by Kurt Johansson¹, Rune B. Larsen², Markku J. Lehtinen³, Lars Persson⁴, Mika Räisänen⁵, Stig A. Schack Pedersen⁶, Pär Weihed⁷, and Nils-Gunnar Wik⁸

Industrial minerals and rocks, aggregates and natural stones in the Nordic countries

¹ Swedish Stone Industries Federation, Industrigatan 6, SE-291 36 Kristianstad, Sweden. E-mail: kj@marmorgranit.se

² NTNU, NO-7491 Trondheim, Norway.

³ Nordkalk Oyj Abp, Poikkitie 1, FI-53500 Lappeenranta, Finland.

⁴ Geological Survey of Sweden, SE-751 87 Uppsala, Sweden.

⁵ Geological Survey of Finland, PO Box 96, FI-02151 Espoo, Finland.

⁶ Geological Survey of Denmark and Greenland, Ø. Voldgade 10, DK-1350 Cph., Denmark.

⁷ Division of Ore Geology and Applied Geophysics, Luleå University of Technology, SE-971 87 Luleå, Sweden. E-mail: par.weihed@ltu.se.

⁸ Geological Survey of Sweden, SE-223 50 Lund, Sweden.

The Nordic countries, including Greenland, have a long tradition in mining. The industrial minerals sector is expanding in most Nordic countries and extensive development has taken place during the last few years. The main commodities mined are carbonate rocks, quartz, feldspar, apatite, olivine and talc.

A number of different types of dimension stones are quarried in all countries. Rock aggregates are increasingly important, replacing sand and gravel aggregate as construction materials in some countries due to the need to protect ground water supplies.

Introduction

This paper presents a review of industrial minerals and rocks, aggregates and natural stones in the Nordic countries. Industrial minerals are mined in all Nordic countries (Figure 1 and Table 1). Major commodities include carbonate rocks, talc, olivine, apatite, quartz, feldspars and nepheline syenite, wollastonite, mica, clay, and diatomite. Today, the volume of the industrial mineral industry is increasing in all Nordic countries and extraction of industrial minerals is also expanding in Greenland (Figure 2).

Industrial rocks are rocks which, like quartzites used in ferrosilicon production or rocks in the stone wool manufacture, are used as such without any mineral processing. Natural stone is the oldest construction material and has been used by human beings since prehistoric times although modern quarrying, as we know it, started with the use of metal tools (Shadmon, 1996). Stone for architectural purposes in the Nordic countries was introduced with the Christianity, at around the year 1000 AD. The principal lithologies extracted are granite, gneiss, diabase/dolerite, schist, sandstone, quartzite, slate, marble, limestone and soapstone (Figure 3). The rock type names used by the stone industry are often different from normal geological nomenclature. Some of the Nordic stone varieties are well known and have become world brands (Nordic Stone, 2003). As natural stone is a durable, sustainable and often beautiful construction material, which can be fully recycled, its use has increased on a global scale.

The Nordic countries have vast resources of high-quality aggregates. Traditionally, in Finland, Norway and Swe-

Figure 1 Industrial mineral and rock mines and quarries of the Nordic countries. Geology from Lahtinen et al. (2005).

den, the Quaternary deposits have been main source of supply. However, these resources are diminishing and the use of crushed bedrock has steadily increased. Thus, it has been decided in Sweden that, by 2010, gravel and sand will constitute only 12% of the aggregates. Furthermore, the use of recycled material is increasing. In Denmark marine sands are used, and in Iceland the young volcanic rocks. The Nordic countries, especially Norway, are exporting big volumes of high-quality crushed bedrock; these are much in demand in countries where soft sedimentary rocks dominate the bedrock, for example, in the North Sea and Baltic regions.

Industrial minerals

The Nordic countries have a very active industrial minerals industry (Table 1). The resources are described below by country, with most of the data from 2006.

Norway

Industrial mineral production in Norway had a turnover of USD 500 million in 2006 from 31 deposits throughout the country (Neeb and Brugmans, 2007). By comparison, the production of metals had

Table 1 Industrial minerals and rocks deposits in the Nordic countries (incl. Greenland). Numbers corresponds to deposit numbers in Figure 1 for Denmark, Finland, Norway and Sweden.

Denmark			
1. Thisted	Limestone	18. Steinsvik	Olivine
2. Mors and Fur	Diatomite	19. Åheim	Olivine
3. Løgstør	Chalk and limestone	20. Stranda	Olivine
4. Ålborg	Chalk	21. Løfdal	Olivine
5. Batum, N Salling	Chalk	22. Gudvangen	Ind. rock (Anorthosite)
6. Mariager	Salt	23. Hamar	Limestone
7. Ølst, Randers	Clay	24. Skien	Limestone
8. Silkeborg	Quartz sand	25. Kragerø	Ind. rock (Quartzite)
9. Faxe	Limestone	26. Bjørntvedt, Dalen	Limestone
		27. Glamsland	Feldspar, quartz
Finland		Sweden	
1. Kalkkima	Dolomite marble	1. Masugnsbyn	Dolomite marble
2. Ristimaa	Quartz (from quartzite)	2. Bunnerviken	Talc
3. Reetinniemi	Dolomite marble	3. Kallholn	Calcitic marble
4. Lahnaslampi	Talc (from soapstone)	4. Jutjärns kalkbrott	Calcitic marble
5. Punasuo	Talc (from soapstone)	5. Falu koppargruva	Iron ore
6. Uutela	Talc (from soapstone)	6. Hamre (Båltarbo)	Clay
7. Pyhäsalmi	Pyrite (Sulphur)	7. Styggberget	Other
8. Kinahmi	Quartz (from quartzite)	8. Tistbrottet	Dolomite
9. Joutsenenlampi	Ind. rock (Anorthosite)	9. Vittinge (Gillberga)	Other
10. Matara	Dolomite marble	10. Wappa	Clay
11. Pehmytkivi	Talc (from soapstone)	11. Broby	Quartz sand
12. Ryytimaa, Vesterbacka	Dolomite marble	12. N. Allmänningbo	Feldspar
13. Siilinjärvi	Apatite, mica, carbonates	13. Fanthytan	Dolomite marble
14. Horsmanaho	Talc (from soapstone)	14. Grythytan	Ind. rock/natural stone (Slate)
15. Ankele	Dolomite marble	15. Gåsgruvan	Calcitic marble
16. Ruokojärvi	Calcite and Dolomite marble	16. Latorp	Other
17. Otamo	Dolomite marble	17. Björka	Dolomite
18. Vanhasuo	Ind. rock (Gabbro)	18. Forsby	Calcitic marble
19. Lehlampi	Ind. rock (Olivine rock)	19. Flåtungebyn	Ind. rock (Quartzite)
20. Ihalainen	Calcite marble, wollastonite	20. Ulerud	Ind. rock (Quartzite)
21. Punola	Dolomite and calcite marble	21. Kilane	Ind. rock (Quartzite)
22. Matkusjoki	Dolomite and calcite marble	22. Kilane	Ind. rock (Quartzite)
23. Sallittu	Ind. rock (Peridotite)	23. Råda	Quartz sand
24. Skräbböle-Limberg	Calcite marble	24. Arnemossen	Other
25. Kalkkiranta	Calcite and Dolomite marble	25. Österplana	Calcitic marble
26. Tytyri	Calcite marble	26. Horn	Clay
27. Ala-Aulis, Kyrkoberget	Feldspar, quartz	27. Billingsryd	Ind. rock (Diabase)
28. Förby	Calcite marble	28. Våmb	Limestone
		29. Berga	Limestone
		30. Uddagården	Limestone
		31. Baskarp	Quartz sand
		32. Brogården	Quartz sand
		33. Gärsd	Clay
		34. Stucks	Limestone
		35. Stora Vikers	Limestone
		36. Västra brottet	Limestone
		37. Rings i Hejnum	Limestone
		38. Albrunna	Limestone
		39. Ventlinge	Limestone
		40. Sternö	Ind. rock (Diabase)
		41. Ullstorp	Limestone
		42. Ignaberga	Limestone
		43. Fuglunda	Quartz sand
		44. Böringekloster	Clay
		Greenland	
		1. Qaqaarsuk	Phosphorus
		2. Sarfartoq	Phosphorus
		3. Seqi	Olivine

a turnover of USD 200 million from two operations. Economically, calcite-products from marble deposits comprise by far the highest production value (USD 320 mill.). This is followed, in decreasing order of value, by olivine, nepheline syenite, quartzite, talc, dolomite, feldspar and anorthosite. High purity quartz and graphite are examples of small, but growing products of strategic niche commodities (Neeb and Bruggans, 2007).

Most of the calcite is produced from Ordovician amphibolite-facies marbles situated in the Upper- and Uppermost Allochthons of the Scandinavian Caledonides. Ophiolitic mantle fragments in the Uppermost Allochthon also host the only operating talc deposit (Altermark). In addition, large talc resources have recently been documented in mantle fragments of the Upper Allochthon (Raudfjellet, Linnajavri). Olivine is chiefly produced from ultramafic intrusions emplaced in granulite-facies gneisses of the Western Gneiss Region (South Norway).

Granitic pegmatite comprises the most important resource of ceramic-grade quartz and feldspar in Norway. Quartz, sodium and potassium feldspars are produced from the Neoproterozoic Glamsland pegmatite in South Norway, and high-purity quartz from the Mesoproterozoic Drag pegmatite (Northern Norway). This type of quartz comprises less than 40 g/ton impurities; hence it may obtain world market prices beyond 1,000 USD/ton. Many of the Norwegian pegmatite occurrences, together with some hydrothermal dykes, comprise large resources of high-purity quartz (Larsen et al., 2004; Ihlen et al., 2004), in places matching the quality produced at Spruce Pine in USA, the largest high-purity quartz producer in the world. Potentially another emerging mineral resource is rutile in eclogitised oceanic lithosphere belonging to the Upper Allochthon. The Engebøfjellet rutile deposit (western Norway) is at an advanced stage of a feasibility study and comprises 386,000 Mt with 3.96 % rutile. It is aimed for the TiO_2 pigment market and as a raw material for the production of Ti metal. Traditionally, rutile is produced from ilmenite or leucoxene from beach placers, whereas the idea with the Engebø project is, for first time ever, to produce rutile directly by crushing and processing of a solid rock.

Finland

Industrial minerals and rocks were mined from 34 mines and quarries in 2006. These, excluding the natural stones, accounted for 24.4 Mt of mined rock and 80% (16.0 Mt) of all ore mining during that year. Crystalline limestones have been utilized by industry in Finland for well over 100 years, beginning with lime production and later the production of cement, fillers, and paper pigments. Large good-quality limestone deposits exist at Lappeenranta, Parainen (Pargas), Lohja and Kerimäki. Altogether, 4.28 Mt of carbonate rocks were mined from 17 mines and quarries (data from Ministry of Trade and Industry), as shown in Figure 1 and Table 1. Geologically, all of these Finnish carbonates are Paleoproterozoic (ca. 1.9 to 2.0 Ga) calcite and dolomite marbles.

In 2006, total quicklime production was about 710,000 tonnes, which is largely based on imported limestones, burned in Finland. The total cement production at Parainen and Lappeenranta was about 1.68 Mt. Dolomites and dolomite-bearing limestones, ~657,000 tonnes, were used for agricultural purposes. The large domestic paper and paperboard industry utilized about 3.3 Mt (dry) of pigment minerals. Of these, nearly 30 % derived from the bedrock of Finland. The “domesticity order” of these minerals was: talc and gypsum (100%), calcium carbonates combined (about 34 %), kaolin and TiO_2 (0%). Slightly more than a half of the 1.2 Mt (dry) of ground calcite (GCC) used by the domestic paper industry, was produced at Lappeenranta and Förby, both floating and micro-grinding domestic calcite marbles, whereas all production of precipitated CaCO_3 (PCC) in Finland (about 480,000 tonnes) was based on imported quicklime and limestone.

In 2006, there were 12 other open pit mines/quarries in operation for industrial minerals that produced ca. 11.46 Mt of ore (apatite, talc, quartz, feldspar, mica). By far the largest industrial minerals mine in Finland is hosted by the Archean (2609 Ma) Siilinjärvi carbonatite. This produced 9.81 Mt of apatite ore, from which 860,000 tonnes of apatite concentrate were recovered as the main product for fertilizer production. In addition, carbonate based by-products (135,000 tonnes) for other agricultural and environmental uses and mica concentrate (8,100 tonnes) and gypsum (103,000 tonnes) for pigment and other end uses, were also produced. Another resource of phosphorus (the Sokli deposit) is located in NE Lapland in a large regolith, which was formed by weathering of the surface parts of a Devonian (ca. 365 Ma) carbonatite.

Finland is the biggest talc producer in Europe; globally the fourth largest. Altogether, in 2006, 1.27 Mt of talc ore were mined from 5 open pit soapstone and talc schist deposits in East Finland. These soapstones are interpreted to be part of metamorphosed ophiolites, ca. 1.95–1.97 Ga in age.

Quartz and feldspar ores (ca. 337,500 tonnes) were mined in eastern and southwestern Finland, at Nilsjö and Kemiö (Kimito), respectively. Feldspar is also produced from the Lapinlahti anorthosite. Production of feldspar amounted to 56,000 tonnes and quartz production to 169,300 tonnes. The quartz deposits are mainly ca. 2000 Ma quartzites, but include by-product quartz from the island of Kemiö where the feldspar deposits include pegmatites and pegmatitic granite (1810–1830 Ma).

Other Finnish industrial minerals include wollastonite (16,200 tonnes concentrate), produced as a by-product of calcite flotation at Lappeenranta. Globally, Finland is the fifth largest producer of wollastonite. Stone wool at Parainen, Oulu and Lappeenranta use anorthosite, gabbro, amphibolite, and diabase, and imported dolomite. The production of pyrite concentrate from Pyhäsalmi mine, mainly used for domestic sulphuric acid production, was 512,000 tonnes in 2006.

The main focus of the Geological Survey of Finland (GTK) in industrial minerals exploration, at present, is on a 500 km², Li pegmatite province in Ullava-Kaustinen area of western Finland. At Lääntä (Ullava), the start-up of mining spodumene ore is planned for the autumn 2008, as is the production of LiCO_3 and by-products at Kaustinen. Towards the south from this Li province, at Kälviä and Halsua, GTK has previously explored and evaluated some ilmenite deposits, classified as mafic (gabbro or gabbro-norite) intrusion-hosted magmatic titanium ores (Sarapää et al., 2001). For additional information on the industrial minerals and rocks of Finland, see Lehtinen (2006), and Pihl and Lehtinen (2007).

Sweden

In Sweden, the total production of industrial minerals was 10.9 Mt (excluding dimension stone) from 44 open pits in 2006. By far, the largest production was of carbonates (limestone, dolomite, marble) which contributed 9.7 Mt or c. 90% of the total production. Carbonates are quarried both from Paleoproterozoic limestone and dolomite marbles in Masungnsbyn, Tistbrottet, Fanthyttan, Gåsgruvan (underground) and Björka and from the younger Ordovician-Silurian limestones in Dalarna, Västergötland, Gotland, Öland and Cretaceous chalk and limestones in Skåne (Figure 1). The products are used as fillers, insulation, agriculture and water treatment and are burnt for the iron and steel industry.

The second most important industrial mineral produced in Sweden is quartzite and quartz sand, with a production of approximately 850,000 tonnes in 2006 (SGU, 2007). These are mainly produced from Paleoproterozoic and Mesoproterozoic quartzites in Bergslagen (Broby) and Dalsland (Flåtungaby, Uleryd och Kilarne). Quartz sands are also produced from Phanerozoic sandstones in Västra Götaland (Baskarp, Brogården) and Scania (Fuglunda). The quartzite is used mainly in metallurgical, mechanical, chemical and refractory industries (Wik, 2002). Of the quartz sands, 50% are used in foundries, 30% as filters and 10–15% for concrete and some in sanitary ceramics (Wik, 2002).

Paleoproterozoic crushed schists are produced at Grythyttan in Bergslagen and diabase is mined for stone wool production in both Västra Götaland and Blekinge. The only feldspar production reported in 2006 was from Forshammar in Bergslagen. Talc and

soapstone were mined in the Handöl quarry in the Caledonides of western Jämtland. Ground talc is used as a filler in roofing and soapstone is produced as block stone for interior fireplaces and heat-resistant cooking plates (Wik, 2002). The famous Swedish red ochre, used as pigment in the red paint from Falun, is still produced. This paint is used widely in Sweden and is seen in the characteristic red colour on many countryside wooden buildings throughout the country.

Denmark

The geology of Denmark is largely composed of sedimentary rocks of late Cretaceous to Neogene age, dominated by the Danian Limestone in the east and the Miocene deltaic sediments in the west. These are overlain by an extensive cover of Quaternary sediments, varying in thickness from a few to more than 200 m, mainly deposited during the glacial periods from 300,000 to 15,000 years ago. No underground mining is taking place in Denmark, except for the solution mining of salt from the Hvornum diapir at Mariager; this is the only salt mining in Scandinavia, with a yearly production of 600,000 tons. Figure 1 shows the location of occurrences. More information on production statistics can be found in Miljø og Energi (2006).

The exploitation of chalk and limestone amounts to 2.3 Mm³, and the main part is used for the cement production located in Ålborg (Portland), northern Denmark. In eastern Denmark, the Danian limestone is excavated at Faxe for paper filling and the remaining chalk production is used for agricultural fertilization and in minor specialised industrial applications.

Plastic clay, exploited in the central part of east Jutland, is used for clinker. The production varies a lot and was, in 2005, about 330,000 m³. It is foreseen that an additional need for bentonite will increase the exploitation of Palaeogene clays in the coming years. Clayey diatomite from ash layers in the Eocene Fur Formation form the basis for the production of cat litter granulate and insulation bricks on Mors and Fur in the Limfjorden region. The production is very stable with an average consumption of 225,000 m³ molclay (moler, clayey diatomite).

During the last five years, the exploitation of quartz sand has increased to more than twice the earlier production, to an average of 500,000 m³ per year. The Miocene quartz sand was deposited in a coastal environment, which 10–15 million years ago was situated in the central part of Jutland. The sand is very pure, without flint and limestone, and with less than 1% heavy minerals. The main application is as filter sand and in high quality concrete. Furthermore, it is used for casting sand and for sports fields.

Sand and gravel from Pleistocene outwash-plain settings are excavated all over Denmark. In the western part of the country, they are obtained from glaciofluvial settings of Saalian age (300,000 years B.P.), with the source of the sediments located in southern Norway. In eastern Denmark, the glaciofluvial settings are mainly of Weichselian age (25,000 years B.P.), with the source related to the ice advance in central Sweden and the Baltic Sea. In 1982 and 1993, the production was at a minimum of ca. 20 Mm³, but in 1987, 1999 and at present the production amounts to 30 Mm³.

The production of brick clay has for the last 20 years remained relatively constant at 700,000 m³ per year. The exploitation is concentrated to a few glacio-lacustrine settings of late Weichselian age, which are mainly regarded as ice-dammed lakes.

Greenland

A large, homogeneous resource of industrial olivine is in production at the Seqi deposit in West Greenland and mining occurred in the past century at the Ivittuut cryolite deposit, and the Amitsoq graphite mine. Greenland also has a good potential for phosphorous. Figure 2 shows the location of major deposits.

Figure 2 Industrial mineral deposits of Greenland. Geology and deposits from Minex, Greenland mineral exploration letter 30 (2007).

Iceland

Iceland has few identified mineral resources, although deposits of diatomite (Kuo, 2003) and hydrothermal silica are mined at Lake Myvatn, northern Iceland. In 2005, over 30,000 tonnes of diatomite and 120,000 tonnes of ferrosilicon were produced.

Aggregates and natural stones

The distribution of resources naturally reflects the geology. Natural stones quarried in Finland (mainly granites and soapstones) range from Proterozoic to Archean in age, whereas in Sweden and Norway (various rocks) the ages are from Proterozoic to Palaeozoic. In Denmark, natural stone (granites) is quarried on the island of Bornholm, south of Sweden in the Baltic Sea. On Iceland, the young volcanic rocks are used. Figure 3 shows the location of major deposits of natural stone in the Nordic countries.

For 2006, 57 quarries reported information about production (delivery) of dimension stone in Sweden. The main rock types are marble and limestone (64,000 tonnes), granite (318,000 tonnes), gneiss (212,000 tonnes), and diabase and gabbro (259,000 tonnes). The total production amounted 886,000 tonnes (SGU, 2007b). The aggregate production in Sweden in 2006 amounted approximately to 92 Mt, of which 20 Mt came from gravel and sand (SGU, 2007b). The total production has slightly increased since 2003, owing to increased infrastructure building; at the same time, there has been a decrease in the production of gravel and sand. In Norway, the 2005 production was 53 Mt of which 12 Mt tonnes (mostly crushed bedrock) was exported (Erichsen et al., in press).

Bedrock investigations are performed in Sweden in order to evaluate the bedrock resources. Bedrock quality is investigated by the Geological Survey of Sweden (SGU); they provide information for the construction industry about such characteristics as are relevant for construction material and for planning tunnels and other underground works. The latter has prompted the development of 3D bedrock models, providing geological and geotechnical information for underground excavations e.g., tunnels and caverns in Sweden, especially in the Stockholm metropolitan region (Persson, 2002).

In terms of production, aggregates are the largest extractive industry in Finland, the total amount used annually being 95 Mt. Due to groundwater protection and reduced resources, the use of alluvial and fluvial aggregates is decreasing and other sources are needed. According to Rintala (2007), the potential use of rock aggregates has increased 35% since 1995, but glaciofluvial material still makes up over 60% of the total production. Presently, there are about 3500 active quarries in Finland, but the number of small quarries will probably decrease due to increasing need of high quality aggregates, and the introduction of standardised testing and productivity requirements.

In high latitudes, the cold climate places particular demands on the quality of the aggregates. Cars use studded tyres during winter to obtain more traction on the icy road surfaces and, therefore, asphalt aggregates need to have good resistance to abrasive wear. Frost may reach to a depth of 2.5 m, which affects the material choices in all

Figure 3 Most important natural stone quarrying areas in the Nordic countries. *Geology from Lahtinen et al. (2005).*

layers of road construction. The quality requirements of an aggregate, which are based on the rock texture and modal composition, depend on how it will be used. For example, high-quality asphalt aggregates will not necessarily be appropriate in concrete or for gravel-road maintenance.

The Geological Survey of Finland has mapped ca. 24,000 sand and gravel deposits since 1970s in order to define both the quality and quantity of the country's aggregates and groundwater reserves. Inventories of rock aggregate outcrops have been made since 1989 (Härmä et al., 2006). This inventory has shown that less than 1% of the bedrock outcrops studied met the highest quality requirements, yielding aggregates suitable for motorway surfaces. The best rock types for this purpose are fine-grained felsic and intermediate metavolcanic rocks in which mineral grains are tightly interlocked, as well as strongly deformed plutonic rocks that have tonalitic and granodioritic composition. Lower quality aggregates can be pro-

duced from medium- and coarse-grained granitic rocks and gneisses containing abundant mica minerals. However, these aggregates are suitable for most common end-use applications. High-quality rocks are located mainly in the schist belts and their aggregates should be used only for applications where they are essential, because demand for such material will increase as reserves decrease. Knowledge of the distribution and quality variations of rock aggregates (Härmä et al., 2006) is becoming increasingly important.

Traditionally, the Finnish stone industry has been firmly based on the quarrying and processing of granites. The annual production is about 900,000 tonnes, of which granites account for 700,000 tonnes. Several worldwide famous commercial granite types (e.g., Baltic Brown, Carmen Red, Balmoral Red), from the Mesoproterozoic rapakivi granites (Figure 3), are quarried in the SE and SW Finland. A speciality of today's Finnish natural stone industry is the advanced production of soapstone products that represents approximately 50% of the total stone industry turnover (200 million euros). In 2006, soapstone was quarried from 4 Archean deposits in E Finland for oven and other fireplace manufacturing. The total output of usable soapstone was ca. 185,000 tonnes, of which 50,300 tonnes of soapstone products were manufactured (data from MTI). Altogether about 384,000 tonnes of natural stones, worth about 100 million euros, were exported from Finland in 2006, of which 66 million euros were from soapstone products. The main export countries of Finnish natural stones are Germany, China, Italy, Spain, Sweden, Belgium and Poland. Small quantities of natural stones are also imported, amounting to 13.8 million euros in 2006. The most important import countries were China, Norway, Portugal, Italy and Sweden (http://www.nordicstones.org/finnish_natural_stone_associ.htm, Leino, 2007).

Denmark has an aggregates industry which supports the domestic demand of sand and gravel (produced both onshore and offshore). The production of gneiss and granite aggregates from the Danish island of Bornholm varies a lot depending on the demand for new traffic constructions. The Øresund connection between southern Sweden and Copenhagen has been the most recent major aggregate consuming project. During its construction the annual production of granite from Bornholm amounted 400,000 m³, but recently production has decreased to about 190,000 m³. For protection of the coastal areas and the construction of harbour piers, sand and gravel are exploited from the sea-bed surrounding Denmark. This production varies a lot depending on the constructional activities, but in general it amounts to 6 Mm³.

On Iceland, pumice, scoria, sand and crushed basalt are mined with a total production of 105,000 tonnes in 2005 (Kuo, 2003).

Concluding remarks

The non-metallic extractive industry in the Nordic countries is indeed an expanding industry with extensive development especially within the industrial minerals sector during the last few years. The main commodities mined today include carbonate rocks, quartz, feldspar, apatite, olivine and talc. Crushed rocks are to a large extent replacing sand and gravel as construction materials in Finland, Norway and Sweden due to the need to protect ground water supplies. The natural stone industry is diverse and includes some world famous commercial granite types quarried from Rapakivi intrusions in Finland and anorthosites (Larvikite) from southern Norway.

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Kurt Johansson, M.Sc. and M.Ba., is President of the Swedish Stone Industries Federation, and since 2006 also President of EURO-ROC, European & International Federation of Natural Stone Industries. Johansson is furthermore CEO of the Swedish company Marmor & Granit AB. He has for many years been actively involved in R&D issues related to the industry and been one of the driving forces behind the large national Swedish research programme MinBaS.

Mika Räisänen is Regional Director in Eastern Finland Office of Geological Survey of Finland. Docent in applied geology at Department of Geology in the University of Helsinki. Membership of professional bodies: Finnish society of engineering geology; Finnish Geotechnical Society; International Association of Engineering Geology (Secretary of aggregate commission); Confederation of Finnish Construction Industries RT, Finnish TC 154 Mirror Committee of standardization of aggregates.

Rune B. Larsen, Dr From 2004, associate professor in mineral deposit geology at Department of Geology, Norwegian University of Science and Technology. Chief consultant, Nordic Mining AS. Before 2004, senior geologist at the Geological Survey of Norway. Current research projects in Norway, Greenland and Mozambique. Several publications on granitic pegmatite mineral deposits, PGE-Cu-Ni deposits, fluid-melt interaction processes.

Stig A. Schack Pedersen, Dr. scient., seniorgeologist at the Geological Survey of Denmark and Greenland (GEUS), graduated from the University of Copenhagen. He has studied sulphide ore geology in Norwegian Caledonides and mapped mountain ranges in north Greenland. For 25 years he has consulted clay companies in Denmark with exploration for clayey diatomite (moclay) and bentonite. Furthermore he is responsible for the surface mapping of the Danish land area and its Quaternary deposits.

Markku J. Lehtinen, Ph.lic. in geology and mineralogy from the University of Turku, Finland. A 25-year career mainly with industrial minerals and rocks as a production geologist and mineralogist in private mining companies and senior research scientist with the Geological Survey of Finland. Presently as a senior geologist with Nordkalk Corporation, Lappeenranta. Past president (2000–2002) of the Mineralogical Society of Finland. Since 2001 member of the National Geological Committee of Finland.

Pär Weihed is professor in ore geology and head of the Department of Chemical Engineering and Geosciences at Luleå University of Technology, Sweden. He is currently president of the Geological Society of Sweden, an elected member of the Royal Swedish Academy of Engineering, a fellow of Society of Economic Geologist, where he also acts on the editorial board of *Economic Geology*, and he is a councillor of SGA (Society of Geology Applied to Mineral deposits).

Lars Persson, bedrock geologist at the Geological Survey of Sweden in Uppsala. Ph.D. in Mineralogy and Petrology, Past President of the Swedish Society of Engineering Geology 1995–1997. Past Vice-President of IAEG, 2002–2006, President of the the Swedish National Committee of Geology, subcommittee to the Royal Swedish Academy of Sciences.

Nils-Gunnar Wik, bedrock geologist, Senior state geologist at the Geological Survey of Sweden, Head of Programme Documentation of Industrial Mineral Resources. For more than 30 years he has been investigating national non-metallic resources.