The Geological Survey of Finland strengthening its role as a key player in mineral raw materials innovation ecosystems

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Abstract: The Geological Survey of Finland (GTK) has over 130 years of history in mapping and studying mineral resources and their sustainable use. This has resulted in a globally top-ranking geodatabase and profound knowledge of Finnish geology and mineral resources, and has had a crucial impact on the continuously developing mining and exploration business in Finland. The basic mandate of the GTK has remained the same, but the strategic focus and mode of operation have changed considerably to meet new demands. Today, the GTK plays a vital role in providing geoscientific expertise and specialist services for a wide range of stakeholders and commercial clients in government, the business sector, academia and the wider community, in Finland and internationally. The GTK is actively building new ways to co-operate with universities, research organizations and companies to support future development and to expand its own expertise. This is further supported by the proactive use of cutting-edge technologies, such as the geomaterials research infrastructure, which allows studies from the nanoscale up to kilotons for diverse applications of mineral materials. The GTK plans to further strengthen its role as a key player in the minerals sector innovation ecosystems with a focus on primary minerals, the circular economy, digital solutions and water issues, which are expected to be essential factors for sustainable development through the 2020s and beyond. The GTK’s main challenge is to ensure the continuous enhancement and renewal of expertise, to adapt and respond to future opportunities.

Geoscience has a long history in Finland (Haapala 2005; Haapala & Papunen 2015). The origin of geological survey activities in Finland was closely connected with Nils Nordenskiöld, who served as the General Intendant of the Mining Council during 1823–55. His initiatives led to the founding of a geological office to the government’s Mining Council in 1870 and the commencement of geological surveys and exploration funded by the government. The work of these early geologists and surveyors was effective: they mapped much of southern Finland and made some promising findings of gold, iron, base metals and other commodities. The first Chair in Geology and Mineralogy was established at the University of Helsinki in 1852. Mineral chemical research began even earlier in 1800, while Finland was still under Swedish sovereignty, and Johan Gadolin, Professor of Chemistry at Åbo, successfully isolated the first known rare earth element, yttrium. His achievements were subsequently recognized in the naming of another element, gadolinium.

The Geological Survey of Finland (GTK, Geologian tutkimuskeskus in Finnish) has a history extending over 130 years. The predecessor to the GTK, the Geological Commission of Finland, was established in 1885, when Finland had a distinct autonomous status within the Russian Empire. The Geological Commission started its operations in 1886 and was renamed the Geological Survey of Finland (GTK) in 1945 (Kauranne et al. 2010). The tasks of the Geological Commission were defined according to the Imperial Decree of 1885:

To carry out economic geological research, bearing in mind the needs of the mining industry and other branches of the national economy in accordance with the standards of science and good practice, and to provide information, through maps and explanatory notes, about the geology of Finland.

Apart from the ability to provide information in more diverse digital formats, this charter remains as concise and clear, and relevant, as it was then.

The GTK has evolved and diversified into the pre-eminent geoscience agency in Finland, with the same objectives of serving the nation through acquiring and assessing geoscientific data and an understanding of Earth processes for sustainable growth and well-being, and providing the government and industrial and public stakeholders with reliable and comprehensive data and advice pertaining to mineral resources. Today, the GTK plays a vital role in providing geoscientific expertise and specialist services to stakeholders and commercial clients in government, the business sector, academia and the wider community, not only in Finland but also increasingly internationally (Kauranne et al. 2010; Nenonen & Nurmi 2011; Vasara 2018).

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The basic mandate of the GTK has remained the same but the strategic focus and mode of operation have changed considerably to meet new demands. Although the scope has thus widened to include the construction, water, energy and environment sectors, the minerals sector has retained the leading role in GTK activities throughout its history. Success in this area has been built on the considerable advancements in knowledge of Finnish geology and mineral resources during the last few decades (e.g. Lehtinen et al. 2005; Maier et al. 2015) and the effective application of modern technologies and digitalization across all spheres of activities (e.g. Rasilainen et al. 2016; Sayab et al. 2016; Heinonen et al. 2019; Niiranen et al. 2019; Torppa et al. 2019).

Throughout its history, the GTK has been responsive to new trends and directions as required by society and industry, as well as regulatory environments. For many years, in the absence of foreign mineral exploration, the responsibility for exploration and discovery in Finland was principally shared by the GTK and Outokumpu Oy, but this changed with the accession of Finland to the EU in 1995. Further examples include the search for natural stone for the building industry, both at the turn of the twentieth century and more recently from the 1980s, underpinning the revival of the Finnish stone quarrying industry. Energy security and supply concerns also led to systematic peat resource assessment, as well as a specialist role in repository selection and characterization for the nuclear industry.

In recent years, the GTK has become more engaged in addressing environmental and water management issues, both in relation to mining activities and for wider community needs, as well as geoengineering and assessment of the material supply chain for road construction and urban development. However, the role of mineral resources remains paramount, underscored by the recognition of the importance of Finland within Europe.

Throughout all these activities, there has been a growing emphasis on identifying areas for enhancing expertise and alignment with customer needs, amidst changes to the GTK’s financing model – an essential response to progressive cuts in appropriation funding, in line with general government programmes to reduce public sector expenditure. Currently, the GTK employs 430 staff spread across five separate locations, and annual spending is about €45m, of which about 35% derives from commercial services and science and innovation funding bodies.

This paper aims to provide an understanding of the widening and evolving role of the GTK in the minerals sector, which is stated to remain as the most important area of activities for the 2020s. Accordingly, the paper begins with an overview of the exploration and mining context, followed by a reflection on the changing role of the GTK through time, and concludes with a review of research activities fundamental to the GTK’s continued success.

**Finland’s minerals cluster**

Finland has a strong minerals cluster including diverse mining companies, globally recognized mining technology and service providers, and a strong mineral-based downstream industry (Vasara 2018). The Precambrian Fennoscandian Shield is the most richly endowed area of mineral resources in Europe (Cassard et al. 2013; Nurmi & Molnár 2014). Finland, located in the centre of the shield, has a wide variety of mineral deposits in various geological settings (Eilu 2012; Maier et al. 2015), and mining is a traditional, well-established and economically significant business in Finland (Puustinen 1997; Nurmi & Rasilainen 2015).

The opening of several new mines has led to steady growth in ore extraction since 2007 to reach the current levels of activity, which are at an all-time high, following the decline in the 1990s and early 2000s (Fig. 1). In 2018, 49 megatons of ore were extracted from 46 mines, ten of which are metal mines (Tukes 2019). Major mines include the Sotkamo nickel–zinc–cobalt, Kevitsa nickel–copper–platinum, Kemi chromium, Kittilä gold and Siilinjärvi apatite deposits (Fig. 2a). In addition to these and other operating mines, about half a dozen deposits are undergoing feasibility stage investigations, and there are numerous active exploration projects.

Finland has been one of the most active countries in Europe in mineral exploration during the past 20 years (e.g. Hinde & Farooki 2018). Annual exploration spending has varied between €35m and €80m, and the number of exploration companies from 40 to 50 (Fig. 1). The Fraser Institute Annual Survey of Mining Companies has consistently ranked Finland globally in the top ten in mining investment attractiveness since 2010 (Stedman & Green 2019). Exploration has focused on base metals, particularly nickel, copper and zinc, as well as gold and platinum group metals, and recently increasingly on battery minerals for lithium ion batteries.

Attractive incentives for further exploration are provided by the largest gold mine in Europe (Kittilä), one of the largest nickel mines in Europe (Kevitsa), and the recent world-class Sakatti copper–nickel–platinum discovery, which has a preliminary mineral resources estimate of 45 megatons at 3.5% Cu-equivalent (Brown 2016; Anglo American 2017). Sakatti may indeed prove to be the largest single deposit yet discovered in Finland. Despite this, Finland can still be regarded as largely underexplored. The number of known deposits and recent positive exploration results, associated with the typically favourable Precambrian shield geology,
indicate good potential for significant future discoveries (Eilu 2012; Eilu et al. 2019; Maier et al. 2015; Nurmi & Rasilainen 2015; Makkonen et al. 2017). Apart from the mineral potential, Finland has a favourable operating environment for mining, a stable, predictable and transparent legal framework, excellent physical and IT infrastructure, low corporate taxes, and top-ranked geological databases created, maintained and distributed by the GTK.

Finland also has a significant mineral refining industry, which includes nickel, copper, zinc, cobalt and ferrochrome refineries and steel mills, as well as stainless steel and copper products (Fig. 2b; https://tekniikka.tekniikka.fo/en/current/statistics). Industrial minerals are processed as fertilizers and carbonate products. Of globally annual production, Finland produces 4% nickel, 10% cobalt and 1% stainless steel (USGS 2019). Finnish mining technology and metallurgy companies and expertise are well known worldwide. Taken as a whole, the metals and minerals industry cluster accounts for over 10% of Finnish exports.

The GTK’s changing role in mineral exploration

The GTK has played an important role in the development of Finland’s mining industry. Already in the early years, the GTK performed exploration for mineral deposits in addition to general mapping of the country. This led to a major success in 1910, when the classic Outokumpu copper deposit was discovered in eastern Finland. This rich deposit was mined for 75 years, and it formed the basis for the development of modern mining and metals industries in Finland (Haapala & Papunen 2015). The discovery also drew attention to the important role of geology in the development of natural resources and the economy of the country. Further success followed in 1921, when a rich nickel deposit was discovered in Petsamo (now known as Pechenga) in northernmost Finland (Haapala & Papunen 2015). The area was ceded to the Soviet Union after World War II and has developed into a world-class mining camp, which has to date produced more than 7 megatons of nickel, 3 megatons of copper and 0.25 megatons of cobalt contained in ore (Eilu et al. 2019).

The GTK’s role and budget grew considerably from the 1950s onwards, when country-wide geological, geophysical and geochemical mapping programmes were initiated. The number of employees reached a maximum of over 900 people, more than double the current staff level.

The development of exploration techniques and practices has always played an important role at the GTK. An example is the use of boulder prospecting in the glaciated terrain of Finland. This has been supported by the traditional layman sampling practice in Finland, which already started in the 1700s. It was systematically developed as a GTK programme in the 1950s and is still ongoing. This early citizen science crowdsourcing practice included nationwide, regional and thematic campaigns, promotion and training. It has been modernized to employ smart phones to collect initial information (https://kivinayte.gtk.fi/en/homepage/). The GTK annually receives thousands of mineralized samples from people around the country and, historically, the first indications of a number of mines have been received from these layman samples. The GTK was
Fig. 2. Finland’s minerals cluster. (a) Active mines and mine projects in the feasibility stage in Finland; (b) smelters, steel mills, refineries and fertilizer plants in Finland; and (c) metallic mineral deposits originally discovered by the GTK that have led to mining. Dates indicate years of operation, active mines in blue.
also a pioneer in training dogs for boulder hunting (Kahma et al. 1975). Altogether, 16 dogs were used for prospecting from 1962 to 1994 (Valkama 2011).

The development of geochemical techniques for exploration in glaciated terrains and the extensive geochemical databases later, provided an invaluable basis for the emerging field of environmental geochemistry (Nurmi & Sorjonen-Ward 1993; Salminen 1995; Sarala 2015). Geophysical instrument development and systematic airborne surveys, culminating in the routine acquisition of magnetic, electromagnetic and radiometric data, were critical not only in direct exploration targeting but in supporting the geological mapping of poorly exposed terrain (Airo 2005, 2015).

As a result, the GTK has been very successful in mineral exploration. Based on initial discoveries by the GTK, 21 mines have been developed in Finland. These include several yet operating major mines, including the Kevitsa nickel–copper, Kemi chromite, Sotkamo nickel–zinc and Kittilä gold mines (Fig. 2c; Eilu 2012; Haapala & Papunen 2015; Makkonen et al. 2017). Apart from metal mineral deposits, several industrial mineral deposits discovered by the GTK have commenced production.

The calculated gross value of metallic minerals produced from the mines developed as a direct result of initial GTK discoveries totals €47b, and the remaining gross (in-situ) value of present resources is €224b. These simplified calculations are based on the metals produced over time and remaining indicated and inferred mineral resources. The metal prices used in the calculations are averages over ten years (2007–16). The national direct long-term impact of GTK exploration has been remarkable, particularly if we take into consideration the overall historic exploration expenditure by the GTK, which has been calculated by them to be roughly €500m in present-day currency.

On top of the GTK discoveries comes the value of the GTK databases and geoscientific information, which form the basis for active mineral exploration and the mining business in Finland. During 2008–18, cumulative mining investments by private companies totalled €3.1b and exploration investments €640m (Fig. 1; Tukes 2019). The minerals industry has a particularly important function in regional prosperity, since much of the activity has been, and is, focused on northern and eastern Finland, where the development of other types of industrial activity is limited. Moreover, domestic mining was the initial trigger for the development of the mineral refining and manufacturing industries in Finland.

Mining and exploration were legally restricted to domestic companies until 1994, when Finland signed an agreement with the European Economic Area and joined the European Union in 1995. Prior to that time, the GTK’s mineral discoveries were tendered through the ministry responsible for GTK activities (currently known as the Ministry of Economic Affairs and Employment) exclusively to Finnish mining companies, particularly Outokumpu Oy and Rautaruukki Oy. These were the two largest operators in the metals industry in Finland and both were largely government owned. These companies also had their own exploration activities focusing on the base and ferrous metals needed for their own metallurgical plants (Fig. 3).

Since the changes in mining legislation, dozens of foreign junior exploration companies and some mining companies have come to Finland and have made major investments in both mineral exploration and mine development. Outokumpu Oy, the only remaining major domestic exploration company,
ceased exploration activities in 2002, a decision that was accelerated by the low metal prices in the 1990s. The GTK’s database created over the decades and the geoscientific expertise in Finnish geology and mineral deposits accordingly proved to be important assets for the newcomers (e.g. Brown 2016). The GTK took an active role in promoting Finland globally and also commenced offering consulting services to exploration companies. Transparency in all actions was deemed of crucial importance from the beginning.

These changes in the business environment also required the GTK to reconsider its role in relation to exploration. After conducting several surveys of the exploration and mining community to determine what they expected and wanted from the GTK, there was a gradual transition away from nationwide mapping programmes towards more thematic and synthetic pre-competitive map products and services.

Detailed exploration and resource delineation by the GTK, which had been routine and indeed essential prior to the entry of privately funded explorers, was no longer considered necessary. However, the inherent volatility in raising capital by junior explorers meant that exploration activities focused on a narrow range of commodities and, instead of greenfield areas, typically on previously identified deposits and their surroundings. Moreover, only a few major mining companies maintained long-term exploration activities in Finland over longer periods, and these also tended to have a limited focus.

To rectify the ensuing lack of greenfield exploration, the GTK embarked on a new programme of pre-competitive mineral potential mapping, an initiative endorsed by many explorers. Priority is given to areas and commodities where there is little or no privately funded activity, the aim being to stimulate interest in future exploration investments and to augment geological knowledge in less well-known areas.

Research results are reported regularly, and possible new mineral indications with commercial potential are tendered to the private sector through the Ministry of Economic Affairs and Employment. The GTK may still apply for exploration licences over limited areas before the drilling of potential targets of interest, to allow transparency for any possible tender process.

In addition to assessing new areas (‘mineral potential mapping’), the GTK actively defines and investigates the main mineral systems in Finland, develops exploration models and performs 3D data compilations of important mining camps (e.g. Sarala 2015; Molnár et al. 2016; Niiranen et al. 2019; Torppa et al. 2019). These projects are typically carried out in close co-operation with mining companies and academia and financed by public research and innovation financing bodies.

Geodata, the cornerstone of success

Finland’s geoscience data are globally unparalleled in terms of their quality, comprehensive nature and ease of access. The data have been assessed for several years in a row as among the best in the world by the Fraser Institute in its annual mining company surveys (Stedman & Green 2019). Apart from data quality, active promotion of the exploration potential and available information over the past 25 years in global forums, such as the annual conventions of the Prospectors and Developers Association of Canada (PDAC), has been important in continually attracting exploration and mining investment to Finland.

The national geodata managed and distributed by the GTK not only contain data systematically collected by the GTK over the decades, but also mineral exploration data provided by mining and exploration companies. The largest proportion of company data comes from Outokumpu Oy’s extensive exploration activities over a period of 50 years until 2002. According to Finnish mining legislation, companies are required to report their data and exploration results from their exploration licence areas on an annual basis to the Chemical and Safety Authority (Tukes), which is the Finnish government body responsible for mining licensing. New data are transferred by the GTK to the national database and become available for release to the public after the licences have expired. Currently, this forms the main flow of new data.

The various available geodata resources for Finland are summarized in Table 1, from which it is evident that geophysical datasets form an integral part. The GTK in 1951 was among the first countries to commence systematic airborne geophysical surveys. Low-altitude mapping of the whole country was undertaken during 1972–2007, with a terrain clearance of 30–40 m and nominal line spacing 200 m (Airo 2015). The country-wide airborne geophysical database includes magnetic, electromagnetic and gamma-ray spectrometric measurements. Extensive crustal-scale reflection seismic surveys were undertaken during 2001–08, with 2000 line-km acquired during the crustal-scale FIRE survey (Finnish Seismic Reflection Experiment, Kukkonen & Lahtinen 2006) and subsequently 820 line-km of detailed surveys down to 8 km depth over significant mining camps in the HIRE (High Resolution Reflection Seismics for Ore Exploration 2007–10) project (Kukkonen et al. 2011). These are complemented by the earlier BABEL profiles collected during offshore surveys in the Baltic Sea (Korja & Heikkinen 2005).

Extensive potential field (magnetic and electromagnetic) and gravity data are also available for the most important ore-potential provinces. Systematic till geochemical mapping was initiated in the
1970s, and the data include both nationwide surveys and regional and target-scale projects; this mapping was later followed by an extensive lithogeochemical sampling programme comprising more than 5000 multi-element analyses (Salminen 1995; Sarala 2015).

In bedrock mapping, the traditional map sheet products (1:100 000 scale) have been replaced by a single seamless bedrock map (Vuollo et al. 2011). A register of geological bedrock units is an important element of the database, and both databases observe international stratigraphic standards and employ IUGS/GCI vocabularies. The map database has a nominal scale of 1:200 000 but includes much more detailed data on most mineral-potential areas, and the maps are fully scalable.

The GTK has over 35 years of experience in digital data management, data architecture, GIS, data analysis, visualization and information delivery. These technologies have also been transferred to a number of developing countries, particularly in Africa and Central Asia. Today, the GTK’s digital libraries allow easy Internet access to all publications and reports (see http://hakku.gtk.fi/?locale=en). Visualization of exploration data has been available through an Internet map server since the late 1990s. The latest version uses advanced technology and gives access to all relevant data for mineral exploration (see http://gtkdata.gtk.fi/mdae/index.html).

### Mineral systems research and prospectivity modelling

The GTK’s comprehensive research into the Archean and Proterozoic bedrock geology of Finland and associated mineral systems forms the basis for information on the mineral potential in Finland (e.g. Nironen 2017; Eilu et al. 2003; Lahtinen et al. 2005, 2009, 2018; Lehtinen et al. 2005; Eilu 2012; Maier et al. 2015; Makkonen et al. 2017; Molnár et al. 2018). The discovery of outcropping, high-grade and/or big-tonnage mineral deposits is becoming increasingly difficult, at least in mature terrain, and exploration costs have considerably increased. Therefore, there is a growing need for the development of knowledge-based and cost-effective exploration methods that are capable of predicting mineral resources at depth, or beneath sedimentary cover. New exploration technologies are available, cutting-edge laboratory techniques allow more detailed geochemical and isotopic studies on the origin of mineral deposits, and advances in data analytical tools make it possible to integrate and evaluate huge amounts of diverse data.

The mineral systems concept has been developed as a holistic approach to understand the sources, transportation pathways, deposition and preservation/re-mobilization mechanisms of metals in the Earth’s crust, and it forms a useful basis for the application of modern concepts in mineral exploration (Fig. 4; e.g. Molnár et al. 2018; Gessner et al. 2018). It is important to understand ore-forming processes in the context of crustal evolution. First of all, we need to define the potential areas for different ore types, as well as the parameters that are connected to mineralization. This is based on geodata and research from regional to detailed scales. It is also crucial to understand the post-depositional metamorphic and structural processes.

Research into the mineral systems, associated with 3D geological modelling at the GTK, is helping with the development of new mineral-potential maps and exploration models. When combined with new

### Table 1. A snapshot of the GTK’s geodata on geophysics, geochemistry, bedrock geology and mineral occurrences

| Category                  | Details                                                                                     |
|---------------------------|---------------------------------------------------------------------------------------------|
| Airborne geophysics       | Nationwide coverage of low-altitude magnetic, electromagnetic and radiometric data (200 m line spacing, 30–40 m terrain clearance). Total of 1.94 million line km. |
| Ground geophysics         | Various ground surveys, 63 million points. Regional gravimetric surveys, 300 000 points (included above). Reflection seismic surveys, 2820 line km. Petrophysical measurements, about 5 million samples |
| Geochemistry              | Nationwide coverage of till surveys, 82 000 samples (nominal density 1 sample per 4 km²). Various detailed till surveys, about 710 000 samples. Nationwide rock geochemistry, 6544 samples, 54 elements. |
| Bedrock mapping           | Nationwide coverage of seamless bedrock map database (nominal scale 1:200 000). Bedrock mapping: 679 000 observations. |
| Mineral occurrences       | 1016 occurrences.                                                                          |
| Drill-core archive        | 37 500 drill cores.                                                                       |
| Age determinations        | 1450 samples (zircon U/Pb).                                                                 |

For more detailed information, see: https://hakku.gtk.fi/en/locations/search
exploration methods, the application of advanced computerized mineral prospectivity mapping tools enhances the efficiency of exploration and assists in the recognition of hidden resources. The GTK’s recent emphasis has been on orogenic gold and nickel–copper–cobalt mineralization, which are the key targets of the exploration industry in Finland today (Nykänen et al. 2015; Niiranen et al. 2019; Torppa et al. 2019). A mineral system portal on orogenic gold is already available via the GTK website (https://minsysfin.gtk.fi/index.php/overview-of-the-orogenic-gold-metallogeny-in-finland/), and we are working on a similar portal for nickel–copper–cobalt mineralization.

Mineral prospectivity mapping applied to orogenic gold in Finnish Lapland, which is currently the most targeted for exploration, not only demonstrates the advantages of using advanced computational methods in prospectivity modelling, such as fuzzy logic and self-organizing maps, but also emphasizes the important role of geological expertise in the modelling process (Niiranen et al. 2019; Torppa et al. 2019). A regional gold prospectivity map of Finnish Lapland shows a good correlation between the known deposits and predicted prospective areas and suggests that only a small portion of the greenstone belt is highly prospective (Fig. 5).

Mineral systems research and prospectivity mapping aims to promote further exploration investment in Finland, especially by reducing the exploration risk and expenditure through providing industry with more precise constraints on favourable areas for targeting. Using GTK information and know-how, companies can plan and target their projects more efficiently in both greenfield and brownfield terrains, improving the likelihood of economically viable discoveries.
Mineral intelligence and policy support

The GTK is currently strengthening its capacity in minerals intelligence, which is aimed at serving the GTK, policy makers and industry by combining active follow-up of the minerals sector, overarching scientific expertise and foresight. Three major themes are (1) foresight of the change in the minerals sector, (2) raw materials security, and (3) social, environmental and governance factors for mineral resources. Within the minerals intelligence framework, the GTK supports the ministry and other public and private decision makers by providing timely information on the availability of minerals for current and future needs. This is particularly important for minerals defined as critical. We need to understand the economic, environmental and social aspects related to known resources for possible future mining operations, as well as the exploration potential for future discoveries. Information on secondary sources and recycling of mineral-based materials, as well as understanding of raw materials trade flows, are important aspects of mineral intelligence. Currently, the GTK is collecting and analysing information on minerals that are vital for battery technologies.

In addition to the ongoing efforts to obtain more precise information on known resources, the GTK has been systematically estimating potential undiscovered resources for the most important commodities using a three-part quantitative assessment method developed by the US Geological Survey (USGS) (Singer & Menzie 2010). Since 2008, the GTK has carried out assessments for platinum, palladium, gold, copper, nickel, cobalt, zinc, lead, silver, chromium, titanium, vanadium and lithium in the important mineral deposit types occurring in Finland (e.g. Eilu et al. 2015; Rasilainen et al. 2016, 2017, 2018). Currently, the GTK is also developing the assessment methodology in partnership with the USGS and industrial and research organizations.

In 2010, Finland was one of the first European countries to establish a mineral strategy (GTK 2010). The GTK led the strategy preparation process, which was steered by the Ministry of Trade and Industry and compiled in close association with a wide range of stakeholders. The long-term objective of the strategy is to make Finland a global frontrunner with a sustainable mineral industry. The main pillars of the mineral strategy are: (1) promoting domestic growth and prosperity; (2) solutions for global mineral chain challenges; and (3) mitigating the environmental impacts of mining. These strategic objectives outline the steps that will make Finland a global leader in the sustainable utilization of mineral resources, with the minerals sector being one of the foundations of the Finnish national economy. The Mineral Strategy has been followed by several
important actions for developing the minerals industry in Finland, to make it more acceptable and sustainable. Such initiatives include the Green Mining RDI (research, development and innovation) programme, discussed later in this paper, and the Finnish Network for Sustainable Mining, which is a joint forum of the mining industry and its stakeholders.

Developing laboratory infrastructures to support RDI

The GTK’s laboratory infrastructures have undergone considerable changes during the last 20 years. The most significant of these changes was the Government decision to transfer the responsibility for the Mintec Minerals Processing Pilot Plant, based in Outokumpu, from the Technical Research Centre of Finland to the GTK in 2004. This expansion of capabilities into the minerals processing space has enabled the GTK to engage in both research and the provision of services across the whole spectrum of exploration and mining activities. In addition to performing feasibility studies for industry at the pilot plant, upgrades to analytical facilities at the GTK Mintec facility allow more detailed mineral deportment and environmental monitoring studies to be undertaken.

In 2007, as part of a government restructuring programme, the GTK geochemical laboratories were converted into an independent analytical service provider, Labtium Oy. This ended the long tradition in the development of analytical techniques at the GTK, but led to a renewed focus on mineralogical, isotope and minerals processing activities.

As a result, the GTK actively sought to develop shared facilities in partnership with Finnish universities. The first consortium was the establishment in 2014 of the Finnish Geosciences Research Laboratory, located at the GTK, with five university partners. The laboratory is well equipped with the latest instrumentation and boasts a staff recognized internationally for their expertise in the analysis and study of geological materials. The laboratory’s main areas of focus are isotope geology and applied mineralogy, and it is highly regarded for innovative and adaptive method development for solving the specific challenges of its clients and partners.

The facility now provides the capabilities for researchers in Finland to image samples with 3D tomographic scanning, and then target and analyse very fine particles down to a few tens of nanometres in size and to analyse elemental concentrations down to ppq (solutions) and ppt levels (solids). A particular strength is the ability to combine the versatile instrumentation and use multiple methods to solve problems, and to be able to carry out this work *in situ*. In addition to mineral systems and geological research, new possibilities have been employed to characterize the products of concentration and smelting, environmental samples, as well as to assist in ore exploration and mine planning. The laboratory’s research and analysis services are used both in-house and by external clients, which include mineral exploration firms, mining companies, metallurgical refiners, energy companies, universities and other research institutes.

Today, the GTK has a unique geomaterials research infrastructure, which allows studies from the nanoscale up to kilotons. The GTK Mintec Minerals Processing Pilot Plant and mineralogical laboratories form a platform for the development and testing of mineral beneficiation processes anywhere along the beneficiation chain, from mineralogical analysis to dealing with process waste. The pilot plant has a feed capacity of 0.5–5 tons per hour, and the typical sample size used for a series of grindability and flotation tests is 100–300 tons. This has generated a global customer network and provided the GTK with opportunities to gain increasing experience with a variety of mineral deposits from around the world on a commercial basis.

We have also participated in numerous jointly funded RDI projects to develop resource-efficient minerals processing. One current plan is to employ automation and artificial intelligence in the pilot plant in close co-operation with partners from industry and the RDI community, with the final aim being to build a digital twin for the physical pilot plant.

Finland’s Green Mining concept

Mining has become increasingly difficult for various societal and environmental reasons not only in Finland but all over the world, and there is increasing competition with other priorities for land use. The availability of water and energy and the need to reduce carbon and water footprints have created further significant challenges for mining. Many people are not ready to radically reduce the use of mineral-based products, but increasingly oppose mining. The industry faces major challenges to improve its performance and image.

In order to promote comprehensive improvements in industry practice and public perceptions, the GTK proposed the implementation of Finland’s Green Mining concept in 2011, in partnership with other research organizations and industry. This was one of the direct outcomes of Finland’s Mineral Strategy, whereby the Green Mining concept was designed as a mechanism to position Finland as a frontrunner in sustainable mining and to assist the mining industry in earning the social licence to operate.
This concept is based on five pillars (Fig. 6; Nurmi 2017). Green Mining promotes material, water and energy efficiency to reduce the environmental footprint of mineral-based product life cycles. It allows the recovery of all useful minerals and minimizes mining waste, and aims to ensure the availability of mineral resources for future generations, which requires long-term investment in exploration supported by geoscientific mapping, mineral systems research and the development of exploration techniques. An important goal of the concept is to minimize adverse environmental and social impacts in all stages of the operations, and to maximize local benefits. Green Mining helps to organize the operations in such a way that they are safe and meaningful to employees and harmless for local residents and the environment. After mine closure, restoration of the mining areas to make them safe and preferably to allow other types of land use should be undertaken according to the concept. The broad-based participation of local residents and other stakeholders is crucial throughout the mining life cycle, from early exploration to mine closure.

The Finnish Funding Agency for Innovations (Tekes), nowadays known as Business Finland, decided to establish a major Green Mining research and innovation programme in 2011 based on the Green Mining concept, with the aim of making Finland’s minerals cluster the world leader in intelligent and minimum impact mining. The five-year programme included over 100 projects covering all five pillars of the Green Mining concept with a total budget of €116m, and involved 185 partners from industry to academia. The results of these projects will continue to help the mining industry improve its performance in all areas of Green Mining, and to make it economically, environmentally and socially more viable and acceptable in the future. Although many projects produced interesting findings, the final results of the programme cannot yet be evaluated, because the commercialization of innovations and changes in operating practices takes many years.

The programme also had a major impact for the GTK, which co-ordinated or participated in 18 projects, enabling wide expertise development and the strengthening of partnerships with research organizations and industry. The GTK’s projects included exploration techniques, mineral processing, mine environments and social aspects related to mining (e.g. Sarala 2015; Aatos 2016; Kauppila & Tarvaisen 2018).

The GTK’s future focus on mineral raw materials

The availability and use of mineral-based raw materials is one of the major global challenges for the future, given the continuing trends of population growth and increasing urbanization. Huge amounts of mineral resources are needed for developing new and replacing ageing infrastructure, as well as for new technology solutions. The economy, social structures, energy sources and consumption, infrastructure, transportation and material products will all look very different in the latter half of the twenty-first century than at present (Lusty & Gunn 2014; Nurmi & Molnár 2014; Tuusjärvi et al. 2014; World Economic Forum 2015; Arndt et al. 2017). Sustainable production, the circular economy, new materials, product design and consumption optimization will become key issues in the use of materials. For societies, companies and individuals, impacts on the environment and climate change will become key criteria in decision making. The demand for low-carbon energy has grown significantly and decisions to stop using fossil fuels have made new energy solutions inevitable.

Finland aims to continue long-term support for the development of the mining industry and the whole minerals cluster as an important part of the economy. The GTK’s strategy for the 2020s emphasizes solutions for more sustainable growth. We want to support Finland’s economic growth by using mineral resources in a more efficient and sustainable manner, and create innovations that increase resource efficiency, the circular economy, and solutions leading towards the implementation of a low-carbon society. The GTK aims to take an active role in developing innovation ecosystems, build high-level partnerships and strengthen the influence of geosciences in RDI and decision making by companies and society. This demands improved high-level expertise in selected focus areas and the further development of research infrastructure, working closely with appropriate partners. We clearly need to improve our understanding of customer and societal needs to be able to succeed.

The GTK has selected strategic focus areas for the next four years (2020–23) that are highly likely

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Fig. 6. Finland’s Green Mining concept (Nurmi 2017).
to create significant solutions for sustainable growth in Finland, to which the GTK could make a major contribution. The selected focus areas are primary minerals, the circular economy, water and digital solutions. We aim to be an internationally respected actor in providing research and pragmatic solutions towards the sustainable use of mineral-based materials within innovation ecosystems in the circular economy. We promote the exploration and mining of primary minerals, particularly for the fast-growing energy storage business. We intend to take a leading role as an expert in raw materials in Finland’s emerging battery ecosystem. The GTK aims to be an international leader as a supplier of geodata management and smart application solutions for internal processes and customers worldwide. In water management and hydrogeology, our aim is to offer comprehensive solutions, particularly for mining.

A prominent role in domestic and European innovation ecosystems is essential for continued success. The GTK is actively seeking new ways to co-operate with universities, research centres and businesses and to ensure further success in obtaining RDI financing through both EU and national instruments. The most important innovation ecosystem for the GTK today is the Raw Materials Knowledge and Innovation Community of the European Institute of Innovation and Technology (EIT RawMaterials), which is the world’s largest community of its kind in the raw materials sector, having more than 300 partners from over 20 EU countries. The partners represent an ideal balance of research organizations, universities and various enterprises from start-ups to major industrial companies. The ambitious goal is to develop raw materials into a major strength for Europe by driving innovation, education and entrepreneurship along the raw materials value chain from exploration and mining through to the circular economy and substitution. The GTK is one of the 66 core partners and a founding partner of the EIT RawMaterials. We have a major project portfolio of over 20 projects, with a focus on the validation and up-scaling of innovations towards commercial applications.

EU Framework Programmes offer important possibilities for RDI in the minerals sector. Currently, the GTK has over 40 company partners, 42 research institute partners and 34 university partners from over 20 countries in a dozen projects, which are focused on sustainable mining and exploration. Finland’s Battery Cluster and the European Battery Alliance are examples of developing innovation ecosystems in which the GTK is aiming to have a strengthening role.

To evaluate and improve our performance, the GTK has applied the so-called ‘synergy model’, which means balanced and smooth co-operation between science and innovation, customer assignments and geodata (Fig. 7). These are the three main areas for impact and interaction with innovation ecosystems, customers, academia and society. In-house, there is a need for seamless co-operation between the three synergy apices and the agility to focus knowledge and resources as needed.

Within the synergy triangle, the main goal of science and innovation activities is to create scientific results and innovations to solve major challenges as an active partner in innovation ecosystems. We recognize the need for proactive enhancement of in-house expertise and capabilities in priority areas, such as mineral systems science, geological modelling, minerals processing, smart digital solutions and mineral-based materials applications, and to create high-level partnerships and alliances to acquire complementary knowhow. Science and innovation activities are expected to represent an increasing proportion of GTK operations.

In geodata-related activities, the GTK produces, gathers, refines and delivers data and information relevant for an increasingly diverse range of stakeholders, and is developing new ways to apply geodata. This is important for promoting future investment and sustainable, cost-effective solutions. Data on and new interpretations of mineral resources, exploration potential, and 3D bedrock geology are a key focus.

For the customer assignment apex of the triangle, the focus is on projects demanding high-level expertise, knowhow, and the application of advanced research infrastructures in order to improve the customer’s competitiveness. Key business areas include mineral exploration, geomechanical...
studies, mineral-based materials characterization, minerals processing and mine environments, both in Finland and worldwide.

Final summary

The availability of critical minerals and sustainable use of raw materials are emerging global challenges. This creates great opportunities for expert organizations, such as the GTK, to strengthen their role as key players in those ecosystems that will prove essential for sustainable development through the 2020s and beyond. The GTK’s main challenge is to ensure continuous enhancement and renewal of expertise, so as to adapt and respond to future opportunities. Almost half of the current staff are due to retire within the next ten years, and it will be very difficult to replace them with suitably educated and skilled people to create knowhow in areas of future strategic importance. In order to anticipate these changes and to ensure the continuity of expertise, the GTK has commenced systematic skills development programmes with various in-house instruments, and global recruitment of research professors, senior scientists and post-doctoral researchers, particularly within the identified focus areas.

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