy, and it decided in 1957 to establish an exploration department of its own with the aim of increasing the ore reserves. Heikki Paarma was appointed the head, as he had been in charge of geological investigations from the very inception of mining operations at Otanmäki and he also felt deeply concerned about the procurement of ore for the planned ironworks.

Otanmäki Oy's request to the Geological Survey led to airborne magnetic surveys in the Misi area, in the eastern part of the Peräpohja schist belt, in the municipality of Kemijärvi, where the **Kärväsvaara** iron occurrence was known since 1921. On the basis of geophysical surveys, Suomen Malmi Oy investigated the area and discovered in 1955 the small Sääski magnetite deposit. In 1957, Otanmäki Oy obtained the mining rights to the Kärväsvaara deposit, and with the opening of the mine, the district became an exploration target of the company's own exploration department. The **Raajärvi** magnetite deposit was discovered the following year. The deposit was covered with a thick sand layer, and magnetic gradient measurements with correct interpretation played a significant role in the discovery of the ore. In 1958, the company carried out a low-altitude aeromagnetic survey that led to the discovery of the **Leveäselkä** magnetic anomaly, and a deposit containing 1 Mt of magnetite ore was inventoried in 1960. The discovered ores of the Misi district (Nuutilainen, 1968; Niiranen et al., 2003) contained no harmful additional components, but, on the contrary, the concentrate contained magnesium, which was advantageous for mixing with the titanium-bearing iron concentrates. Hence the new discoveries facilitated the decision to establish a blast furnace in northern Finland dependent on local ore reserves.

The mining rights to the **Rautuvaara** ore discovered by Suomen Malmi Oy in the Kolari district were transferred in 1960, along with the title to surrounding tracts, to Otanmäki Oy. As a result of intensive exploration, including low-altitude airborne magnetic surveys, the Laurinoja open cut mine was established in 1982 in the **Hannukainen** ore field (Hiltunen, 1982).

The Otanmäki Company merged into Rautaruukki Oy in 1969. Already in 1959 an exploration office was opened in Rovaniemi, and the exploration operations were concentrated in northern Finland. From there the staff in charge of ore exploration moved in 1966 to Oulu, where the head office of the Rautaruukki Oy was later transferred.

Earlier, in 1957, Otanmäki Oy received laymen samples of magnetite gabbro associated with the layered mafic intrusions of Koillismaa. The region was studied with low-altitude airborne magnetic surveys in 1961, and as a result, magnetite gabbro horizons were located in the intrusions. The Mustavaara deposit was drilled and inventoried in 1970–1971, and in 1976 the **Mustavaara** mine was opened. However, at Mustavaara, magnetite was so intensely intergrown with ilmenite that the production of a magnetite concentrate was not possible, but the high vanadium content of the ore was extracted in the vanadium works

at the site (Juopperi, 1977). In the 1980s, based on the Otanmäki and Mustavaara vanadium works, the Rautaruukki Company produced about 10% of global vanadium consumption.

The first indication of a nickel occurrence at Oravainen was obtained in the summer of 1972 when a local prospector sent a sample of a glacial boulder with a nickel content of 2.24% for inspection. By means of boulder tracing, geophysical surveys, and geological mapping, the provenance of the boulders was found in February 1973. On the basis of diamond drilling, 1.3 Mt of ore with 0.95% Ni and 0.16% Cu were inventoried by the end of 1974. The ore deposit was in 1976 transferred to the ownership of Outokumpu Oy, and in 1976–1991 Outokumpu Finnmines evaluated the possibilities of mining the ore, but the resource was not indicated suitable for mining.

Rautaruukki Oy's ore exploration project of the longest duration was in the Sokli area of northeastern Finnish Lapland known as Itäkaira (Eastern Wilds). Many factors contributed to the discovery of this carbonatite, which ranks among the world's largest in area. In the years preceeding the discovery, Heikki Paarma had become acquainted with the geology and alkaline rock intrusions of the Kola Peninsula. He also knew that on the Russian side, close to the Finnish border, was the Kovdor magnetite mine in a carbonatitic alkaline rock intrusion. Itäkaira was selected for prospection since it is located adjacent to the Kovdor magnetite-rich carbonatite deposit. A mosaic of good aerial photographs were obtained from the area, and from it Jouko Talvitie located a ring structure, which, however, was proven to be a granite intrusion. Low-altitude airborne geophysical measurements were started in May 1967, and the first two profiles showed a strong magnetic anomaly in the Sokli area.

The first samples of carbonatite were found in a boulder field of the Sokli area. At the same time, the heavy mineral investigations carried out in the area yielded pyrochlore, a Nb-mineral characteristically present in carbonatites. Subsequently, a low-altitude airborne geophysical survey was flown over the whole area, and the results were useful in determining the extent and structure of the carbonatite sub-outcrop. The Sokli carbonatite complex was investigated by Rautaruukki Oy until 1980, and Dr. Heikki Vartiainen was in charge of the studies. The mineral of main economic interest was apatite. Besides directing the exploration and mining tests, Vartiainen extensively studied the petrology and mineralogy of the occurrence, collaborating with domestic and international experts, including Dr. Allan Woolley from the British Museum and Soviet geologists, geophysicists, and dressing/process engineers. Heikki Vartiainen published the scientific results in his extensive doctoral thesis (Vartiainen, 1980) and several shorter articles. He also compiled the exploration history of Sokli in Finnish (Vartiainen, 2012).

Heikki Paarma was in charge of research and ore exploration until 1977, and since then the operations were directed by Dr. Juhani Nuutilainen. The ore exploration by the Otanmäki and Rautaruukki companies was traditionally concentrated on the search for iron ore and the compound metals in steel making. Abundant and adventurous experimentation and application of geophysical methods characterized the work, and many new methods came into general use in Finland through their development and testing in prospecting. These include, for example, the investigation of large-scale structures by means of satellite pictures and aerial photographs, the use of false color photography, and the use of heavy minerals in mineral exploration. In order to cut exploration costs, from 1982–1985, the Rautaruukki and Outokumpu companies had a joint venture called Lapin Malmi. In 1979–1984, Rautaruukki Oy, together with Soviet experts, carried out extensive research on iron ore potential of the territory of Finland called the RAETSU project. As a result of the research the potential to find new exploitable iron ore reserves was considered to be low, and so Rautaruukki Oy decided to terminate exploration in 1985. The personnel were joined with Outokumpu exploration, and the ore exploration data file moved to Outokumpu's data file.

EXPLORATION BY PRIVATE COMPANIES

The Oy Prospektor Ab was founded in the late 1930s. Its predecessor was Avtalsgruppen, which comprised a number of enterprises interested in ore prospecting. Among them were about a dozen firms, including the leading cement manufacturers Paraisten Kalkki Oy and Lohjan Kalkkitehdas Oy. The prominent mining and industrial tycoon Petter Forström was the chief promoter of the Prospektor Company, and Professor Hans Hausen acted in the beginning as the geological expert. In the 1930s Oy Prospektor Ab investigated the Talvivaara black schist occurrence in Sotkamo, but after the war the main attention was focused on the chalcocite occurrence at Kiiminki. In 1954, the company started regular exploratory work and hired Rolf Bosröm and Matti Tavela as geologists. In 1956, the name of the firm was changed to Oy Malminetsijä Ab; this Finnish version was thought then to be more suitable for the popular ore prospecting competitions. In 1964, Oy Malminetsijä Ab was taken over by Paraisten Kalkkivuori Oy, and its operations were terminated in 1971, when it was absorbed by the parent organization. Oy Malminetsijä Ab operated all over the country, but major prospects in addition to the aforementioned Kiiminki and Sotkamo districts were the nickel occurrences at Parikkala in southeastern Finland and at Sääksjärvi, east of Pori, as well as the Huhus iron ore deposit in the frontier municipality of Ilomantsi.

Hackman & Co. had engaged in intermittant ore prospecting mainly in North Karelia, ever since the discovery of the Outokumpu deposit. At the beginning of the century it had claims at Luikonlahti, for example. In the 1950s, the company had its own organization for ore exploration, and the targets were at Kotalahti, which later became an active mining area by Outokumpu Oy, and at Varpaisjärvi, where Hackman & Co. discovered the molybdenum occurrence of Kylmämäki. The geologists working for the company were Juhani Nuutilainen and, at some stage, Ossi Näykki.

Preliminary mineral exploration was undertaken in the provinces of Oulu and Lapland by Pohjois-Suomen tutkimussäätiö (Research Foundation of Northern Finland) between 1950 and 1957. The executive director of the foundation was Veikko Loppi, and the board of directors included prominent citizens interested in the research of Lapland, including Governor Kalle Määttä, Director General Kaarlo Hillilä, and Dr. Paavo Haapala. The foundation organized an ore prospecting competition in the region, and within its framework geologists Erkki Aurola and Väinö Makkonen, as well as geophysicist Holger Jalander, carried out exploration programs. The foundation withdrew from the sponsorship of prospecting competitions at the beginning of 1957, but after that the Lapin Maakuntaliitto (Provincial Federation of Lapland) and the Lapin Tutkimusseura (Research Society of Lapland) continued the operations between the years 1958 and 1962.

In the summer of 1954, to secure the domestic reserves of iron ore, the steel-making company Oy Vuoksenniska Ab undertook an extensive exploration program in the **Jussarö** region (Mikkola et al., 1966). Airborne magnetic surveys were made over an area of approximately 70 km^2, and the details of observed anomalies were examined either from a boat or from the ice in winter. Divers collected required samples from anomalous areas under the sea, and diamond drilling was done using a tower structure erected on the sea bottom. In the beginning of 1957, a test shaft was driven on the island and the underground investigation of the banded iron ores continued until the mining operations began in 1961. Vuoksenniska closed the mine in 1967.

A similar investigation was conducted also close to the island of Nyhamn to the south of the Åland Islands simultaneously with the exploration of Jussarö. In addition to the geophysical surveys carried out by boat and on the ice, a diver took samples from the exposure at the sea bottom. The work

continued with sinking a test shaft on the island of Nyhamn, and from there a tunnel was dug into the ore body. A test sample was mined from the ore, but as the Jussarö deposit was found to be of better grade, the exploration at Nyhamn was discontinued in 1959.

Malmikaivos Oy started exploration in the **Luikonlahti** area in 1940, and the promising Asuntotalo ore body was discovered by boulder tracing and excavations in 1944. Eleven staked-out claims were secured since 1947. To retain the claims, the company continued the prospecting in 1957. The Kunttisuo deposit was intersected by diamond drilling, and in the following year the deep extensions of the largest ore body, the Asuntotalo deposit, were intersected by drilling. In 1958, the landowner, Ruskealan Marmori Oy, and Malmikaivos Oy decided jointly to sink a test shaft into the Kuparivuori (also known as Copper Mountain) to investigate the Asuntotalo ore underground. In 1965, the decision to open a mine was made, and production commenced in 1968. When the operations came to an end in 1983, a total of approximately 7.7 Mt of ore had been mined with a content of 1.2% Cu, 0.12% Co, 0.09% Ni, and 0.65% Zn. When the mine was closed, the company started to exploit talc ores, and the exploration department continued to investigate talc deposits in North Karelia.

The discovery of kimberlite boulders in the Kaavi area in the early 1980s started an interesting period of exploration, and, as a result, the company had a test mine at Lahtojoki. In 1984, Malmikaivos Oy established a joint venture with the Australian company Ashton Mine Ltd., which had special experience in diamond prospecting. The operations to find kimberlite pipes were kept secret, and it was a big surprise in 1996 when Malmikaivos Oy finally revealed that the joint venture had discovered 24 kimberlite pipes in eastern Finland and that diamonds were discovered in 14 of them. Despite interesting results, Malmikaivos Oy sold its rights in the joint venture to Ashton Mine, which continued the exploration for some time. Later on, the claims were transferred to international enterprises, which have continued the diamond exploration but without major new discoveries.

In 1955, private companies that were dependent on electric power in their operations founded Atomienergia Oy to investigate the feasibility of utilizing nuclear power. Erkki Aalto headed the new company at its initial stage. The search for raw materials became the central task. Professor Kalervo Rankama, a specialist in nuclear geochemistry, was consulting for the company, and on his recommendation, Atomienergia Oy undertook exploration for uranium deposits in Finland. In summer 1956, Tauno Piirainen was hired to conduct ground investigations, including studies of prospective geological formations and inspection of ore specimens collected by laymen. In the next year, the brothers Eino and Matti Justander, armed with a Geiger counter, ran across radioactive boulders at Hutunvaara, in the municipality of Eno. The samples initiated intensive investigations between Koli and Kaltimo. Accumulations of uranium-bearing quartzite boulders were found at Herajärvi and Riutta.

At Hutunvaara, the ore was found in the bedrock, and diamond drillings indicated the extent of the occurrence. The company decided to extract uranium ore concentrate on a small scale from the Paukkajanvaara mine. Altogether 30,700 tons of ore was extracted in 1960, but the **Paukkajanvaara** deposit turned out to have insignificant resources. Since no other deposits were available, mining operations were discontinued in the fall of 1960 (Piirainen, 1968). Other investigation targets of the Atomienergia organization were in the municipality of Kisko, where minor pitchblende dikes were discovered in the old Malmberg iron mine. From 1956, the company employed five geologists, headed by chief geologist Heikki Wennervirta. When Atomienergia Oy finished the active exploration, Outokumpu Oy continued the uranium exploration in eastern and northern Finland, and the Geological Survey in southern Finland, until the 1980s.

The paper and pulp company Kajaani Oy was reopening the old Tipasjärvi pyrite mine in northeastern Finland during a sulfur shortage in 1952. It founded its own ore exploration organization in 1971 and started systematic prospecting in the Kainuu region. Timo Kopperoinen was engaged as chief geologist. The Tipasjärvi area in Sotkamo became the most important target. A Zn-rich boulder sample from the Hiidenkirkko area led the company to start geochemical till exploration in 1980. At the same time, a bedrock research project of the University of Oulu discovered zinc ore boulders and also a mineralized outcrop in the Taivaljärvi area northeast of Hiidenkirkko.

Kajaani Oy got the exploration claims to the Taivaljärvi area and soon after the discovery of the Oulu University team, Kajaani Oy localized with diamond drilling the Taivaljärvi Ag-Zn-Pb deposit near the mineralized outcrop. The deposit was drilled from the surface to the depth of 150 m, and the result was so encouraging that an inclined shaft was constructed to take a major ore sample from the deep portion of the ore for process testing. In the final stage of Tipasjärvi exploration in 1989, Kajaani Oy had a joint venture with Outokumpu Oy called Taivalhopea (Papunen et al., 1989). It made additional inventory drilling underground, but the feasibility study indicated that opening a mine there would not be economic at that time.

With that decision, Kajaani Oy gave up exploration. However, the exploration of the Taivaljärvi deposit was reactivated after a hiatus of 20 years, when Silver Resources Oy, now Sotkamo Silver Oy, acquired the mining rights in 2005 and completed the mineral resource estimate with additional studies. A mining license was granted in 2011 and the production was expected to start in 2015. With a cutoff grade of 50 ppm Ag (eq) the deposit contains 3.52 Mt measured and indicated resources with 0.72% Zn, 0.27% Pb, 91 ppm Ag, and 0.27 ppm Au, and additional inferred resources of 1.5 Mt with equal composition (Lindborg et al., 2015).

Partek (Paraisten Kalkkivuori Oy, Paraisten Kalkki Oy) and Lohja Oy (Oy Lohjan Kalkki Ab), two conglomerates that had their main interest in industrial minerals and rocks, also carried out some exploration for certain ore deposits. In the 1960–1980s, initiated by a discovery of spodumene-bearing pegmatite boulders, Paraisten Kalkki Oy/Partek carried out exploration for lithium (spodumene) in the Kaustinen–Ullava area, and discovered promising spodumene pegmatite dikes. Since 1999, Keliber Oy has continued exploration and made preparations for exploiting the deposits. In the 2000s, the Geological Survey contributed by exploring the Kaustinen-Ullava area and discovering new spodumene pegmatites.

The occurrence of sericite schist as an alteration product of felsic volcanic rocks in the Orivesi area, Tampere schist belt, has been known by geologists since late 1940s. Between 1946 and the 1980s, several companies studied the occurrence located northwest of Lake **Kutemajärvi** as a sericite deposit, including Viento Oy, Renlundin Tiili Oy, Suomen Mineraali Oy, Kemira Oy, and Oy Lohja Ab. The investigations of Kemira Oy included detailed geological mapping and diamond drilling. It was estimated that the deposit contained 14 Mt of sericite schist containing 37% sericite, 6% topaz, 8% kaolinite, 1% andalusite, and 48% quartz. Kemira also considered the possibility that this F-rich alteration assemblage was caused by fluorine-rich hydrothermal fluids, and analyzed the schist for metals known to follow fluorine, such as Li, Sn, Rb, Au, and Ag. The concentrations were not encouraging, and the company abandoned the claim in 1974. Lohja Oy had the claim to the deposit after Kemira Oy from 1975 to 1990, and studied it as a possible source of industrial minerals sericite and topaz. After detailed inventory studies and process tests, it decided that exploitation would not be economic.

The Department of Geology at the University of Helsinki had from 1980–1983 the so-called Porphyry Project to explore for porphyry-type Mo, Cu and Au deposits in association with the

Svecofennian granitoids (Nurmi, 1985). The project was led by Professor Gabor Gaál and Pekka Nurmi. The project had several targets in the Tampere schist belt, and the Kutemajärvi sericite schist in Orivesi was one of them, selected because the alteration assemblage resembled those of porphyry-type deposits. The exploration was conducted in collaboration with Lohja Oy. Together, 72 rock samples were taken along three N-S profiles across the sericitized zone. The profiles showed a zoned anomaly pattern with barren sericite schist in the north, gold in the middle, and base metals in the south. Two diamond drill holes made by Lohja Oy in 1982 on the anomalies intersected an ore-grade rock that became known as Pipe 2. Later, diamond drilling unearthed a deposit consisting of three subvertical pipes of gold ore. With a cutoff grade of 2 ppm Au, the deposit was estimated to contain 0.63 Mt of ore with 9.4 ppm Au (Ollila et al., 1990; Kinnunen, 2008). Outokumpu Finnmines Oy purchased the mining rights to the deposit in 1990 and continued technical and feasibility studies, including pilot mining in 1990–1993. The Orivesi Gold Mine was officially opened in 1994 and was operated by Outokumpu until 2003, when the mine was sold to Polar Mining Oy/Dragon Mining. Mining was resumed in 2007, with Dragon Mining focusing efforts on the Sarvisuo lode system, which was discovered in 2002. Sarvisuo is located 300 m from the Kutema deposit.

When the ore reserves of Finland's mines declined in the early 1970s and several mines had to be closed, the Ministry of Trade and Industry established in 1971 a special fund to support ore geological research in universities targeted especially at northern Finland. Originally, the funds were available from 1971–1977, but because the results were encouraging, the program was extended to the 1990s. The geological departments of the Universities of Oulu, Helsinki, Turku, and Åbo Akademi, as well as the Helsinki University of Technology, had research projects financed by this fund. The projects produced results that have been useful in planning and carrying out successful exploration programs in different organizations, and in two cases (Orijärvi and Taivaljärvi) the projects have directly contributed to the discovery of ore deposits. The projects have also contributed to the training of exploration geologists, who have subsequently taken responsibility for exploration in the Geological Survey and mining enterprises.

Exploration by foreign companies

Finland's entry into the European Union in 1995 and changes in the mining law made the country open for international mining and exploration enterprises. This led to a rush of international mining companies to Finland, and large areas in northern Finland were blanketed with applications for ore prospecting permits. Much of their activity comprised follow-up and feasibility studies of known ore prospects, discovered previously by Finnish exploration enterprises and the Geological Survey, as described earlier in this chapter, but in addition, important new discoveries have also been made.

The Sakatti Cu-Ni-PGE prospect near Sodankylä is one of the most promising new discoveries. It was found in 2009 by an exploration team of Anglo American Ltd., led by geologist Jim Coppard. The Sakatti area was one of the targets selected for closer study on the basis of geological models of the Central Lapland Greenstone Belt and related mafic–ultramafic igneous intrusions and extrusions, and existing basic geological, airborne geophysical, and till geochemical maps from the Geological Survey. Several targets were tested before the diamond drilling hit the Sakatti occurrence. The exact size and grade of the deposit is not yet known, but the existing data indicate that it is a large and rich magmatic Cu-Ni-PGE deposit. Unfortunately, the deposit is located at the margin of the Viiankiaapa Mire Reserve, a Natura 2000 area, which complicates the exploration and exploitation of the deposit.

The Rompas Au-U ore field in Ylitornio was discovered by France's Areva NC in 2008 on the basis of an airborne radiometric survey. In the follow-up studies, a large number of hydrothermal high-grade gold and uraninite-bearing pockets with mineralized veins, breccias, and disseminations were found in

the rocks of the Peräpohja schist belt, within an area of approximately 10 km × 10 km. The Canadian company Mawson Resources Ltd. purchased the property in 2010 and has continued the exploration.

SUMMARY

The preceding description of mineral exploration in Finland covers a long timespan from the seventeenth century to the present time. Initially, traditions and activity of mineral exploration in the territory of Finland relied mainly on the skills of Swedish mining experts, who knew the characteristics of the Swedish mineral deposits and applied their knowledge in looking for analogous formations in the bedrock of Finland. A simple device for magnetic surveys, the mine compass, was the only instrument to help in the search in the areas covered by overburden. Also the geology of Finland was poorly known until the end of the nineteenth century when the Geological Survey was established and regional bedrock mapping was started.

The first attempt to take samples from the deep part of the bedrock with diamond drilling was made at the end of the 1890s in Pitkäranta, where the initiator of multidiscipline mineral exploration in Finland, Otto Trüstedt, studied the feasibility and extension of the Fe-Cu-Sn-Zn deposits. Later on, Otto Trüstedt was employed by the Geological Survey of Finland, and in this capacity he successfully located the provenance of the high-grade copper ore boulder of Kivisalmi, eastern Finland, and discovered the Outokumpu copper deposit in 1910. The exploration process and discovery was a turning point in the mining history of Finland, and the discovery became the backbone of the domestic mining industry, metal works, and new methodology in mineral exploration. In the follow-up exploration operations, glacial boulder tracing, geophysical surveys, diamond drilling, and application of geological bedrock mapping were in common use, although the development of suitable equipment for drilling and geophysical surveys took some time. Another significant discovery of the Geological Survey took place in 1924 in Petsamo (Pechenga), and the exploration in difficult remote conditions took all the available resources of the Survey for more than 10 years.

In the mid-1930s, the government of Finland increased its interest in geological studies, and Suomen Malmi Oy was founded to improve the capacity of exploration. The Geological Survey discovered several new deposits before the outbreak of the Second World War. The knowledge of regional geology was still imperfect and greenfields exploration was largely based on ore-bearing samples sent by laypeople. After the war, several extensive campaigns were organized to intensify the layperson's prospecting, resulting in a great number of samples, which initiated the study of new discoveries.

After the war, the efficiency of the Geological Survey was increased with funding, new organization, and addition of personnel from 14 to 143 in 1959, which gradually increased to 944 in 1988. By 1951, the Geological Survey had started regional airborne geophysical surveys, and in the timespan of about 50 years the whole of Finland has been covered with accurate geophysical information. Systematic geochemical mapping since the 1970s has produced important data for mineral exploration and environmental welfare. Mineral exploration was a key area of the Survey until the 1990s, but the role of environmental questions and other services of the Survey have grown since then.

State-owned mining companies, Outokumpu Oy and Rautaruukki Oy, established their own exploration departments in the 1950s, and besides geological mapping, geophysical, and geochemical surveys, they participated in the development of methodology and instrumentation of exploration. These companies also had access to brownfields exploration around the existing mines, since they had experience in the geology of mineralized areas. Over time there was discussion about the overlapping of the exploration duties of the Geological Survey and the state-owned companies, and also the competition

between different state organizations to claim mineral deposits begun to be questioned. Finland, however, was one of few countries where grassroot mineral exploration was preserved in the national Geological Survey, whereas during the 1980s the surveys in the neighboring Nordic countries, for example, left the exploration activities or transferred them to a specific company.

Until 1995, when Finland joined the European Union, private exploration companies played a relatively minor role, but a few important metallic ore deposits, such as Haveri (gold), Jussarö, Luikonlahti, and Taivaljärvi, were discovered and developed until that time. From 1995, foreign exploration companies can stake claims in Finland, which led to the discovery of the Sakatti and Rompas deposits. In contrast, the exploration and development of industrial mineral deposits has largely been conducted by private companies.

In 1985, Rautaruukki Oy abandoned mineral exploration and its personnel and data were transferred to Outokumpu Oy. At the same time, Outokumpu strengthened its exploration abroad and its domestic activity decreased. At the turn of the millennium, Outokumpu Company had become an international mining giant and had mineral rights in many parts of the world, its exploration division had discovered several new mineral deposits, and it had active mining in Ireland, Australia, Chile, and Canada. The company, however, decided in 2002 to exit the mining business and with the means acquired from its exploration and mining assets, it developed the stainless steel works at Tornio.

The Geological Survey continued its role as an exploration organization. At present, however, grassroots exploration plays a minor role, and the Survey has changed to a databank of geological information. In this way it services all the exploration enterprises. In the role of geological databank, the Geological Survey of Finland is a world leader. The Canadian Fraser Institute annually ranks countries on the basis of their attractiveness in exploration and mining via surveys that are sent to approximately 4100 exploration, development, and other mining-related companies around the world. In the 2013 annual survey, Finland was ranked second for attractive mineral exploration, and Finland, Alberta, and Nevada have been consistently ranked in the top 10 over the last five surveys.

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