CHAPTER

INDUSTRIAL MINERALS AND ROCKS 9.5

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ABSTRACT

Mining of industrial minerals and rocks in Finland dates back at least to the year 1329 when the first known mining for limestone in southwestern Finland took place. It has developed into an important industry in Finland, and from 1949–1966 and 1983–2009, mining of industrial minerals and industrial rocks exceeded tonnages of the metallic ores. However, this trend has reversed recently, and by 2013 it totaled 15.4 Mt, or about 42% of the total ore mining in Finland. Most of the currently exploited deposits were discovered before 1960. Since the 1950s, important technological advances—often in collaboration with domestic clients such as the paper industry—have been made in mineral processing and product development for a number of commodities such as talc, apatite, TiO_2, feldspars, and wollastonite. The domestic restructuring of the nonmetallic sector began in the late 1980s, and while the entry of Finland into the European Union (EU) in 1995 opened new export markets, it also brought about increased competition, resulting in the takeover of most of the main Finnish producers by leading foreign companies. Some earlier domestic production has been replaced by substitutes, or even raw material imports, but the huge influx of foreign capital and investments seen in the metallic mining sector has not materialised to the same degree in the nonmetallic sector.

Keywords: industrial minerals; industrial rocks; geology; production; Finland.

INTRODUCTION

The term *industrial minerals* is still rather purely defined, varying at extremes between the academic and end-user terminologies. According to Harben and Bates (1990): “The industrial minerals, broadly defined, include all those materials that man takes out of the earth’s crust except for fuels, metallic ores, water, and gemstones. A commonly used synonym is *nonmetallics*; a somewhat more precise one is *industrial minerals and rocks*,” which will be used in this text. A more recent review of the classifications was completed by Jeffrey (2006). Pondering the limitations and difficulties of the evolving classifications, he concludes: “A robust classification system must address the geological, compositional, economic, and end-use properties of each commodity.” What makes industrial minerals and rocks different from their metallic counterparts is the critical need for development work with the end-users, by which mineral products are tailored based on the variable geological possibilities of each deposit. Good examples of this are found in Finland.

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The product range of industrial minerals is large, varying from low-value, locally used bulk products, to high-value niche products (e.g., those used in nanotechnology). Companies are also increasing their efforts to convert as much of all mined rock into marketable products as possible. This chapter will not cover all industrial minerals and rocks, because carbonatites and kimberlites, as well as the high-tech metals, are described in separate chapters. Also, even though the main Ti-oxide minerals are metallic minerals, they are mostly classified as industrial minerals, as 95% of their use is as high-brightness TiO_2 pigments. Even chromite has important industrial mineral uses, but is clearly thought of as metallic. In this book, all of these minerals are described in detail in Subchapters 3.4 and 9.2.

Industrial rocks are rocks utilized as such, without specific mineral separation processes, as raw materials for making products. As examples, the rocks used in making stone wool or soapstone for fireplace manufacturing can be classified as industrial rocks. They can also be classified as natural stone, whereas talc and magnesite floated from soapstone, are industrial minerals. These increasingly important types of materials are also classified as industrial rocks.

The publications on *Industrial Minerals and of Rocks in Finland* include some older summaries (e.g. Aurola, 1954a, 1964a, 1964b, Boström, 1986), Industrial Minerals and Industrial Rocks in Finland by Haapala (1988), and a number of more recent comprehensive review papers covering the broader topic of the Nordic countries. These include Lehtinen (2006), Johansson et al. (2008), and the latest by Kananoja et al. (2013). The industrial mineral deposit map of the Fennoscandian Shield (1:2,000,000) was published in 2013 (Gautneb et al., 2013). In terms of available data, the mining statistics of industrial minerals and rocks in Finland before 1946 are incomplete, but very good thereafter. The availability of product data for this sector is good from the 1960s to 2011. Since 1974, annual production summaries have also been published in *Kemia* (formerly *Kemia-Kemi*) magazine. However, after 2011, the situation noticeably worsened, with far fewer data available to the public. In this chapter, the mining data are, with few exceptions, based on those published annually by the Ministry of Employment and the Economy in Materia (formerly Vuoriteollisuus-Bergshanteringen). Only the most important, potentially important, or previously exploited, commodities are presented in this chapter.

Localities of all the known industrial mineral and rock mining operations in Finland from the 1300s to 2013 (inclusive), with their respective commodity symbols and total ore extraction classes (<1000, 1000–99,999, 100,000–999,999, and >1,000,000 tons) are shown in Fig. 9.5.1. While specific reference may not be made to this map in the commodity descriptions that follow, it is suggested that the reader refer to it on a regular basis. The main trends of ore mining from 1965–2013, are shown in Fig. 9.5.2. The largest commodities, "apatite ore" (including the carbonates from that mining), "carbonate rocks" (of sedimentary origin), and "talc ore," are also shown as separate trend lines. All of the other industrial minerals (IMs) shown in the figure exclude the carbonates, apatite ore, and talc ore.

Trend lines of ore mining of soapstones quarried for fireplace manufacturing (Fp soapstones), and industrial rocks (IRs)—that is, the stone wool rocks and diabase quarried for the cement industry—show that these materials are mined only in relatively small quantities. The trend line of metallic ore mining is shown for comparison to the trend line for all industrial minerals mining. The economic recession years, 1991 and 2009, are clearly reflected in the trend lines of the nonmetallic commodities.

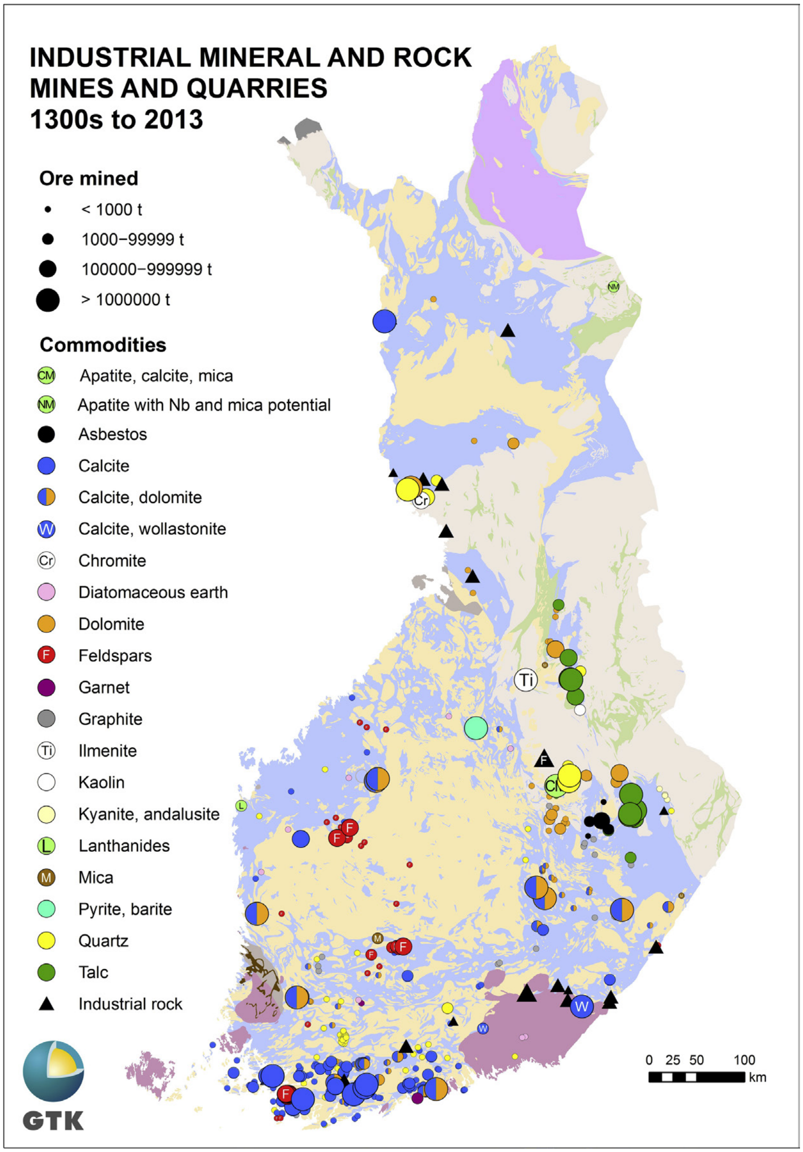

FIGURE 9.5.1 Locations of all the known industrial mineral and rock mining operations in Finland.

Shown are those from the 1300s to 2013 (inclusive), with their respective commodity symbols and total ore extraction classes: <1000, 1000–99,999, 100,000–999,999, and >1,000,000 tons.

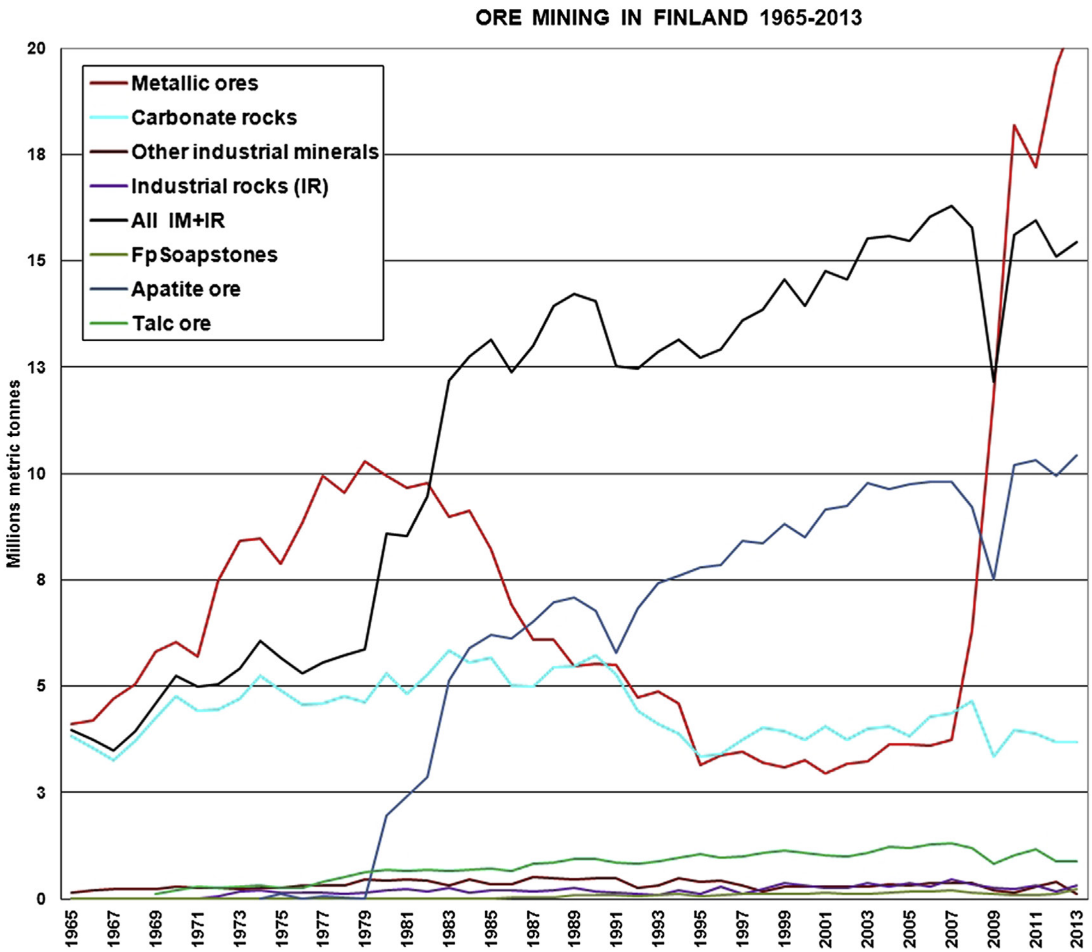

FIGURE 9.5.2 The main trends of ore mining from 1965 –2013.

CALCITE AND DOLOMITE

GEOLOGY AND MINING

Nearly all of the sedimentary carbonate rocks of mainland Finland are Paleoproterozoic marbles. Of these, most of the calcite-rich varieties occur in the Svecofennian domain, whereas the dolomite-rich ones dominate in the Karelian sedimentary rocks deposited on the Archean basement (see Fig 9.5.1). Eskola et al. (1919) and Pekkala (1988) recognized this rough geographical division and provided additional defining geochemical characteristics of these two groups. Eskola et al. (1919) also subdivided the types of the carbonate rocks by mineralogy within their respective geographic division into the following lithological types: (1) quartz-carbonate rocks, (2) tremolite-carbonate rocks, (3) diopside-carbonate rocks, and (4) wollastonite-carbonate rocks. These mineralogical differences reflect the dominant metamorphic grade with the marbles showing more mineralogical complexity in the higher metamorphic grade areas.

Mined deposits, both calcite and dolomite varieties, have been described by several authors in the compendium *The Mines and Quarries of Finland* edited by Aurola (1954a). A number of papers have been written concerning the Jatulian carbonate rocks of Finland and nearby Russian Karelia, including Metzger (1945), Perttunen (1985), Sokolov (1987), Melezhik et al. (2001), and Laajoki (2005). Later carbon isotope studies by Karhu (1993) confirmed earlier models regarding depositional environments and provided new ideas, especially in his division of the Karelian sequences into cratonic and marginal types. Reinikainen (2001) focused on the petrogenesis of four marble areas in the Svecofennian domain: two in the Uusimaa Belt, and two in the Virtasalmi District.

The carbonate rocks of the Svecofennian domain, mainly in southwestern and southern Finland, are ~1900 Ma old. In contrast, the Karelian occurrences found in the North Karelia, west Kainuu, Peräpohja, and the Kuusamo belts represent the upper part of the Jatulian sedimentary succession, which is ~2100–2060 Ma in age (Hanski and Melezhik, 2012). Upper Jatulian dolomite marbles, especially in the Rantamaa formation in the Peräpohja belt, contain well-preserved stromatolite structures similar to those described from Russian Karelia. Their presence suggests an intertidal to supratidal marine environment. The lower age limit of the Rantamaa formation can be constrained by a U-Pb zircon age of ~2106 ± 8 Ma obtained for the underlying mafic tuffs (Karhu et al., 2007).

Deposition of the Svecofennian carbonate rock suites are interpreted to have occurred in deeper basin environments compared to the Jatulian ones, which were deposited in shallow, mostly closed basins (Pekkala, 1988). This depth of deposition is seen in the predominance of calcite (deep) or dolomite (shallow), although later metamorphism and alteration have, at least in the higher grade areas, overprinted the mineralogy of the original sedimentary precursor. In practice, it is difficult to ascertain how much the present marbles retain their primary sedimentary mineral compositions. For example, at Ihalainen in Lappeenranta (Fig 9.5.3), the calcite marble with highest modal calcite has anomalously high Sr content compared with the other types, which might indicate that $CaCO_3$ precipitated originally in a shallow sea as aragonite, as aragonite tends to incorporate Sr more easily than calcite (Lehtinen, 1995). Recrystallization during metamorphism has produced a calcite marble with a distinctive trace element signature.

Younger carbonate rocks occur only in very limited or difficultly accessed areas in Finland. These include the seabed of the Selkämeri portion of the Gulf of Bothnia; Ordovician limestones under the sea in the Lumparn fjärd, southeastern Åland; the very impure dolomitic carbonate rocks in the parautochthonous Jerta or Valddejohkka plate in the Caledonian part of northwestern Finnish Lapland; and some from ice-age erosion sheltered carbonate rock remnants. Today these are known only from erratics on continental Finland (Lehtovaara, 1982).

Economically, the most important calcite marbles in the Svecofennian domain are located at Ihalainen, Lappeenranta (Lundén, 1979; Lehtinen, 1995, 1999), Limberg-Skräbböle, Pargas (Metzger, 1945; Fjäder, 1991), Tytyri (with Törmä and Solhem ore bodies), Lohja (Parras and Tavela, 1954), and Louhi, Savonlinna (Heiskanen, 1954; Lehtinen, 1999) on the northeastern border area of Svecofennia. Other, smaller, active, and/or recently mined or investigated sites are located at Förby (Saarmaa, 1983) and Hyypiämäki in Salo; Mustio and Kuovila in Raasepori (Sarapää et al., 2001, 2003); and Kalkkiranta in Sipoo (Tavela, 1954; Pakarinen, 1992). Of these, Tytyri, Louhi, Kalkkiranta, and Förby are underground mines (Förby closed in 2009).

A large number of abandoned, smaller quarries and some underground mines also exist in this Western Uusimaa–Kimito–Pargas carbonate rock province ("the leptite belt" by Eskola et al., 1919; Sarapää et al., 2001, 2003), which also hosts many deposits classified as mixed calcite-dolomite deposits that have also been exploited for agricultural products. Nearly all of these calcite marbles occur southwest

FIGURE 9.5.3 Ihalainen in Lappeenranta.

A view into the northern part of the Ihalainen open pit mine. White-light grey rocks are calcite marbles. Dark rocks with bedding conformable marbles, are leptites (rhyodacitic composition). Cross-cutting these are variably dark, granitic and composite dykes; the darkest are diabases. Average bench height is ca. 15 m.

Photo M.J. Lehtinen, 2014.

of the Savonlinna–Kuopio–Middle Ostrobothnia "line," but one large unexploited occurrence is geographically distinct, that being the rather dark calcite marble at Äkäsjoensuu in Kolari, west Lapland (Nurmi, 1989).

The largest dolomite marble resources occur in the Jatulian host rocks of Peräpohja (Tervola–Tornio–Keminmaa area), Kuusamo, and Kainuu belts. The Kalkkimaa quarry in Tornio has been operated since the 1500s (Härme, 1954). Several deposits in Vimpeli, Vampula, and Siikainen in western Finland and Ankele (earlier also Montola at Pieksämäki), Louhi, Juuka, Paltamo, and Kesälahti in eastern and southeastern Finland have been active sites for dolomite-based agrilime production, which continues to the present day. Predominantly dolomitic or dolomite-rich deposits in Siikainen, Kesälahti, Huutokoski, Muhos, and Utajärvi were not mentioned in the monograph of Eskola et al. (1919) because they had not yet been discovered.

Of the 652 carbonate rock deposits and occurrences documented by Eskola et al. (1919), Puustinen (1999, with a personal communication, 2013) lists 328 carbonate rock deposits that have been known to have been exploited in Finland up to 2013. The estimate of the total amount of carbonate rock mined in Finland up to that time is approximately 288 Mt. Only 15 of these have had a total of >1 Mt of carbonate rock mined, and 15 others were in the area ceded to the Soviet Union in 1944. The four sites with the largest volume of carbonate ore mining (excluding Siilinjärvi carbonatite) have been from Pargas (~98 Mt), Ihalainen, Lappeenranta (~63 Mt), the Lohja area mines (present Tytyri and the former Ojamo and Pitkäniemi mines; ~46.7 Mt), and from Louhi (previously named Ruokojärvi) (~13.3 Mt).

These, together with the Äkäsjoensuu deposit area (4.5 Mt ore mined), have the largest future calcite marble reserves. Due to production restructuring, increased competition with imports abroad, and markedly lower sales to the domestic agriculture, the annual mining of carbonate rocks—calcitic and dolomitic combined—has declined from 5.1 Mt/a in the period of 1970–1991 to an average of 3.7 Mt/a between 1992–2013. The import of foreign limestone and dolomite, 1.5–1.8 Mt/a and 0.045–0.092 Mt/a, respectively, represents a marked increase for the period 2007–2013.

CARBONATE PRODUCTION AND USAGE

Indirect information of the likely oldest quarrying and utilization of crystalline limestone in Finland comes from the "Black Book" of the Turku Cathedral in 1329, at that time under construction, and relates to the Krakanes limestone hill in the Förby area, southwestern Finland (Boström, 1986). The first industrial-scale lime production at Förby was started by Karl Forsström Ab in 1882 and ended in 2009, serving its last decades practically only as a source of calcite marble for the nearby paper pigment production. The first commercial cylinder lime kiln was built in 1862 in Helsinki (Boström, 1986). This kiln was fed with calcite marble brought from Pargas.

Many other similar kilns were erected thereafter in the 1800s. Nowadays, domestic calcite marble is being burned only by Nordkalk Oy Ab using rotary kilns in Lohja, Louhi, and Lappeenranta (ended in 2014). The calcite content of such calcite marble must usually be >88%, and HCl-soluble MgO <2 wt%. For floated, wet-ground $CaCO_3$ (GCC), calcite contents in the feed above 80% are feasible, if the brightness of calcite is high. Based on the demand of the steel industry and precipitated $CaCO_3$ (PCC) manufacturing, the amount of imported quicklime has grown remarkably since the end of the 1980s. Nordkalk and SMA Mineral Oy also burn imported limestone in shaft kilns in Finland.

The first cement plant was built in 1869, and operated until 1894 at Savio in Kerava. Larger scale Portland cement production began at Pargas in 1914 (Eriksson, 2014). The number of cement plants continued to increase, located near larger calcite marble deposits including Virkkala in Lohja (1919–1994), Lappeenranta (1938–present), and Kolari (1968–1989; Kitunen, 1970). The present cement producer, with an annual production of ~1.4 Mt, is Finnsementti Oy, which is owned by the Irish company CRH. Different grades of calcite marble are delivered to the cement plants where they will be optimally mixed with other needed mineral-based ingredients to achieve the desired chemical composition for the raw mix for Portland cement production.

After World War II, rebuilding of the country required a rapid expansion in cement and lime production, as well as increased lime demand for the growing pulp and paper industry. Begun in 1940, the initially sporadic production of PCC at the Tervakoski paper mill has been continuous since 1967. Increasing demand for PCC from 1990 to the early 2000s resulted in quicklime burned from Ihalainen and later from Louhi calcite marbles also being delivered to other PCC plants in Finland, until the early 2000s, when the use of domestic raw material for PCC gradually ended. Of much more importance has been the production of GCC for paper and paperboard coating and filling by Omya at Förby (1982–present) and Suomen Karbonaatti at Lappeenranta (1983–present). Nowadays the Förby plant uses white calcite marble from Tytyri and Hyypiämäki as its raw material. In the comparison made by Wilson (2008), the brightness of GCC produced from Ihalainen calcite marble (see Fig. 9.5.3) was the highest (95.0, ISO 457) among the major European GCC production sites.

Since the 1990s, GCC has gradually replaced imported kaolin as the main paper pigment. Domestic, annual GCC consumption has recently been 1–1.3 Mt (dry tons), and roughly half of that is imported GCC. In contrast to the United States, PCC has by use stayed well behind GCC in Finland, 0.3–0.5 Mt (dry), and in other European countries. The highest consumption of paper pigments (GCC, PCC, chalk, kaolin, talc, gypsum, TiO_2) was between 1997 and 2008, and peaked in 2004 at ~3.5 Mt (dry). Of the total paper pigment consumption between 1990–2012, ~41% was kaolin, ~31% GCC, ~11% PCC, ~10% talc, ~5% chalk, ~2% gypsum, and «1% TiO_2. Of these, all kaolin and chalk were imported, most quicklime for PCC was burned from foreign limestone in Finland, or was imported as quicklime, and all TiO_2 was produced in Finland during that period from foreign raw materials. Digitalization of media is an increasing threat to paper pigment consumption, both in Europe and North America. White dry-ground calcite fillers are also produced from Finnish calcite marbles for different end-uses at the main production sites.

MAGNESITE

In addition to calcite and dolomite, magnesite is a carbonate mineral with economic interest in Finland, especially when obtained as a potential by-product of talc production from soapstones. This carbonate mineral forms the $MgCO_3$–$FeCO_3$ solid solution and in Finland is mostly ferroan magnesite (breunnerite) in composition.

In 2013, global magnesite production was about 25 Mt (USGS estimate), with the macrocrystalline (sparry), "Veitsch-type" magnesite from ancient marine platform carbonate deposits (e.g., in the Chinese-North Korean province, Austria, and Slovakia) fully dominating. This type has been found mainly from dolomitic carbonate rock occurrences of Archean to Carboniferous ages (Ebner and Wilson, 2006). According to Wilson (2013), of the world's 13.1 bn tons of magnesite resources, as estimated in 2012, 93% of exploited magnesite was obtained from macrocrystalline and 7% from the microcrystalline deposits. Deposits of the latter type (also known as cryptocrystalline) include: (1) ultramafic-hosted, tectonically controlled magnesite (Kraubath-type, mined, for example, in western Turkey, the Balkans, Greece, Iran, and Pakistan); and (2) deposits in clastic, lacustrine sediments near ophiolite complexes (Bela Stena-type).

Melezhik et al. (2001) described a Paleoproterozoic sedimentary magnesite mineralization from the ~2000-Ma-old stromatolite-dolomite-"red bed" sequence in the Tulomozerskaya formation, Russian Karelia, which they interpreted to have formed in a combination of shallow-marine and nonmarine, evaporitic environments. Later Morozov et al. (2010) documented a discovery of several hundred meters of Jatulian magnesite-bearing anhydrite-halite strata in the Onega region of Russian Karelia. Potential for this type also exists in the upper Jatulian sequences in Finland. From 1986–1988, plant-size tests ending with a short production period were carried out at Luikonlahti by Myllykoski Oy to float a pure magnesite product (this resulted in 83–96% magnesite with 16.1% dolomite) for the fertilizer industry. Other markets were also studied, but the product (total <10,000 t) proved to be uneconomical.

TALC

Commercial Finnish talc deposits occur in ~2000 Ma ophiolitic ultramafic rocks that are significantly altered to talc-magnesite rocks, called soapstones (Fig. 9.5.4). The main minerals of these ultramafic rocks are talc (40–65%) and ferroan magnesite (35–55%). The most common other minerals include dolomite, chlorite, and in less pure soapstones, some serpentine (antigorite). Pyrrhotite and pentlandite are the most common sulfides, the latter also having economic importance in some locations. Ferritchromite and magnetite represent the main oxides. Talc schists also occur, especially along the border zones between the ultramafic bodies and their wall rocks (typically gradational black schists to mica

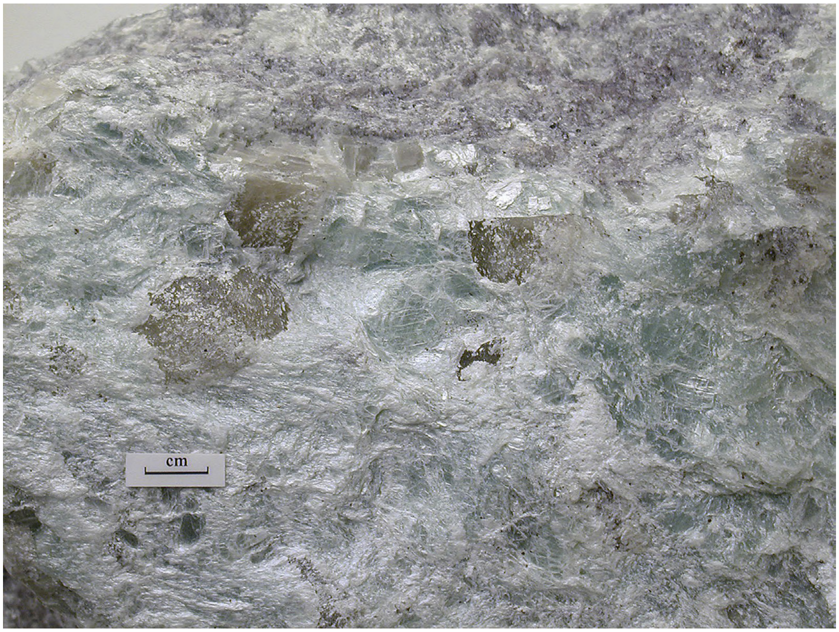

FIGURE 9.5.4 Commercial Finnish talc deposits.

Talc (flaky), with sparry magnesite (larger) and some lighter dolomite grains. Lipasvaara open pit mine, Polvijärvi. Scale bar 1 cm.

Sample: M.J. Lehtinen, photo: J. Väätäinen.

schists), also along which thin skarns are commonly developed. Vesasalo (1965) described more than 100 Finnish talc occurrences, some of which Wiik (1953) already had discussed in his description of the origin of soapstone. A more recent review was given by Niemelä (2001).

The first production of talc in Finland used dry processing by Suomen Mineraali Oy (later Paraisten Kalkki Oy) at Kinttumäki, Outokumpu in the 1940s, at Jormua, Kajaani from 1951 to 1971, and by Liperin Talkki Oy at Leppälahti, Liperi (1950–1953, 1955) (Aurola and Nieminen, 1954).

Based on quality factors, talc production has until now been restricted to the soapstones in the Karelian schist belts in Polvijärvi, North Karelia, and Sotkamo and Paltamo, western Kainuu. To the west of Polvijärvi, the higher metamorphic grade, along with the increased occurrence of amphiboles (cf. asbestos), has limited the usability of those soapstones for talc extraction. To the east of Polvijärvi in the Archean soapstones, the mineralogy (e.g., more oxides, and chlorite ± serpentine) and the texture of the main minerals, based on tests, do not favor the production of high brightness talc products.

Between 1969 and 2013, using modern froth flotation-based processing, 15.6 Mt of talc concentrate was produced out of ~35.8 million tons of ore from 11 different open pit mines. This production was started by Suomen Talkki Oy, with its main owners United Paper Mills Ltd. and Lohjan Kalkkitehdas Oy. The Lahnaslampi plant was the first talc flotation plant in Europe. Later names for this producer have been Finnminerals Oy and Mondo Minerals. Other producers were Myllykoski Oy (1979–1988) and Partek Corp. (1988–1990) with their mining at Repovaara and Lipasvaara in Polvijärvi, and processing at Luikonlahti. During its production time, from 1969–2010, the largest mine, Lahnaslampi in Sotkamo, alone produced ~17.6 Mt of talc ore. In addition to Lahnaslampi, >1 Mt talc ore has been mined from Horsmanaho, Pehmytkivi, Lipasvaara, and Vasarakangas in the Polvijärvi area, and from Punasuo in Sotkamo. At Mieslahti, Paltamo, remarkable talc reserves exist, but environmental constraints have thus far prevented any mining. An additional important, yet unmined, talc reserve is at Alanen in southernmost Sotkamo.

For the first time in Finland, a talc deposit other than soapstone type was test mined in 2010 by Mondo Minerals B.V., which extracted 5600 tons of ore from altered dolomites at Pihlajavaara, Puolanka in the Kainuu schist belt. Globally, the biggest commercial talc deposits are of this type; examples are in China (e.g., Liaoning, Shandong), the United States (Montana), Western Australia (Three Springs), and the French Pyrenees (Trimouns near Luzenac).

Finnish talc has been mainly used in paper, paperboard, plastics, and pitch control (adsorption of organic impurities in pulp and paper processes). The brightness range has been 84–90 (ISO 457), depending on the mineralogy and the grain size of the product. The recent production cuts of the European paper industry have hit talc production hard. Finland and France have been the largest European talc producers, and Mondo Minerals is globally the second largest single producer. Nickel concentrate has been a by-product of Finnish talc production since 1969. Until recent years, ~10,000 tons of nickel concentrate have been produced annually. Additionally, the potential of a magnesite by-product still holds economic potential for the future.

Of the Archean soapstone bodies in east Finland, the most important ones are those in the Nunnanlahti area, Juuka, and in the Suomussalmi–Kuhmo greenstone belt in eastern Kainuu. During the "new era" (1985–2013) of soapstone fireplace manufacturing in Finland, ~3.2 Mt of soapstone ore were mined from those areas. These quarries are not shown earlier in Fig. 9.5.1; however, the trend line of mining of fireplace soapstones is shown in Fig. 9.5.2.

QUARTZ

The earliest quartz production for small local glass factories was from the Somero-Tammela area, southwestern Finland, for the Åvik glass factory (1748–1833). Later production was from many other pegmatites in southwestern (Kimito island), southern (Orivesi), and western (Kuortane, Seinäjoki) Finland. The same ~1800 Ma, late-orogenic granite-related pegmatites have more recently turned out to be the main source of feldspars exploited in Finland.

The ~2300–2060 Ma Jatulian sedimentary rocks in eastern and northern Finland include thick quartz-dominated sequences (Paavola, 1984; Saikkonen, 1986; Laajoki, 2005). Some of these units consist of very little else besides quartz. This is the case with the Kinahmi quartzite in the Nilsiä, Kuopio area, the dominant quartz source in Finland. Kinahmi quartzite has been exploited since 1914 and since the production modernization and enhancement by Lohja Corp. in 1976 and 1980; the processing is based on flotation. Quartzite at Kinahmi is white, light gray, or a bit reddish in color (Fig. 9.5.5). The quartz content of the exploitable quartzite is 96% on average and the most abundant impurity is 2–8% sericite. Sheared areas contain kaolinite, and in places pyrophyllite. The total accessory mineral content is usually less than 1%. The quartzite ores are classified into three types: soft ("super quality"), semihard, and hard. The Fe_2O_3 and Al_2O_3 contents of the soft ore can be even lower than 0.015 wt% and 0.15 wt%, respectively.

Low titanium is also a benefit for special applications. The hard ore is too high in iron to be suitable for glass manufacturing, but finds use in refractory masses, plasters, and other special products. The main part of the Nilsiä quartz was delivered for glass-making (flat and package glass), but closures of

FIGURE 9.5.5 Quartzite at Kinahmi.

A view to “Super” quartz ore horizon in Kinahmi quartz quarry, Nilsiä (Kuopio). Mobile hydraulic hammer serves as a scale.

Photo: M. Häggman, Sibelco Nordic, 2010.

the Lahti flat glass and Karhula package glass factories in 2009 have strongly hit this end-use segment. Other end uses of Nilsiä quartz have been in induction ovens, sandblasting, refractory and white plasters, tiles, water glass, and crushed materials. Companies with production at Nilsiä have shifted over time: 1992–1997 by Partek Corp., 1998–2009 by SP Minerals Oy Ab, and since 2010 by Sibelco Nordic Oy Ab.

Very pure Jatulian quartzites also occur in the middle part of the Peräpohja belt of southwest Finnish Lapland. Here the <200-m-thick Kvartsimaa formation occurs between the overlying tuffitic Tikanmaa formation and underlying mafic volcanic rocks of the Jouttiaapa formation (Perttunen, 1991). Quartz in this orthoquartzite occurs as granoblastic mass, in which clastic grains can hardly be recognized from the matrix, where the sericite content is very low. This formation also contains minor dolomite and conglomerate intercalations. These quartzites were mined in 1966, 1980–1982, and 1984 from Tikanmaa (Tikka); in 1993–1995 from Kvartsimaa; and continuously between 1993 and 2012 from Ristimaa in Tornio. This mining supplies lump ore for the nearby stainless steel industry. More recently, production in Tornio has been by SMA Mineral Oy Ab. Since 2009, new lump quartz production for the same end use has been made available by Morenia Oy and comes from Juokuanvaara in Keminmaa, and also part of the Jatulian quartzite formations.

Since 1914, ~10 Mt of quartz ore from quartzites has been mined in Finland, of which quarries at Nilsiä alone account for ~86%. Of the total amount, lump ore as a product accounts for ~1.3 Mt (~14%). Altogether, 8.7 Mt of other, floated quartz products have been produced. This number also includes quartz produced as a by-product of feldspar production from Kimito Island. Tailings (i.e., fine-grained quartz and in Nilsiä also sericite) serve as additional potential credits if markets for these materials can be found.

FELDSPARS

The complex pegmatites which were the earliest sources for feldspar production in Finland occur at Somero-Tammela (Mäkinen, 1912), Kimito island (Pehrman, 1945; Lindroos et al., 1996), South Ostrobothnia (Haapala, 1966; Alviola et al., 2001; Mäkitie et al., 2001), and Orivesi (Volborth, 1954; Lahti, 1981). Similar pegmatites also exist elsewhere in Finland, including the Valkeakoski, Kisko, and Kitee areas and have been the focus of a great number of mineralogical investigations. The Li-pegmatites (albite-spodumene type) of the Ullava–Kaustinen–Kruunupyy area, western Finland, planned for mining in the near future, are described in Chapter 9.2.

The 1800 Ga pegmatites of Kimito Island represent beryl pegmatites (beryl-columbite subgroup) and albite pegmatites, except the Lövböle RE-pegmatite, which belongs to the gadolinite subgroup. These pegmatites are mostly hosted by gabbros (Lindroos et al., 1996) and their distribution is shown in Figure 5 of Eilu et al. (2012). Feldspar quarrying in Kimito followed previous quartz extraction for glass and iron works, presumably since about 1686. In 1737, the occurrence of tantalite was described from the Skogsböle pegmatite. Better organized production was between 1917–1954, when Suomen Mineraali Oy dry-processed Kimito feldspar, mainly quarried by local small enterprises.

FIGURE 9.5.6 Ala-Aulis.

Ala-Aulis pegmatite quarry, Island of Kimito. Reddish rock is pegmatite, dark one gabbro. Quarry length 490 m, width 70-140 m.

Photo: M. Häggman, Sibelco Nordic, 2014.

This was followed by Lohja Corp., which in the early 1960s conducted more extensive drilling in the Fröjdböle, Skogsböle, and Brokärr areas, resulting in 1966 in the first flotation-based feldspar plant in Europe with by-product quartz production. Present-day K-feldspar production in Finland is limited to Kimito, depending on the situation, and comes from pegmatite or both pegmatite (Ala-Aulis; Fig. 9.5.6) and late-orogenic (1840–1830 Ma) microcline granite (Kyrkoberget). Depending on the product, the K_2O content varies between 4 wt% and 7 wt%, K_2O/Na_2O ~1, and Fe_2O_3 ~0.1% (SP Minerals Brochure, 2001). The main end-uses of feldspar have been in the ceramic and glass industries, and for the Kimito quartz, in the domestic glass fiber and ceramic industries.

Of the Ostrobothnian ~1800 Ma RE-pegmatites, the complex pegmatites of Haapaluoma and Kaatiala have been classified by Alviola et al. (2001) as members of the spodumene subgroup. The Kaatiala dike (30 m wide, >200 m long) in Kuortane is a spodumene pegmatite, and the Haapaluoma dike (10–30 m × 500 m) in Seinajoki is a spodumene-lepidolite pegmatite. The country rocks for these pegmatites are foliated granodiorite and sillimanite-muscovite-biotite gneiss. Approximately 152,000 tons of K-feldspar, 44,000 tons of quartz, 700 tons of mica, and several tons of beryl, columbite, loellingite, and spodumene were extracted from ~516,000 tons of ore from the zoned Kaatiala pegmatite mined in Kuortane by Suomen Mineraali Oy between 1942 and 1968 (Puustinen, 2003). Production by Lohja Minerals and later by Partek Industrial Minerals Oy from the Haapaluoma pegmatite in Seinäjoki, from 1962–1997, was ~650,000 tons of feldspar + quartz ore (Puustinen, 2003). The Haapaluoma feldspar ore was famous for its high K_2O (~8 wt%) and low Fe_2O_3 (~0.04 wt%) content. Quartz was also obtained as a by-product.

The historical production of quartz and feldspar from the ~400 km^2 Somero-Tammela area, with more than 100 pegmatitic granites and pegmatites (1850–1750 Ma), indicates good potential for many rare element minerals as sources of Ta, Li, Be, Cs, and Rb (Teertstra et al., 1993; Alviola, 2001; Eilu et al., 2012). Exploration and testing have been carried out by the GTK and several companies.

Combining official production data for 1965–2013 with best estimates of older production (Puustinen, 2003), the main feldspar (+ quartz + in some cases small amounts of beryl, columbite, tantalite, etc.) ore-mining regions in Finland are ranked by Puustinen as follows:

- Kimito Island, southwest Finland: 5.82 Mt pegmatite (diverse quarries) and (pegmatitic) granite (Kyrkoberget) ore
- Seinäjoki-Kuortane (nearly all from Haapaluoma and Kaatiala) in western Finland: 1.17 Mt pegmatite ore
- Orivesi, southern Finland: 0.15 Mt pegmatite ore, mainly from the Viitaniemi pegmatite, and from at least 23 pegmatite quarries since the 1920s

Finnish anorthosites and anorthositic rocks have been studied (Sotka, 1988), tested, and used as raw materials for different purposes, including dimension stones (Ylämaa in Lappeenranta, Jaala in Kouvola, and Angeli in Inari), lapidary material ("spectrolite" from Ylämaa), and in larger tonnages as industrial rocks and minerals (Lapinlahti). In 1984, Kemira Corp. tested production of aluminum sulfate from Teerisuo in Lapinlahti by mining 27,166 tons of rock from the anorthositic part of the ring-structured orogenic (~1895 ± 15 Ma, from gabbro pegmatoid) Lapinlahti gabbro intrusion (Paavola, 1988). The bytownitic plagioclase (An_{75-85}) yielded to the whole rock the Al_2O_3 content of 27.5–30.5 wt%, and although Al solubility was favorable, 85–90%, production was found to be uneconomic for the planned water purification end use.

Since 1998, Paroc Oy Ab has used anorthositic rock from the same area for stone wool production in its factories around the Baltic Sea. The use of Joutsenenlampi anorthosite has grown faster than any other stone wool rock type in Finland, and between 1998–2013 ~2.07 Mt of ore was produced. The reason for that growth is the demand of better biosolubility of mineral wool fibers. The EC directive

97/69/EC of December 5, 1997, excluded certain mineral wools as a potential carcinogen: "Man-made vitreous (silicate) fibers with random orientation with alkaline oxide and alkali earth oxide (Na_2O + K_2O + CaO + MgO + BaO) content greater than 18% by weight."

Additionally, the International Agency for Research on Cancer concluded in 2001 that mineral wool insulation material was "unclassifiable as to its carcinogenicity to humans." Toward the end of the 1990s, SP Minerals Oy Ab (now Sibelco Nordic Oy Ab) also tested the suitability of Finnish anorthosites as another raw material for its Kimito feldspar plant. It started to buy the <40 mm fraction from Paroc's Lapinlahti crushed material and now sells the wet-processed product mainly to the fiberglass industry (refer to "F" inside the industrial rock symbol in Fig. 9.5.1). Besides Lapinlahti anorthosite, only anorthosite from Gudvangen in Aurland, west Norway, has been exploited for this type of use, although a potential White Mountain project in southwest Greenland is in the testing phase.

WOLLASTONITE

Wollastonite is a minor industrial mineral with a USGS-estimated worldwide crude ore production of ~600,000–630,000 tons in 2012, and product sales in the range of 500,000–540,000 tpa. Finnish Nordkalk Oy Ab was globally among the first two commercial producers of wollastonite and the pioneer in its wet processing. In 2012, China was the dominant wollastonite producer (~51%), followed by India (~24%), the United States (~12%), and Mexico (~9%) (BGS, World Mineral Statistics), with Finland still among the seven countries that produced natural wollastonite. Two deposits have been exploited in Finland, namely, Ihalainen in Lappeenranta and Perheniemi in Iitti.

At Ihalainen, wollastonite-rich carbonate rocks have been traced at least 1.5 km, mainly conforming to the roughly north–south strike and 65° eastward dip of this large calcite marble deposit, ~3 km long. Until now, mining for wollastonite has only taken place in the main wollastonite zone on the western and south-southwestern part of the present open pit mine, where the zone is widest (up to 65 m) and most massive (see App. 2 in Lehtinen, 1995, and Figure 1 in Lehtinen, 1999). Two types of wollastonite ore can be distinguished. The main ore type consists of sets of calc-silicate bands (wollastonite and diopside ± quartz), each band up to several centimeters wide, in a matrix of white to bluish calcite (Fig. 9.5.7). The wollastonite content of this ore type seldom exceeds 30%. Wollastonite is predominantly short-needled and, to the naked eye, the bands it forms look dense and sugary.

Calcite is, however, by quantity the main economic mineral (55–75%) in this ore type. This formation of wollastonite seems to be older than the rapakivi magmatism (~1600 Ma), because rapakivi dikes clearly crosscut this silicate banding, and an age determination from the titanite fraction from this type yielded 1858 ± 20 Ma (unpublished data, determination by H. Huhma; Lehtinen, 1995). The variable fluorescence and phosphorescence is less definitive, but indicative of differences between the two ore types. This older wollastonite ore type is thought to have its origin in upper medium- to high-grade metamorphism, when tectonic activity and temperature at a greater depth fractured this originally more impure siliceous limestone zone, allowing fluids to flow and CO_2 to escape.

The second, younger skarn-type wollastonite ore is at its best massive with a wollastonite content normally exceeding 30%. Its occurrence is related to the later thermal effects of larger granite dikes emanating from the nearby rapakivi intrusion, especially in the south-southwestern part of the open pit mine. In smaller scale and volume, younger wollastonite can also be seen along the main zone as wollastonite-dominated reaction skarns on the contacts with the mafic and intermediate volcanic rocks,

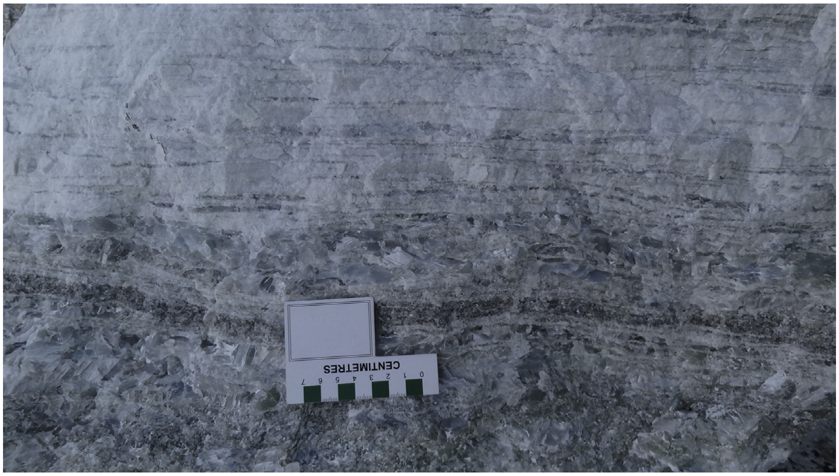

FIGURE 9.5.7 The main ore type of wollastonite consisting of sets of calc-silicate bands (wollastonite, diopside ± quartz).

Typical banded wollastonite ore (main type) in calcite marble from Ihalainen open pit mine, Lappeenranta. Dense white silicate bands consist of wollastonite+diopside ± quartz. Calcite is bluish.

Photo: M.J. Lehtinen, 2014.

very likely also as a result of the thermal effect of the rapakivi intrusion. In this younger ore type, besides wollastonite, calcite, diopside, and quartz, in places also grossular, vesuvianite, titanite, and fluorite occur. Wollastonite in this ore type has the highest aspect ratio of any in the deposit. Late overprint by hydrothermal alteration was related to the final stages of the rapakivi magmatism. In addition to some Mg hydrosilicates, fluorapophyllite, fracture-filling graphite, and pectolite characterize this late evolutionary stage. It is important to mention that in most cases there is no wollastonite skarn at the contact with the rapakivi pluton itself.

Until 1947, wollastonite at Ihalainen was seen as an impurity mineral in the calcite marble. In the 1950s, lump wollastonite was variably used as a small component in local stone wool manufacturing; since 1956 it was used for specific wall tiles of Turun Kaakeli Oy; and regular exports started in 1965. Production from the first wollastonite-specific beneficiation flotation plant began in 1966/1967, followed by flotation capacity enhancements in 1972 and 1986. Lump ore deliveries ended in 1977. Production from the present wollastonite-calcite plant initially went mainly for ceramics and metallurgy, but now is mainly for plastic filler end uses.

Until 2009, Lappeenranta was the sole continuously operated natural wollastonite producer in Europe. Besides Nordkalk, the only flotation-based processor of this mineral worldwide is NYCO Minería. The period of highest wollastonite output in Lappeenranta (1988–1997) produced in excess of 20,000 tons, peaking at 31,436 tons in 1989.

Another deposit that has been exploited for wollastonite in Finland is located at Perheniemi in Iitti (Arhe, 1980). This calcite marble with wollastonite skarns was first utilized as raw material for lime, supplied for the building of the Medieval Häme Castle, believed to have been built at the end of the thirteenth century. Wollastonite and diopside dominate in thin (<0.5 m) reaction skarns between the calcite marble and the viborgitic rapakivi granite intrusion. The wollastonite itself is of excellent quality, in part acicular, in part fine, platy "Tafelspat." Original mineralogical zoning and later alteration have been described by Arhe (1980). In the 1950s, Suomen Mineraali Oy quarried the easily exploitable reserves and sold ~400–500 tons as lump ore, mainly to Denmark.

The largest known unexploited wollastonite deposit with economic potential is at Kaihtula, Savitaipale, 35 km northeast from Lappeenranta. It likely represents the same carbonate rock system as the one at Ihalainen that has been distorted and disrupted by intrusion of the younger rapakivi granite. It was found in 1984 by Partek, when tracing the source of numerous glacier-deposited carbonate rock boulders, and finally with geophysics and drilling. There are no outcrops and the deposit is under a rather thick, mostly wet overburden. In 1995, the deposit was again drilled and evaluated, and the wollastonite ore reserves were re-estimated to be ~14 million tons. Additionally, the higher Mg content of the wollastonite-carbonate rock (more dolomite and serpentine than in Lappeenranta) is a negative finding (Internal reports of Partek companies, 1982–1995, Lundén, 1988).

In the Lake Saimaa district, there are numerous small occurrences of wollastonite, but their development is unlikely due to environmental reasons.

APATITE AND MICAS

Since 1979, production of apatite and mica (tetraferriphlogopite) in Finland has been from the Archean Siilinjärvi carbonatite (U-Pb 2609 ± 6 Ma; O. Kouvo, cited in O'Brien et al., 2005), which is described in Subchapter 4.3. Including the test production, 21.85 Mt of apatite concentrate out of ~260.4 Mt of ore were recovered between 1975 and 2013 (Kemira Corp., 1979–2007, Yara International ASA, 2007–present). Production since 2010 has been ~0.85 Mt/a. Of the by-products of the apatite production, the carbonate products are most voluminous. The mica production, initiated in 1985 by Kemira Corp. and since 2005 owned by LKAB Minerals (former Minelco Corp.), was ~195,000 t for 1990–2013, and ~12,500 tpa since 2010. The end uses of this mica continue to expand, for example, in the construction, polymer, and electronic sectors. Its growth potential is large, depending on the development of global markets.

Rather than gold miners, as is the case today, the first mineral claim holders of the Kutemajärvi mining area were instead industrial mineral companies. Already in 1947, Renlundin Tiili Oy evaluated local Svecofennian sericite schist as a raw material for bricks, finding sericite reserves at depths to 50 m of 18–20 Mt. Kemira Corp. explored the area in 1966–1974 for Al and K and in their claim area discovered reserves of 2.5 Mt sericite, 1.5 Mt topaz, 1.4 Mt kaolin and andalusite, and 8.5 Mt quartz (Ollila et al., 1990). The sericite content in that schist is 40%, with several percent topaz, and an Al_2O_3 content of ~20 wt% (Sotka, 1988). From 1975–1990, Lohja Corp. explored for sericite and quartz, and in 1982 discovered the epithermal Kutemajärvi gold ore.

Sericite (muscovite) has good potential as a by-product both from the Kinahmi (Kuopio) and Kutemajärvi (Orivesi) mines, but such production still remains unrealized, in part because it requires additional investments to further purify the raw mica-rich material due to variable amounts of pyrophyllite, kaolinite, and some nonphyllosilicate minerals, and to find markets for such by-products. According to Talikka (2007), the pervasive alteration at Kutemajärvi resulted from acidic hydrothermal fluids of magmatic origin at ~1895–1890 Ma, after which the rocks were deformed and metamorphosed during the Svecofennian orogeny.

Aurola (1957) described the Maaninkavaara vermiculite occurrence in Posio. The regolithic phosphate ore above the Devonian Sokli carbonatite in Savukoski, northeast Lapland (O'Brien et al., 2005), holds the best-known potential for vermiculite in Finland, besides its potential for Fe, Mn, Nb, Ta, and rare earth elements (REEs).

CLAY MINERALS

The geological record in Finland suggests there have been many suitable periods for weathering of the crust that may have formed laterites with clay minerals, but the multiple pulses of continental ice sheets have scoured away most such deposits.

The kaolin deposit at Pihlajavaara, Puolanka, in the Kainuu belt, was known already in the 1920s (Väyrynen, 1929). In the 1930s, small amounts of kaolin were extracted for ceramics from Prolanvaara, Soanlahti (ceded to the Soviet Union in 1944), and Pihlajavaara. When buying Turun Kaakelitehdas Oy in 1943, Paraisten Kalkkivuori Oy received the rights to the Pihlaja deposit. After some periods of small-scale kaolin test extraction, it proved to be uneconomic due to transportation costs and easier access to imported kaolin. Weathered kaolinite-bearing zones related to Jatulian quartzites were also test mined at Ruma in southern Sotkamo. Morenia Oy recently tested the usability of Pihlajanvaara kaolin and had a test delivery in 2012.

In 1978, GTK started exploration for kaolin in central Finnish Lapland, continuing from 1980 on in the Puolanka area, in part jointly with Lohja Corp., resulting in seven kaolin deposits and six kaolin weathering showings discovered. The total amount of kaolinized material of variable quality was estimated to be ~25 Mt, of which 8 Mt were of white grade and with ~6 Mt alone in Kerkkä. A kaolinite content of 5–20% is typical for these deposits, reflecting the low primary alumina contents of their protoliths (i.e., lower Paleoproterozoic arkoses and sericite quartzites). The deposits were grouped into in situ weatherings and shear zone kaolins, the first group being volumetrically more important.

Continuation of the GTK kaolin exploration and evaluation projects in Lapland, through the 1980s and 1990s in the Sodankylä area and into the early 2000s in the Salla area, resulted in discoveries of only ceramic-grade material at best. The only known sedimentary kaolin deposit in Finland is located at Saarijärvi, Taivalkoski. It is large, but because it consists of dark-colored, Fe-rich kaolinitic claystone forming intercalating layers with sandstone (Venäläinen, 1988; Pekkala and Sarapää, 1989), it is uneconomical.

Between 1986 and 1992, GTK carried out an extensive survey on kaolin deposits in the Virtasalmi area in Pieksämäki, and described 10 kaolin deposits from an area of 20 $km^2 \times 5$ km^2, of which 6 were evaluated suitable as raw material for paper filling and coating (Sarapää, 1996). Samples were evaluated by several companies, including Kemira Corp., which conducted additional testing on kaolin from two deposits. The dimensions of individual deposits range from 500–2000 m (length), 50–400 m (width), with an average thickness of 30–40 m, up to at most 100 m. Covering these is a 20–30-m-thick Quaternary overburden. The lighter kaolins are altered in situ from quartz-feldspar gneiss, mica gneiss, or tonalite, whereas the mainly iron- and graphite-colored kaolins are weathered from amphibolite or mica schist, respectively.

The kaolinite content varies between 40 and 75%, the remainder consisting mainly of quartz, muscovite, and feldspars. The ISO brightness for samples classified as white kaolin measured in the <20 μm fraction to range between 60 and 86% and <60% for colored kaolins. The amount of <20 μm fraction is reported to be ~60%, whereas that of <2 μm is ~30%. In the processing tests of Kemira, brightnesses of >85% were achieved for paper coating and 79–85% for the filler grade.

Colored kaolin might be suitable for tile production. The probable reserves of light kaolin were estimated to be ~18 Mt, of colored kaolins 16 Mt, and possible additional kaolin reserves ~15 Mt. The age of this kaolinization has been determined to be Mesoproterozoic (K-Ar 1180 Ma from illite; Sarapää, 1996). Subsequently, halloysite, $Al_2Si_2O_5(OH)_4$, (5–50%) has been found in 10 samples taken from the Litmanen and Kahdeksaisiensuo deposits, which fits with earlier observations of in part high viscosities of kaolin suspensions, and also supports a hydrothermal origin of these deposits (Al-Ani et al., 2006). With increasing applications in nanotechnology, halloysite, previously only rarely exploited for ceramics (New Zealand and Turkey), has now met a growing interest.

GRAPHITE

Finnish graphite deposits have been described by Frauenfelder (1924), Laitakari (1925), and Sarapää (1988). Laitakari (1925) lists ~150 graphite occurrences and concludes that graphite is regularly associated with paragneisses, mica gneisses, and metamorphosed limestones (i.e., those with sedimentary protoliths). Only some small, mainly flake graphite-type lenticular deposits from Svecofennian mica gneisses have been mined. According to Laitakari (1925), the largest of those was the Kärpälä deposit in Mäntyharju, from which a maximum of a few thousand tons of graphite ore were mined (Laitakari, 1925; Puustinen, 2003). The sorted ore was sold to England and Sweden.

Aurola (1964b) lists 15 small deposits with carbon contents ≥10%, of which only 4 contain ≥30% carbon: Rääpysjärvi (Kuopio) 60.8%, Soukko (Vammala) 49.6%, Kärpälä (Mäntyharju) 39.0%, and Laivonsaari (Kuopio) 32.6%. Later investigations (Sarapää, 1988) focused in part on the potential energy source from graphite-rich schists, of which the best evaluated deposits are at Hyypiä, Kiihtelysvaara in Joensuu (1 Mt rock with 28.6 wt% C, 2.3 wt% S) and Polvela, Juuka (2.5 Mt with 18 wt% C, 1.5–2 wt% S), both in North Karelia. Volumetrically, most graphite in Finland occurs in the marine uppermost Jatulian sedimentary rocks and in the Kalevian black schists (Sarapää, 1988; Arkimaa et al., 2000).

With improved processing and tailored products, this microcrystalline graphite might become an economically viable by-product (e.g., from certain black schist-related metallic ores) though the carbon content, morphology of the graphite, and sulfur content present critical constraints. However, the best Finnish graphite deposits only represent future potential, if the production from Asia stays at its present level. In 2012, the world production of graphite, 2.12 Mt, was dominated by China (~85%), followed by India (~6%), and Brazil (~4%). Of the European countries, Norway produced ~7000 t and Ukraine 4600 t (BGS, World Mineral Statistics).

SILLIMANITE GROUP MINERALS

These minerals include the Al_2SiO_5 polymorphs sillimanite, kyanite, and andalusite, all theoretically with 62.92 wt% Al_2O_3. Although sillimanite is known to occur in many high-grade gneisses and in some quartzites, no potential deposits have yet been found in Finland. Aurola (1959) summarized the most important kyanite and pyrophyllite deposits. Small amounts of andalusite and kyanite have been used as industrial rocks practically without any mineral processing. Between 1973 and 1981, Partek Corp. mined 83,715 t of andalusite-bearing mica schist from Mantovaara, Sodankylä and used it as an aluminum source in its Kolari cement plant (1968–1989). Andalusite raw materials also have been investigated at Rantakylä, Tohmajärvi; Leteensuo, Hattula; and Kutemajärvi, Orivesi.

Between 1979 and 1984, the Geological Survey of Finland carried out detailed investigations at Kontiolahti, Joensuu where andalusite and kyanite (Fig. 9.5.8) occur together in the lower Jatulian

FIGURE 9.5.8 Kontiolahti, Joensuu.

Coarse kyanite (bluish), quartz (grey), and mica (mainly muscovite) from Kapteeninautio quarry, Kontiolahti (Joensuu). Scale bar in nature is 23 mm.

M.J. Lehtinen, 2001.

Hokkalampi paleosol (Marmo, 1988). The total mineral reserves of the six mineralized zones that were evaluated contain at least 25 Mt of rock averaging 13% kyanite + andalusite and at least 5 Mt of rock with ≥20% kyanite + andalusite (Marmo, 1988). Processing and application tests have been made from raw materials from Hokkalampi and Hirvivaara, Joensuu . In the 1990s, more tests and shallow drilling were conducted at Kapteeninautio near Hokkalampi. Keramia Oy used a part of that 20,000 t mined rock in 2000 as one of the base components of its refractory tiles.

Other studied quartzite and quartzite schist-related Paleoproterozoic kyanite occurrences are at Höllärinvaara, Joensuu and Hallavaara in Sotkamo. Kyanite occurrences in Archean mica schists and gneisses are located at Tetrilampi, Nurmes; Kivisuo, Sotkamo; Peurasuo, Salla; and Mutsoiva in Savukoski, but none of these has proved to be economic.

OTHER NONMETALLIC INDUSTRIAL MINERALS

The use of asbestos in pottery on the shores of Lake Juojärvi, eastern Finland, dates back at least 4500 years. Between 1904 and 1975, ~586,000 t of anthophyllite asbestos were produced from Paakkila, Tuusniemi, and 28,861 t from 1943–1953 from Maljasalmi, Outokumpu (Aurola, 1954b; Palomäki and Halonen, 1968). In this area, asbestos was formed in the local ultramafic rocks due to the heating by dikes from the Paleoproterozoic Maarianvaara granite. Globally, the end uses for asbestos were manyfold, particularly for insulation, flooring, and roofing due to its resistance against heat, fire, and most acids. However, growing data of occupational risks related to asbestos led to a total ban of all types of utilization of asbestos in the European Union (EU) after January 1, 2005. Since 2012, the only practical production of (chrysotile) asbestos has been in Russia, China, Brazil, and Kazakhstan.

Between 1983 and 1989, 51,370 t of barite concentrate were produced by Outokumpu Oy from the Pyhäsalmi mine, central Finland, as were 47,000 t of REE (lanthanides)-bearing apatite concentrate by Outokumpu Oy from 1966–1971 from the Korsnäs lead mine, western Finland. Small-scale production of diatomaceous earth occurred between 1962 and 1970 from several places in central and southeastern Finland, totaling 13,794 t.

Almandine-pyrope–rich garnets are very common in large areas of the high-grade gneissic regions of the Svecofennian domain, as well as in the granulite belt of northern Lapland. Almandine crystals from amphibolite at Isopää, Kalvola area, Hämeenlinna were already famous in the 1800s (Holmberg, 1858). From 1946–1947, Rudus Oy test processed between 1000 and 3000 t (Laitakari, 1947; Puustinen, 2003) of andradite garnet rock from Laajasalo, Helsinki, for floor plates and abrasives. Processing of almandine from Ruostesuo, Kiuruvesi has been tested for an end use as abrasives (Kirjavainen, 1980). Garnets from sulfide deposits tend to have harmful sulfide inclusions, but in suitable mineral parageneses, at least by-product garnet might be economic. The major uses of garnets are for abrasive purposes, including waterjet cutting, but as long as India and China continue to dominate the world garnet production, there seems to be little opportunity for a competitive European production.

The average nepheline content of the Iivaara alkaline complex in Kuusamo is ~40%, with an Al_2O_3 content of 14.2 wt%. According to Sotka (1988), at least 7–8 tons of nepheline-bearing rock needs to be processed to yield 1 t of Al_2O_3 by a calc-sintering process utilized in the Kola Peninsula. More cost-effective, alternative aluminum-rich raw materials are available globally, leaving the Iivaara nepheline intact.

Minor occurrences of different zeolite species are known from Finland, but so far no commercial-scale deposits have been encountered. Of the notable occurrences, the laumontite occurrence in the altered migmatite of the northwest–southeast-trending major shear zone from Sarvasjärvi, Pälkäne, was described by Eskola (1935).

Of the proper industrial rocks, excluding the soapstones, most have been mined for stone wool manufacture. Their composition varies between anorthosite and peridotite, with most being gabbros. Between 1970 and 2013, 8.5 Mt of usable rocks were mined by Paroc Oy Ab, from 21 quarries. Of this amount, 6.9 Mt were stone wool plant feed. Diabase and andalusite rock have been mined for cement manufacture, and phyllite for roofing material.

METALLIC INDUSTRIAL MINERALS

The following commodities are mainly handled in other chapters in this book, but also need to be mentioned briefly here.

Pyrite concentrate, on average ~610,000 tpa and in total ~25 Mt produced from 1973–2013, continues to be sold from the Pyhäsalmi mine for sulfuric acid production, mainly (~350,000 tpa) to Siilinjärvi, but is also exported. Chromite sand from Outokumpu's Kemi mine was periodically sold for industrial minerals end uses (molding sand, etc.), but sales ended in 1997.

The base for the Finnish TiO_2 pigment production was the 3.8 Mt of ilmenite concentrate from Otanmäki, Kajaani. This ilmenite was extracted, along with 7.6 Mt of iron concentrate, 0.2 Mt of sulfur concentrate, and 44,545 t of V_2O_5 in the years 1953–1985 by Otanmäki Oy (1968–Rautaruukki Oy) from 33 Mt of Fe-Ti-V ore mined from the Otanmäki and Vuorokas ore bodies (Paarma, 1954; Pääkkönen, 1956; Illi et al., 1985). In 1961, Vuorikemia Oy began the TiO_2 production by sulfate route method at Pori, which still continues, but since 1986 has been based on imported raw materials, mainly ilmenite concentrate from Tellnes, Norway. Since 2013, this production has been in foreign ownership (actually Huntsman Corp.).

Halsua and Kälviä, in western Finland, have been targets of exploration for potential magmatic ilmenite deposits by GTK and Kalvinit Oy-Endomines (Sarapää et al., 2003). These 1881 ± 10 Ma deposits are based on ilmenite-magnetite ores in layered gabbros at Kairineva, Koivusaarenneva, and Peräneva. From 2012–2013, Cove Resources Ltd. examined the feasibility of exploiting these deposits as well as the Peräkorpi apatite and ilmenite-bearing gabbro at Honkajoki, near Pori, discovered in 1959.

SUMMARY

As shown in the preceding, and verified by past and present mining, Finland's bedrock offers further good potential for the mining of many industrial minerals and rocks. Of the critical raw materials classified by the EU (European Commission, 2010a,b) and the Minerals Strategy of Finland (GTK, 2010) as "economically important," at least talc, "limestone" (= the white calcite marbles), quartz (silica), and feldspar have significant measured reserves and future resources in Finland. Of those 20 critical raw materials included in the classification update (EC, 2014), phosphate rock and chromium (besides the non-industrial minerals PGMs and cobalt) have mineable reserves and proven potential in Finland. Titanium and lithium have shown discovery potential.

Suitable geological environments and even exploited or evaluated deposits of magnesite (by-product, iron-bearing), graphite, and niobium, and in much lesser amounts, the REEs and beryllium, are known in Finland, but to establish their real economic value requires more research, exploration, evaluation, and knowledge of their end uses and markets. The same also applies to many other commodities, such as tantalum, sillimanite group minerals, and garnet, which are actually not produced in Finland. There is much work left to be done to improve the recovery of many economic minerals in present production chains, to minimize the amount of unused mined rock, and, in general, to convert tailings and by-products recovered from the chemical processes into saleable products.

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