Locating Natural Resources Within the Earth Depends on Geophysics

The importance of geophysics is rapidly growing. Better images of deeper subsurface layers are needed to find critical raw materials, geothermal energy sources, and groundwater. Only geophysics can look into the Earth beyond the reach of our hands and eyes in a non-invasive manner. Finland must have strong geophysical research and modern geophysical datasets.

Strategic investment in geophysics for societal benefit

With continuously improving geophysical technology, more accurate knowledge from deeper parts of the Earth becomes available. This underpins societally relevant research, from natural resources – such as minerals, geothermal heat – over infrastructure and construction safety, and environmental and groundwater management, to soils for agriculture and forestry.

Finnish geophysics has traditionally been at the forefront of development but in the last two decades investment in the field has declined so that geophysical datasets and skills have started to age. Worldwide developments like three-dimensional and multi-method geophysics are being adopted relatively late.

Forward-looking investment into the following actions are advised as strategic and low-cost measures with significant societal and economic benefits:

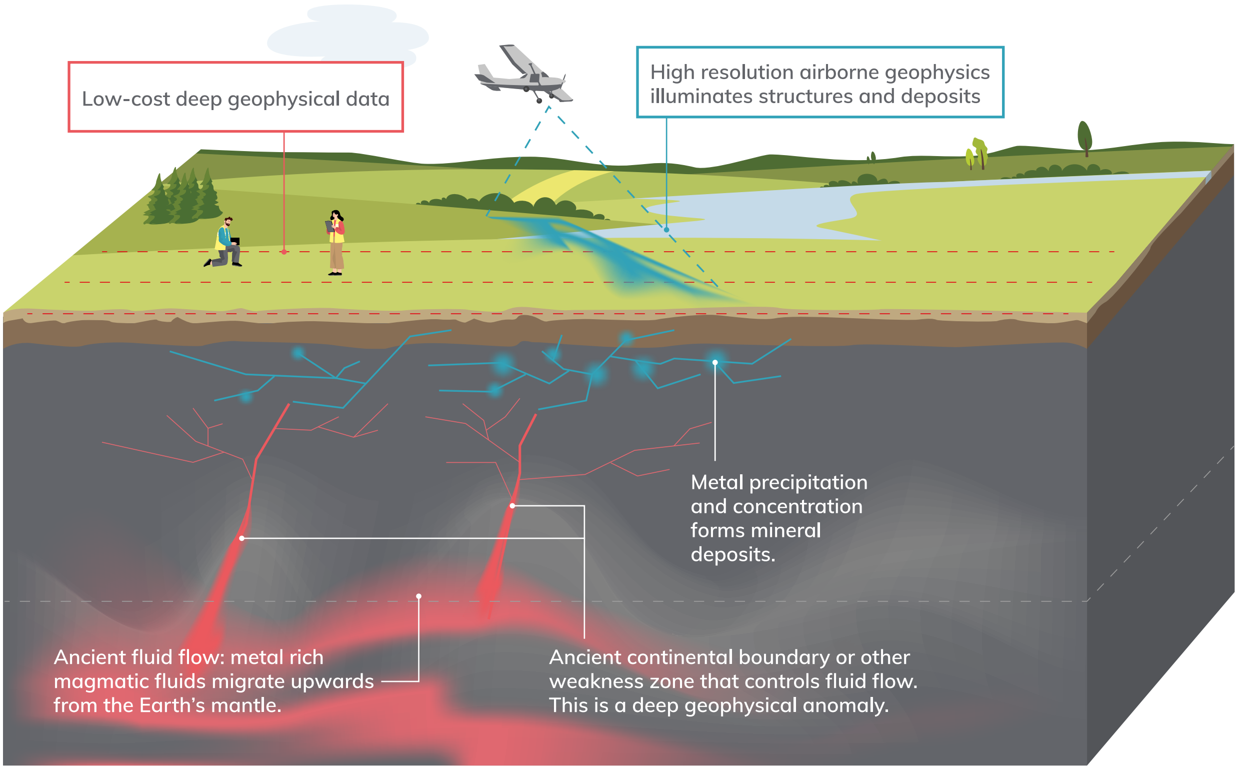
- **Continuous state-of-the-art geophysical base data collection**
- **Development of cutting-edge geophysical measurement technologies and capacities**
- **Development of modern geophysical data integration capabilities including supercomputing and machine learning applications**

What is geophysics?

Geophysics is the study of the subsurface using physical phenomena. For example, electromagnetic or seismic waves are sent through the Earth to learn about its interior. It provides information about what lies beneath the surface in a non-invasive manner.

GTK research presented in this Policy Brief contributes to these United Nations Sustainable Development Goals

Geophysics is used for locating for example raw materials in the Earth



Geophysics is carried out at multiple scales. Inexpensive and comparatively coarse-scale deep geophysics (red lines on the surface) reaches tens of kilometres into the Earth's crust. In this way, we can detect large scale crustal structures like plate boundaries (structures marked with a red hue) relevant to e.g. where fluids from the deep earth used find their way upwards, bringing with them valuable metals. In the smaller scale fault systems near the earth surface, metals may have precipitated and concentrated to form economic deposits (structure marked with blue hue), and shallower (down to 1-2 km depth) high-resolution geophysical methods (e.g. airborne methods) are used to detect the exact locations of those deposits. A similar approach is useful for other natural resources such as geothermal research.

Modern geophysics is a cornerstone for geoscience relevant to society

The subsurface of Earth provides society with important natural resources. This includes groundwater, critical raw materials, and geothermal energy, but also the soil that fosters agriculture and forestry. The subsurface provides opportunities for safe disposal of harmful substances such as nuclear waste as well. However, human operations might pollute the subsurface and consequently our water supply. Therefore, an understanding of the Earth's subsurface is of critical importance to society.

The amount of subsurface knowledge that can be derived from visible surface geology is limited. Drill holes only punctually probe the Earth and are very costly. Geophysics is the only scientific discipline that provides a way to image the subsurface without a shovel or a drilling rig.

Physical phenomena, such as elastic or electromagnetic waves, allow us to visualise the subsurface, with penetration depth and resolution varying from the top centimetres of the soil to many tens of kilometres all the way through the Earth's crust.

Geophysical data collection is commonly carried out covering entire regions to provide large-scale base data as a necessary background for targeted studies. It is used to support or to identify districts and targets for further study, i.e., where dedicated measurements are carefully deployed to investigate specific issues with higher intensity and resolution.

For example, tens of kilometres large and deep ancient fluid migration systems mapped underneath old continental plate boundaries can aid in locating potential hot spots to guide detailed exploration of mineral or geothermal resources within the accessible part of the crust (the outermost few hundred metres). Base datasets are precompetitive and produced by public actors for the whole industry. Smaller-scale targeted studies tend to be more relevant to specific stakeholders such as private enterprise (in the case of mineral exploration) or local communities (in the cases of groundwater or geothermal energy).

Geophysics plays a strategic role for a natural resources-oriented society like Finland

Historically, Finland has been pioneering geophysical methods into and beyond the 1980s and engaged in significantly beneficial geophysical data collection until the early 2000s. The national mapping programmes conducted by the Geological Survey of Finland GTK included complete airborne geophysical coverage of the nation. Finland was the second country in the world with complete airborne coverage – the first being Kosovo, which was also done by GTK. At the time, the datasets provided an unprecedented level of information, which allowed for the study of the bedrock surface, which was otherwise almost completely (94%) covered by soil and vegetation.

The mapping programmes generated € 2.4 of turnover, € 1.1 of value added and € 0.5 of tax revenue (according to the current tax structure) per 1 euro invested. However, Finland has since stopped investing in the acquisition of state-of-the-art geophysical base data and development of geophysical techniques. As other places in the world have stepped up data collection and method development, Finnish datasets, while still valuable, are rapidly aging.

Modern technological improvements allow much higher resolution and at much deeper depth levels, down to hundreds of meters, even kilometres, compared to the few metres' penetration provided by the Finnish datasets. It is now possible to image subsurface structures in all three dimensions, contrasting the existing two-dimensional Finnish geophysical maps.

Solutions to new challenges in deep mineral exploration, geothermal exploration as well as environmental and groundwater mapping, strongly benefit from modern datasets. Therefore, most major industrial countries (outside of Europe) continuously invest in geophysical data collection. Almost the entire continent of Australia has been covered with a variety of state-of-the-art geophysical data that allows investigation of much deeper bedrock levels. It is estimated that publicly funded precompetitive data generation created AUD 76 billion of added value, approx. 3.5% of the GDP, in 2021–2022. Similar initiatives exist in the USA, Canada, and China.

Traditionally, the Finnish geophysics community has been strong in driving technological innovation, e.g., the development of numerous systems that were deemed cutting-edge at the time of their release and the earliest airborne surveying systems. However, the termination of national investments has affected Finnish technology development, and the applied techniques have become outdated. As seen elsewhere, a massive boost to geophysical accuracy is achieved with novel sensors and GPS timing.

Modern off-the-shelf electronics make for robust and easily mass-produced sensor units, in turn allowing the massive scale surveying needed to collect comprehensive, state-of-the-art datasets. Massive computation enables the interpretation and integration of such datasets in full 3D.

Improved geophysical technology is not only crucial for base data collection, but also supports targeted surveying of specific sites with a dedicated interest, such as ore systems, geothermal trends, groundwater aquifer systems, or mine tailings for environmental management and re-mining efforts. Full 3D imaging with higher resolution, to larger depths, and at significantly lower cost, allows surveys of unprecedented scale so that research questions previously out of reach can now be addressed (e.g., natural hydrogen; geoelectric risk, i.e., the risk of solar storms damaging electrical grids).

Currently, as part of its research activities, GTK has made significant progress in the reinforcement of Finnish geophysics. We focus on selected state-of-the-art instrumentation to further the collection of greatly needed large-scale datasets. This is done in connection with the strong computational community in Finland, which participates in its own code developments that leverage Finnish supercomputer ecosystems.

SMEs and the service industry in Finland have acquired technology on a scale possible for smaller companies (e.g., the development of drone-based techniques), but there are no providers of large-scale geophysics (reflection seismics, large-scale CSEM (controlled source electro-magnetic), or airborne measurements. An additional challenge of the geophysics sector is the decline of domestic high-level workforce due to the lack of PhD graduates with a heavily needed focus on geophysical applications, the development of novel geophysical measurement or data processing technology.

Modern base data, measurement methods, and computational techniques are crucial to address 21st century challenges

As easily discoverable mineral resources under little or no soil cover are becoming scarce, discovery rates worldwide have dropped. Ore discovery shifts to explore deeper earth volumes, which requires a transformation of exploration approaches.

Precompetitive deeply penetrating geophysical base datasets covering Finland and Europe as a whole are critically needed to map out and characterise large-scale mineral systems in order to locate deep minerals' potential when there is little to no surficial evidence to be obtained. Only after this step does it make sense to aim expensive and intense deep exploration efforts at those limited locations.

Hence, national mandate and resources are urgently needed for the provision of modern datasets. Such data, while key for directing exploration efforts and therefore attracting private sector investment, falls clearly outside of the domain of the private sector.

For example, the Kuusamo area in Finland is part of a large ancient rift system, i.e., a zone of hundreds of kilometres in extension where the continent was under the threat of being torn apart two billion years ago due to the incipient creation of a new ocean. The rifting stopped after a many-million-years-long attempt. Recently collected geophysical data revealed that the crustal tear manifests as a geophysical anomaly reaching throughout the entire crust.

Imaging this structure in three dimensions, we could reconstruct the large-scale ancient magmatic fluid migration from the deep Earth mantle all the way up to the surface, which, under certain conditions, left behind high concentrations of economically critical minerals. Geophysical data at this scale is not suited to locating mineral deposits, but it does provide critical guidance for explorers towards a haystack where they may find their needle.

Base datasets of this kind are naturally useful far beyond mineral exploration, allowing geothermal exploration or the description of large-scale groundwater systems. For example, geophysical measurements are being used to identify the extent of potentially radiogenic rapakivi granites, an important source of geothermal heat previously unrecognised in the Kymenlaakso area.

The geophysical base data is also important for the mitigation of space weather-borne geoelectrical hazards, which can be detrimental to energy infrastructure. This phenomenon refers to electrical currents that are induced within the Earth and our electrical grids by solar activity. It has been recognised that rare but severe solar storms would nowadays lead to catastrophic power grid damage, widespread and weeks-long power outages with consequent famines, and severe loss of human life. The prediction and mitigation of geoelectric hazard critically relies on knowledge of the electrical structure of Earth, especially around population centres. In Finland, the electrical data used for this purpose is of relatively low resolution and urgently needs to be updated.

Building upon base data, the next step is to mobilise larger resources to carry out targeted measurements of particular areas of interest, for example, in order to foster understanding of details of a specific mineral deposit, groundwater aquifer, mine tailings and the like.

For example, GTK used near-surface methods combined with drilling data in the Pirkkala area. This was done to detect thermal anomalies and fracture zones at specific depths, highlighting areas of enhanced heat transfer and identifying optimal targets for efficient geothermal energy well placement.

Another example is the Kurikka valley, which is a regionally important groundwater source. To reduce the uncertainty of 3D groundwater modelling, the bedrock surface and the glacial sediments of the buried aquifer system were accurately mapped with cutting edge geophysical methods.

The requirements for either resolution or penetration depth (or both) are typically larger when focusing resources on a specific study site, and more intensive technologies need to be brought to the field. While the development of such techniques is currently not happening within Finland, there is an understanding that instrumentation and capability needs to be maintained at a competitive level.

In this way, scientific data can still be collected at a high level. However, the interpretation of such datasets requires computer codes that need to be developed in-house given that, in the field of geophysics, a large open-source community and commercial software is currently lacking. Advanced research almost always entails adopting or developing new methods, modifying codes and experimenting with new ways of treating datasets. Therefore, it is required that on the software side, the Finnish geophysics community reaches the top level.

The way forward: Supporting geophysical base data collection, targeted surveying technology, and computational data integration method development

The following actions are recommended:

Continuous systematic collection and maintenance of state-of-the-art geophysical base data. Continuous collection of data in a structured manner that is supported with long-term plans is the only way to achieve comprehensive coverage that is accessible to all stakeholders. The high-quality base data attracts investments that facilitate the investigation of nation-scale issues, such as the creation of natural resource inventories.

Maintenance and renewal of geophysical technology and capacity. Key geophysical capabilities for targeted deep exploration (e.g., minerals, geothermal research, tectonics, and deep aquifers) as well as near-surface studies (on, e.g., the environment, groundwater, and soil) need to be maintained in Finland. This should encompass the entire workflow, from instrumentation, surveying, data processing, and integrated interpretation with advanced modelling and computational tools. This also entails more focus on the education and training of young geophysicists with the pertinent skills in cooperation with universities.

Develop data integration technology. Data science and data integration are critical frontiers of geoscience. Data from various geophysical measurement methods at different scales must be reasonably integrated with other geoscientific data to enable optimal information extraction. This reduces the ambiguity of results and increases resolution as well as the depth from which data can be interpreted. Modern advances in computation, such as supercomputers, are leveraged increasingly for these purposes. They are used for physics simulation, inverse problem solution and the training of machine-learning models.

Sources and additional information

GTK research areas, policy briefs and research projects

Geophysical Applications – information and research projects

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GTK research news

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- As a World-First, the Geological Survey of Finland Conducts a Nationwide Survey of Black Shale Deposits
- 3D Model of the Upper Crust of Finland Looks below the Earth's Surface
- The Mastering of Natural Resources Helps Uzbekistan to Adapt for the Climate Change
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- **Aerogeophysical maps of Finland are available for browsing in GTK's MDaE-service**
- Examples of aerogeophysical maps downloadable from GTK's Hakku-service:
  - Aerogeophysical anomaly map of Finland
  - Aeroradiometric total count map of Finland
  - Aeroelectromagnetic apparent resistivity map of Finland

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