ABSTRACT BOOK

online short course on

"Fingerprinting techniques in mineral exploration"

June 14-18 2021

Organizers: EiT Raw Materials, MinExTarget project, EIT RM Academy

UiT (The Arctic University of Norway),

GTK (Geological Survey of Finland),

GEUS (Geological Survey of Denmark and Greenland),

OMS (Oulu Mining School),

with participation of NGU (Geological Survey of Norway), AGH (University of Science and Technology, Krakow, Poland), Palsatech Ltd, GSC (Geological Survey of Canada), Vienna University of Technology, UNSW Sydney (The University of New South Wales in Australia)

Zoom link to the lectures:
https://uit.zoom.us/j/62477466358?pwd=Q1dkcSsvaXpZWU1lbEFTV2tqRVVkQT09

Meeting ID: 624 7746 6358

Password: 175890PROGRAM

Presentations will be gradually uploaded here:
https://www.dropbox.com/sh/q0m3to8s0v9jc9e/AADB2V3ADkagM_ortmJGS8wfa?dl=0

PROGRAM

Day 1: 14th of June 2021

Time	***Speaker and Title***
10:30	***Yulia Mun (UiT):*** Welcome word to participants and speakers
10:40	***Lotta Aalto (EIT RawMaterials):*** Introduction to EIT RM Academy
10:50	***Ferenc Molnar (GTK):*** MinExTarget – innovation project in mineral exploration
11:30	***Pasi Eilu (GTK):*** Geology and ore potential of the Fennoscandian Shield
12:15	Lunch
13:00	***Henrik Schiellerup (NGU)***: Mapping the mineral potential; the role of the Geological Survey of Norway
13:30	***Stefan Bernstein (GEUS):*** Mineral systems in Greenland – two examples from globally important deposit types
14:00	***Adam Piestrzyński, Wladyslaw Zygo (AGH):*** Geology and mineral deposit perspectives in Poland
14:30	*Break*
14:45	Introduction to the Student practices in the course
15:00	*Discussion*
15:15	***End of the Day***

Day 2: 15th of June 2021

Time	***Speaker and Title***
10:00	***Hannu Ahola (Palsatech):*** Exploration methods, part 1: Sampling and sample preparation: Heavy mineral sampling, concentration and research in glaciated terrains
10:45	***Sabina Strmic Palinkas (UiT):*** Exploration methods, part 2: Stream sediments and marine sediments in mineral exploration
11:30	***Pertti Sarala (GTK):*** Mineral exploration in glaciated terrain: Case studies from Finland
12:15	***Lunch***
13:00	Practical work in small groups
14:45	*Break*
15:00	***Beth McClenaghan (GSC):*** Application of indicator minerals in mineral exploration in Canada
15:45	*Discussion*
16:00	***End of the working Day***
18:00	***Online social gathering***

Day 3: 16th of June 2021

Time	***Speaker and Title***
10:00	***Walid Salama (CSIRO)***: Mineral exploration techniques in Australia as an example of deeply weathered and covered terrain
10:45	***Lahaye Yann (GTK):*** Non- traditional stable isotope and radiogenic isotopes in exploration

11:45	*Lunch*
12:45	***Alan Butcher (GTK)****:* Geoanalytical techniques: combining optical microscopy, e-beam, X-ray beam & laser beam-based technologies for a multi-modal, multi-dimensional approach
13:45	*Break*
14:00	***Sabina Strmic Palinkas (UiT):*** Fluid, melt and solid inclusions in mineral exploration
14:45	Practical work in small groups
16:15	***End of the Day***

Day 4: 17th of June 2021

Time	***Speaker and Title***
09:30	***Paavo Nikkola (GTK):*** Trace element content of pyrite: a proxy for ore-forming conditions and a potential tool for mineral exploration targeting
10:15	***Ferenc Molnar (GTK):*** Mineral trace element and isotopic footprints of orogenic gold deposits in Finland
11:15	*Break*
11:30	***Sara Raic (GTK):*** Processing and fingerprinting of mineral trace element data by unsupervised machine learning
12:15	*Lunch*
13:00	***Peter Filzmoser (Vienna University of Technology):*** Introduction to data analysis techniques and the CODA approach
13:50	***Maarit Middleton (GTK)***: Quality assurance and quality control of surface geochemical data
14:30	*Break*
14:40	*Practical work in small groups*
16:15	***End of the Day***

Day 5: 18th of June 2021

Time	***Speaker and Title***
09:15	***David Cohen (UNSW Sydney):*** Integration of geochemical databases into the decision-making procedure of mineral exploration targeting
10:15	***David Whitehead (GEUS):*** Storing geochemical data in databases
11:00	*Break*
11:15	Practical work in small groups
12:30	*Lunch*
13:30	Short presentations of students group works
14:50	Concluding word from organizers
15:00	***End of the Short course***

Day 1: Monday 14th of June

MinExTarget – an innovation project in mineral exploration

Dr. Ferenc Molnár and the MinExTarget consortium

Research Professor at Geological Survey of Finland

Dr. Ferenc Molnár received his doctoral degree at the Eötvös Loránd University, Budapest, Hungary. Since that his research career continued as post-doctoral researcher at the Carleton University, Ottawa, Canada, Assistant Professor at the department of Mineralogy, Eötvös Loránd University, research associate at the Natural Resources Research Institute, University of Minnesota, Duluth, and Associate Professor and head of the Center of Earth Sciences at the Eötvös Loránd University. From 2011 until present Prof. Ferenc Molnár works at GTK and being a leader of several research and innovation projects in ore geology.

New ore deposits supporting the sustainable supply of raw materials for our societies are becoming more and more difficult to find. The industry is in need of new tools for exploration, because undiscovered mineral deposits are partly or completely buried and reside deeper in the crust. This also means that exploration in recent years has become more expensive and the number of newly discovered economic deposits is declining.

The MinExTarget project aims development and introduction of a new exploration tool which provides better targeting capacities in the early stages of mineral exploration. Recognition and interpretation of geochemical and mineralogical anomalies that have been inherited from primary metallic mineral deposits in sediments is a widely used tool in mineral exploration. The new, innovative concept of the project is that the primary sources of those anomalies can be better targeted and qualified by the determination of associations and concentrations of trace elements together with stable and radiogenic isotope compositions in selected types of heavy mineral grains preserved in till, stream and shallow marine sediments. The concept and practice may expect wide application in mineral exploration because more than 50% of land surface is covered by glacial, alluvial and coastal sediments north of the 45°N latitude of the northern hemisphere and those areas are also among the frontlines of mineral exploration.

The MinExTarget approach is based on the introduction of automated electron-optical and laser ablation inductively couple mass spectroscopic analytical methods into the everyday practice of characterization of heavy mineral separates. This also means the optimization of sample preparation form the point of view of selected minerals and the needs of analytical techniques. The test areas of the project are located in intensely explored terrains with diverse types of metallic mineral deposits in Northern and Central Europe, as well as in Greenland. The research also evaluates how the better knowledge of heavy mineral geochemistry supports characterization of the quality of the predicted ore deposit. The project also aims to transfer the know-how and technology to SMEs for commercialization of the new exploration tool and also established the MinExTarget Ltd., a startup company which will offer the newly developed kit of services to mineral exploration. Dissemination of results of the project also includes training of university students and young researchers in the field of project-specific analytical and evaluation methods and entrepreneurship in order to support transfer of knowledge to the next generation of experts.

The research consortium is led by the Geological Survey of Finland. The members of the consortium are the Oulu Mining School and Oulu Business School at the University of Oulu, Finland, the Arctic University of Norway in Tromsø, the AGH University of Science and Technology, Poland, the Geological Survey of Denmark, the Mawson Gold Ltd., Australia and Finland, the Palsatech Ltd. Finland and CRS Laboratories Ltd., Finland. More information is available on the MinExTarget web-site: http://projects.gtk.fi/minextarget.

Geology and ore potential of the Fennoscandian Shield

Dr. Pasi Eilu

Geological Survey of Finland, Espoo, Finland

Pasi Eilu is a Senior Scientist at Geological Survey of Finland and Adjunct Professor at University of Turku, Finland. He has a 35 years professional experience in research and training on mineral deposit geology and exploration in Finland, Sweden, Norway, Greenland, Australia, and several countries in Africa, for both the academia and the mining companies. Pasi Eilu has worked on mineral deposit databases, mineral resource, mineral raw material supply, critical raw material, and the UNFC mineral resource classification issues. He is the International Coordinator of the Fennoscandian Ore Deposit Database which is a permanent, four-country, cooperation structure. He also is a member of the IGCP Earth Resources theme Scientific Board, and an Associate Editor of Mineralium Deposita.

Pasi Eilu & Raimo Lahtinen

Global supercontinent evolution stages can be seen as the first-order control for the metallogenic evolution of a region. The majority of metallogenic stages and events in the Fennoscandian shield (i.e., nearly all of Finland, Karelia and the Kola Peninsula, and most of Sweden and Norway) show a distinct correlation with the main stages of supercontinent evolution. This relationship is summarised below in Table 1. VMS, porphyry, epithermal, and most of the skarn deposits relate to subduction and arc accretion stages. Also polymetallic vein, orogenic Ni-Cu, iron-apatite, and IOCG style deposits may relate to accretion. Deposits related to supercontinent final amalgamation include: IOCG, orogenic Ni-Cu, orogenic Au, polymetallic vein, rare metal pegmatite, and eclogitic rutile. Mineralization styles possibly relating to continent break up are: rifting-related intrusion-hosted Ni-Cu-PGE and Cr, red bed Cu, clastic-hosted U-V, black shale Ni-Zn-Cu-Co and komatiitic Ni. Deposits detected in several plate-tectonic settings are: BIF, skarn Fe, mafic intrusion-hosted V-Ti-Fe, clastic-hosted Zn-Pb and Cu±Co±Au, SEDEX, and carbonatite-hosted apatite.

These metallogenic events and their relationship to arc accretion and supercontinent cycles are similar to those recorded in other Precambrian and Palaeozoic terrains.

Table 1. Precambrian supercontinent stages and main mineral deposit types in Fennoscandia.

Age (Ga)	**Supercontinent stage**	**Mineralization style**
3.6–2.75	Pre-Kenorland	Komatiitic Ni; Mafic-ultramafic intrusion Cr; BIF; Porphyry Mo
2.7–2.6	Kenorland assembly	Orogenic gold; Mafic intrusion Ti-Fe-V; Peralkaline to carbonatite P-Nb-REE-Zr; Rare-metal pegmatites
2.50–2.44	Kenorland initial break up	Layered-intrusion Cr, V-Ti-Fe, PGE±Ni-Cu
2.1–1.95	Kenorland main break up	BIF; Ultramafic-mafic intrusion Ni-Cu±PGE; Alkaline intrusion V-Ti-Fe; Black shale Ni-Zn-Cu-Co; SEDEX Cu?; Red-bed Cu; SSC, U-V; Outokumpu Cu-Co-Zn
1.95–1.86	Columbia first stage assembly (arc magmatism, accretion and collision)	BIF; VMS; Porphyry Cu±Au, Mo; Epithermal gold; Metamorphic talc-magnesite±Ni-Co; Orogenic gold; Kiruna Fe-apatite; IOCG; Orogenic Ni-Cu; Mafic intrusion Ti-V-Fe; Skarn Fe±REE, W±Mo; Epigenetic Mo?
1.84–1.77	Columbia second stage assembly	Orogenic gold; IOCG; Rare metal pegmatite; Mafic intrusion Ti-V-Fe; Carbonatite REE-Pb; Epigenetic Mo?; Skarn Fe-Mn, W?
1.68–1.48	Columbia final assembly	VMS; Orogenic Ni-Cu; Mafic intrusion Ti-V-Fe; Skarn Zn-Fe, Fe-W, Orogenic gold
1.25–1.18	Columbia break up	Mafic intrusion Ni-Cu, Ti-V-Fe; Rare-metal pegmatites
1.10–0.92	Rodinia assembly	SSC; Carbonatite Nb-Fe-P-REE; Orogenic gold; Epigenetic Mo; Skarn Fe; Anorthositic intrusion Ti-V-Fe; Orogenic Ni-Cu; Rare-metal pegmatites
0.82–0.60	Rodinia break up	SEDEX Zn-Pb±Cu?; VMS; Mafic intrusion Ni-Cu
0.60–0.50	Passive margins + Caledonian rifting	Stratiform Fe; SSC, Pb±Zn; VMS; MVT Zn-Pb; Black shale–Alum shale U-Mo-V-Ni; Phosphorite U; SEDEX Zn-Pb?
0.50–0.43	Laurasia accretion	VMS Cu-Zn; SEDEX Zn-Pb; Clastic-hosted Pb-Zn; Orogenic Ni-Cu; Porphyry(?) Cu-Mo; Skarn W, Mo, Zn-Pb; Orogenic gold
0.43–0.39	Caledonian collision	SEDEX Zn-Pb?, Orogenic gold; Base-metal vein; Eclogitic rutile
0.38–0.36	Intracontinental rifting	Peralkaline to carbonatite P-REE±Nb-Ta±Zr-Hf, Ti-Fe, ±vermiculite
0.30–0.24	Intracontinental rifting	Porphyry Mo; Vein Ag-Co-As; Mafic intrusion Ti-P-REE

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Eilu P. (ed) (2012) Mineral deposits and metallogeny of Fennoscandia. Geol. Surv. Finland, Spec. Paper Vol. 53, 401 pp.

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Mapping the mineral potential; the role of the Geological Survey of Norway

Dr. Henrik Schiellerup.

Geological Survey of Norway (NGU)

Henrik Schiellerup is Director for Resources and Environment at the Geological Survey of Norway. He has an MSc from the University of Aarhus in Denmark and a PhD from the Norwegian University of Science and Technology. His primary background is in igneous petrology and mineral resources. Since 2001 he has been working at the Geological Survey of Norway both as a researcher and in various managerial roles, including heading the survey laboratories and the mineral resources team through many years. He has been Division Director at the survey since 2019.

The Geological Survey of Norway (NGU) is a research-based government agency dedicated to supplying the Norwegian society with essential and un-biased geological data and knowledge. Part of our mission is to identify and document potentials for mineable mineral resources in Norway. NGU generates, develops, and maintains datasets that are used to target mineral exploration. These datasets include bedrock maps, airborne and ground-based geophysics, soil geochemistry, as well as targeted surveys and characterization of known mineral assets and showings. The combined data are used to constrain prospectivity and delineate areas of elevated mineral potential.

Norway has a long history of metal mining, but today metal extraction takes place from only two producing mines. Industrial minerals, such as carbonates, quartz, and natural graphite dominates the current map of mining activities. However, three mature metal projects, significant exploration activity, and a varied resource potential across Norway, herald the continued importance of Norwegian mineral resources. Rising demand for metals and minerals in general, and commodities needed for decarbonization in particular, are driving the activity in the exploration and extractive industry. The global trends and the focus on critical national and European value chains have opened doors to new commodities and increased activity within the raw materials sector. The presentation will cover aspects of the geological potential and ongoing activity in Norway.

Mineral systems in Greenland – two examples from globally important deposit types

Dr. Stefan Bernstein

Head of Department (Petrology and Economic Geology) at Geological Survey of Denmark and Greenland (GEUS)

Dr. Stefan Bernstein received his doctoral degree at the University of Copenhagen in 1994 in the field of petrology and geochemistry. Since that he was a visiting researcher in Stanford University, and worked as a Senior Scientist at Danish Lithosphere Center and GEUS. From 2002 until 2007 Dr. Bernstein acted as a Board Member at NORDSIM, Natural History Museum, Stockholm, and dedicated 9 years of his career at the Avannaa Resources working as an Exploration Director. From 2016 until present, Dr. Bernstein is a Head of Department at GEUS. His role is to define research strategy, manage scientific and technical tasks.

Over the past couple of decades, the concept of Mineral Systems has evolved to become a widely used and powerful framework, onto which mineral exploration programme can be built and launched in greenfield terrains.

Ice-free Greenland has a complex geology, spanning most of Earth’s history, and contains fundamental features which are similar to those of prolific mining countries such as Canada and South Africa. However, due to logistical challenges and high-cost regime, Greenland remains relatively underexplored. While thus allowing for few brownfield projects, Greenland instead offers vast areas of greenfield opportunities, where the Mineral Systems approach can play an important role in reducing risk and help direct investment decisions.

Two examples of ore deposit types are given, both of which have been yielding large amounts of raw materials for centuries. The deposit camps still continue, supplying raw materials critical for the green transition, while generating income not only to the companies, but often significantly so for the countries that host the mining camps.

Large Igneous Provinces (LIPs) are known to tick several of the requirements for Nature’s making of large, high-grade magmatic Cu-Ni-Co and platinum-group-elements (PGE) deposits. The Tertiary of West Greenland forms part of the North Atlantic Large Igneous Province and hosts one of the worlds larges accumulations of high-magnesium lavas. Such magmas are generated by high-degree melting of the Earth’s mantle and extract, along with the silicate melts, masses of nickel, copper, cobalt and PGE, which in turn are transported to upper crustal levels during lithospheric thinning and volcanic eruptions. Interaction of the high-magnesian lavas with sediments and other crustal material alters the magma to a stage where a sulphide melt segregates while scavenging the silicate melts for its chalcophile and siderophile elements. Structural and volcanic plumbing are ultimately responsible for accumulation of massive or disseminated sulphides with high and minable contents of Cu-Ni-Co-PGE. West Greenland Tertiary contains examples of all these processes while minable deposits still await discovery.

Sedimentary basins with a complex history of deposition of large amounts of clastic sediments, arid conditions with evaporite formation and reducing mudstone/black shale beds can generate large tonnage sedimentary copper deposits. In central East Greenland, Permian-Triassic strata forms an extension to the North European Zechstein basin with its world-class copper-silver districts in Poland and NE Germany. Excellently exposed Permian-Triassic rocks can be traced along more than 300km stretch of land with intermittent copper mineralization, often spatially associated with reduced facies carbon-rich material, but also unrelated to such matter for which other copper segregation processes must be responsible.

Both exploration plays in West and East Greenland have seen shallow drilling, but while these efforts have proved disappointing, the opportunities for discoveries are far from exhausted.

Geology and mineral deposit perspectives in Poland

Dr. Adam Piestrzyński

Professor at AGH University of Science and Technology in Kraków, Poland.

He studies Cu-Ag Kupferschiefer mineralization for over 4o years. In the 90s during underground prospecting for gold, performed for KGHM Polish Cooper Company he described new gold deposit containing minor Pt and Pd, positioned just below copper horizon. He prepared countless industrial reports for Polish mining industry and was the editor and co-author of "KGHM monography" (last edition in 2007), "Bible" of the copper deposit in Lubin-Sieroszowice district. He also worked on sediment hosted copper deposits in Peru and more recently, in Colombia. He also participated in exploration projects and research projects in Australia, Vietnam, Laos, Mongolia, Ukraine and in Kosovo.

Jadwiga Pieczonka, Adam Piestrzyński, Władysław Zygo, Krzysztof Foltyn

Polish territory is covered with thick, up to 350 meters pile of young Paleogene, Neogene and Quaternary sediments. The youngest clastic sediments were transported from Scandinavia. Crystalline basement is outcropping in the SW corner (Sudety Mountains and Sudety Foreland), Holly Cross Mountains (central Poland) and Tatra Mountains (S-Poland) (Fig. 1). Such a geological structure creates great challenges for the exploration of mineral deposits. Thick young sediment cover required the use of special exploration methods based on geophysics and deep drilling. Since the IInd World War, several thousand drill holes were completed (Fig. 2). The numbers of boreholes indicates the intensity of geological exploration conducted during the exploration and the interest in the area. Most of the holes were made for exploration for oil and gas. However,oil drill holes identified the Kupferschiefer (KS) horizon as metal bearing.

Totally 105 concessions for different mineral commodities have been issued by the Ministry of Climate and Environment. Nine concession are open for Cu-Ag exploration. Fore Sudetic Monocline and North Sudetic Through areas are both characterized by world class stratiform Cu-Ag deposits and exploration target. KGHM Polska Miedź owns several mining concessions in the Lubin–Głogów area (SW Poland) (Fig. 3). This company has industrial resources at the level 1.157 Gt of ore grading 0.9-1.7% and 47 g/t of Ag. Typical industrial sections is 4.5 m thick and is composed of going from the bottom, sandstone ore, shale ore (Kupferschiefer), and dolomite ore. The KS ore consist of 10% Cu in average and up to X00 ppm of Ag.

Figure 1. Major geological units in Poland (after Przylibski, 2020, DOI: 10.3390/w12030748)

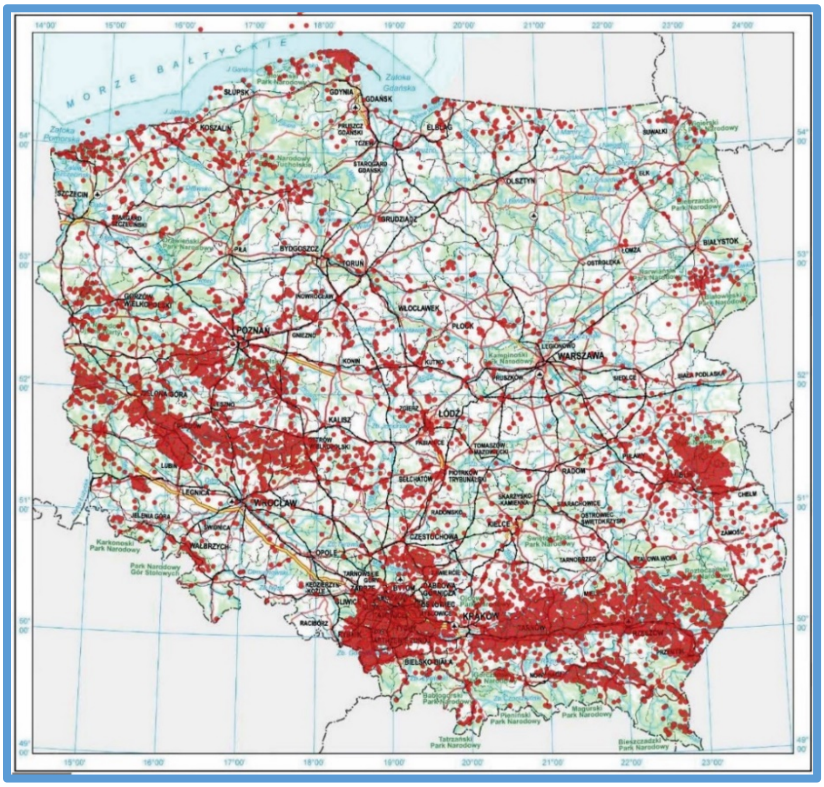


Figure 2. Drill holes emplacement in Poland (geolog.pgi.gov.pl)

Table 1. Mineral production and perspective in Poland (31 XII 2019, PIG_PIB Warsaw, 2020)

	Production in 2019	Resources indicated	Reserves, measured and indicated	**World mining data in 2019**
natural gas	4 976.46 mln m^3	141 971.36 mln m^3	74 953.38 mln m^3	
oil	936.76 kt	22 648.79 kt	12 954.06 kt	
Lignites	52.855 mln t	23 261.83 mln t	994.55 mln t	4th world producer
Hard coal total	64.063 mln t	64 329.84 mln t	4 779.20 mln t	Steam coal 10 World producer
Hard coal GZW	56.807 mln t	52 244.91 mln t	4 162.15 mln t	
Hard coal LZW	7.256 mln t	11 660.95 mln t	616.73 mln t	
Zn-Pb ores	1 510 kt	92.15 mln t	3.76 mln t	
Zn-metallic	40 kt	3.90 mln t	0.15 mln t	28th World producer, 40000 metallic Zn
Lead metallic.	20 kt	1.46 mln t	0.07 mln t	14th World producer
Cu-ores	29.881 mln t	1 951.20 mln t	1 157.28 mln t	
Cu-metallic	0.449 mln t	34.75 mln t	23.17 mln t	12th World producer 398900 t Cu;
Ag-metallic	1.455 kt	103.57 kt	70.02 kt	7th World producer, 1249 t
U			perspective 2000 t	
REE				
S-native	568.24 kt	494.29 mln t	14.68 mln t	
K-salts	-	686.15 mln t	3.46 mln t	
rock salts	4.063 mln t	90 323.39 mln t	1 766.91 mln t	17th World producer,
Gypsum and anhydrite	1.065 mln t	253.889 mln t	66.345 mln t	
industrial materials	78.709 mln t	11 543.25 mln t	3 573.27 mln t	
sand & gravel	182.811 mln t	19 742.66 mln t	4 168.82 mln t	

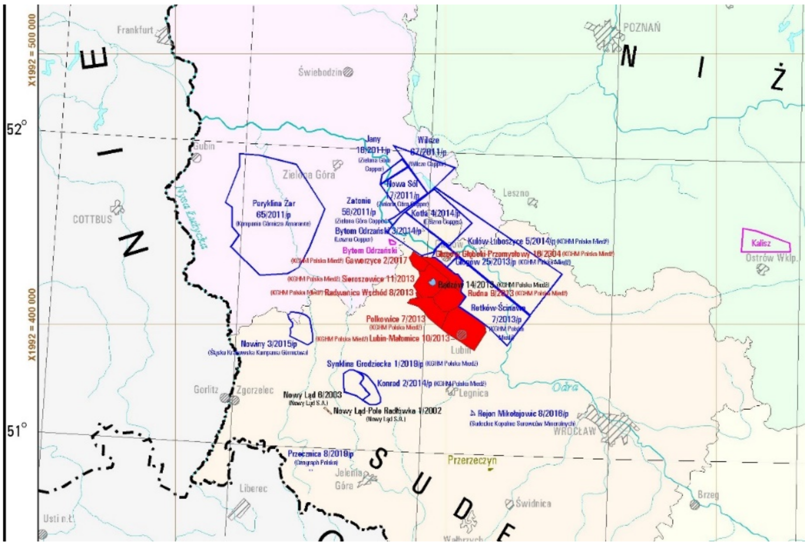


Figure 3. Important Exploration concession for Cu-Ag ores (Polish Ministry of Climate and Environment bip.mos.gov.pl)

Figure 4. Glauconite sand with amber. Prospecting for amber, Górka Lubartowska Deposit, Natural size.

Currently (2021) two concession for Zn-Pb are issued for Polish and international companies. Both are located within relatively well recognized metallogenic province Upper Silesia – Krakow. Exploration for these metals are focus on additional drilling following conventional model based on 2δ radius distance from positive one. Position of ore bodies within the collapse breccia structure results of permanent problem with drill core recovery, which usually not fit to the Jork-Code standards. Initial geophysics IP and Resistivity methods very often show anomalies based only of marcasite-pyrite mineralization with sub-economic concentration of Z-Pb sum e.g. <2.0 wt%. Such exploration and searches increased the resources and the life of the mine Pomorzany. Additional parameter: cut off 2.0% Also interpretation of surface anomalies gives false information because of high historical pollutions and industrial mining.

Tin and cobalt were mined in the past in the area of Krobica-Gierczyn-Przecznica in the Sudety Mountains. Although this mineralization is considered as sub-economic, with low tonnage and grade, new concession for exploration and prospecting has been awarded in recent years for cobalt.

Native sulfur deposits occur in the vicinities of Tarnobrzeg, Staszów and Lubaczów in the northern part of the Carpathian Foredeep. The sulfur occurs in the form of fillings of fissures and small cavities in Miocene rocks, mainly post-gypsum limestones. The production has been carried out from Osiek deposit using the Frasch hot water method.

Polish hard coal deposits belong to the Carboniferous Euro-American coal province and are exploited in two basins of the paralic type - the Upper Silesian Coal Basin (USCB) and Lublin Coal Basin (LCB). USCB is the major coal basin in Poland where all of the operating coal mines are situated except of one mine – Bogdanka in LCB. The third, limnic basin (Lower Silesian Coal Basin LSCB), was exploited in the past but deposits have been abandoned for about 20 years due to difficult geological-mining condition. However, there have been exploring works carried out in this basin recently which resulted in a documentation of new deposits. Coal bed methane (CBM) is natural gas occurring in the form of gas particles adsorbed at coal grains and its deposits have been documented in coal deposits of the Upper Silesian Coal Basin. Draining of CBM by production wells is treated as the natural gas production from unconventional source.

Over 100,000 people is actually working in amber (Fig. 4) industry. It is very popular commodity in Poland known from Roman Empire time. One new amber mine was open in 2018, that is located in SE part of Poland.

Mineral deposits have played an important role in history and economy of the Polish territory since prehistoric times. Bog iron ore, lead, silver, gold and salt production in the medieval period were important sources of economic growth. Extensive prospecting and exploration conducted in Poland in the second half of 20th century allowed to identify important resources of lead–zinc ores, coal and especially native sulphur and copper–silver ores of global significance (Tab. 1).

Day 2: Tuesday 15th of June

Heavy Mineral Methods in Glaciated Terrains

Hannu Ahola

Chief Geologist at Palsatech Oy

Hannu Ahola recieved his master’s degree in geology and Earth Science at the University of Oulu. Since that he worked as a filed assistant followed up with exploration geologist at Store Norske Spitsbergen Grubekompani AS. From 2014 until present Hannu is a Chief Geologist at Palsatech Oy (Finland).

Heavy mineral methods are one of the oldest ways to do exploration and mining. Panning of gold and other valuable minerals have been dated back to the times of the Roman Empire. Nowadays the heavy mineral methods are mostly used in gold panning and mine processing applications. In mineral exploration, the geochemical methods have become more popular since the price for the analytics has come down. At the same time the price for the labour has gone up, which increases the costs for a heavy mineral survey. Still, many companies value the information gained from a heavy mineral survey, espesially at the early stages of exploration.

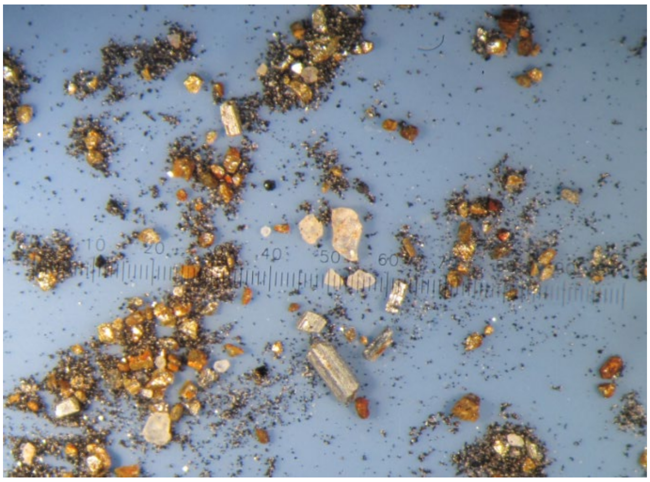


Figure 1. Arsenopyrite and scheelite found in glacial drift, one small gap in scale equals 0.1 mm.

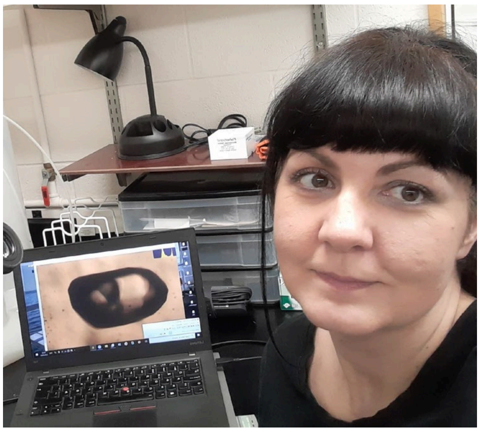
A heavy mineral survey is started with a planning stage (selection of sample medium, size and spacing, sampling method, concentration method, analytics). Surveys typically cover larger areas (regional/district scale) and sample spacing can be kilometres between sample points. The design of the plan reflects the commodity of intrest and local geology. Looking for diamonds (kimberlites) have differences compared to a gold or a porphyry campaign.

Samples are dug with a shovel or an excavator. Drilling methods can be used as well (not very common in Scandinavia), but to get a large volume sample one needs a heavy rig. Some drilling methods are effective but too expensive for routine exploration work. Sample size varies from few litres to tens of litres depending on the commodity and style of sampling. Also the access to sample sites dictates the volume of samples. Sieving to <10mm or <2mm would be good in the field to get rid of the larger stones and pebbles. In remote locations using a pre-concentration method in the field might be necessary to transport the samples out. Panning, sluicing, shaking table, jigs, centrifugal and spiral concentrators are used in the field. However, the recoveries might not be as good as in laboratory settings. Just by using dirty water might influence the performance of the concentration. In addition to all of the above mentioned techniques a Dense Media Separator can be used in laboratory conditions.

After samples are taken and pre-concentrated, the next steps in the processing chart involve sieving(wet/dry), magnetic separation, heavy liquids, washing/etching, (micro)panning and/or hydroseparation. The processing chart will be different for different minerals/metals. Some can be very simple (Knelson+sieving+micropanning→stereomicroscope) and some quite complex (diamond/VMS indicators). The purpose of the sample treatment workflow is to cut the sample volume without loosing the minerals of intrest. When the sample volume is small enough indicator minerals can be studied with a stereomicroscope, picked and mounted on epoxy for further analysis. The amount, size and shape of individual minerals/metals is useful data without any further analysis and give more detailed information than just having geochemical assay data. Having larger samples gives more reliable and repeatable results on gold and PGE exploration (nugget effect).

Modern microanalysis of heavy mineral grains starts normally with an automated scanning electron microscope. MLA and QEMSCAN are examples of two different softwares available. After SEM work, the interesting grains can be selected for further element and/or isotopic composition analysis with for example laser ablation mass spectrometer technique. So called fingerpriting techniques are a sophisticated way to utilize the heavy minerals. To be able to evaluate the origin (source) of different heavy minerals in glacial drift can be a powerfull tool in exploration. It also migh save the companies a lot of time and money when they know what to look for from the beginning.

Stream sediments and marine sediments in mineral exploration



Dr. Sabina Strmic Palinkas

Associate professor at the Department of Geosciences, UiT The Arctic University of Norway, Adjunct Associate Professor at the University of Bergen

Dr. Strmic Palinkas recieved her PhD at the University of Zagreb, Faculty of Science. Her expertise comprises aqueous and high-temperature geochemistry, geochemical/thermodynamic modelling, lithogeochemistry and applications of organic geochemistry and stable isotope systematics to high temperature (ore-forming) and low temperature (environmental) processes. Dr. Strmic Palinkas has been involved in studies of a wide spectrum of ore deposits, including epithermal, hydrothermal-metasomatic, skarn, SEDEX, MVT and pegmatite deposits, as well as in environmental geochemistry studies.

Sabina Strmic Palinkas, Yulia Mun, Johan Bang Hilmo, Carly Faber

Stream sediment geochemistry has been recognized as an efficient tool in mineral exploration of various commodities. The method is based on an assumption that stream sediments represent products of upstream weathering and erosion and therefore are enriched in metals released from primary ore mineralization within the drainage basin. Concentrations of metals in stream sediments are generally higher close to the mineralised rocks and gradually decrease downstream. Therefore, geochemical characteristics of systematically sampled stream sediments can be used as a vector to the primary ore mineralization.

Mobile elements realized by weathering of rocks and primary ore mineralization within the upstream catchment are transported by either groundwater or surface waters and precipitated or adsorbed in stream sediment material. Mobile elements can be transported as ions and ion complexes (e.g., Zn^{2+}, UO_2^{2+}, SO_4^{2-}, MoO_4^{2}), uncharged ion pairs and molecules (e.g., $PbCO_3^0$, $H_4SiO_4^0$), metal-organic complexes, suspended colloidal particles (e.g., Fe-, Al- and Mn-oxides and oxy-hydroxides) and as ions adsorbed on suspended matter. The partition of a metal between these mobile phases is mostly controlled by the chemical properties of the metal and physicochemical characteristics of the aqueous solution.

In stream sediments, metals can be bonded in a crystal lattice of resistant ore minerals (e.g., wolframite, native gold, magnetite, etc.) or rarely in form of sulphides (e.g., pyrite, chalcopyrite, pyrrhotite, etc.). All these minerals have a high density and will be fractionated within the heavy mineral fraction of the stream sediment. Alternatively, metals can be bonded in Fe-Mn-oxy-hydroxides precipitated from the stream water, incorporated in organic material or adsorbed on Fe-Mn-oxy-hydroxides, organic matter and/or clay minerals.

Stream sediment survey is usually conducted in an early stage of exploration with an aim to cover large areas and identify targets of interest for more detailed prospecting. The sample preparation usually combines sieving and mineral separation. Selection of the appropriate analytical methods is directed by: 1) chemical characteristics of pathfinder elements relevant for the target type of ore mineralization; 2) detection limits required for discrimination of the geochemical anomaly from background values; and 3) the sample matrix effect. Traditionally, bulk chemistry of fine stream sediment fractions (<63 µm) accompanied with a sequential extraction of heavy metals have been used. Recent developments in beam analytical techniques, such as scanning electron microscopy based automated mineralogy (SEM-AM) and laser ablation inductively couple mass spectroscopic (LA-ICP-MS) methods, allows utilization of heavy minerals and their trace element, stable and radiogenic isotope compositions for more precise targeting and qualification of the geochemical and mineralogical anomalies that have been inherited from primary ore mineralization.

In contrast to stream sediments, marine sediments are not commonly used in mineral exploration. Anyhow, marine sediment geochemistry has been identified as a potential tool for exploration of mineral resources in countries with steep terrains and long costal lines, such as Norway, and there application in targeting copper mineralization has been tested in the MinExTarget project.

Learning videos on marine sediments:

Gravity core sampling	https://www.youtube.com/watch?v=Kb0fa96L-s0
Core opening	https://mediasite.uit.no/Mediasite/Play/c73768abb1a04f4389b6fe5fd222042b1d
Core Log	https://mediasite.uit.no/Mediasite/Play/ad38edfefddb42538cbea43b073cadd41d
MSCL (multi sensor core logger)	https://mediasite.uit.no/Mediasite/Play/c6a796119a1c4e0eb956c84a464ae75c1d
X-Ray	https://mediasite.uit.no/Mediasite/Play/f4da7d0ca70c41b2bc65595d61316bb41d
Shear strength	https://mediasite.uit.no/Mediasite/Play/f528bcdf4683433eb4dd8a08daa5e11c1d
Sampling of marine sediments	https://youtu.be/QQN3mb2u0so
The stable isotope lab/Ice Breaker Kronprins Haakon	https://www.youtube.com/watch?v=u6V6l1QEtt8

Mineral exploration in glaciated terrain: Case studies from Finland*Dr. Pertti Sarala*

Research Professor at Geological Survey of Finland and Oulu Mining School

Dr. Pertti Sarala is a geologist and geochemist, fields of interest include Quaternary and glacial geology, geomorphology, applied geochemistry, till and weathered bedrock geochemistry and mineral exploration. He is experienced in glacial processes, mineral exploration (project leading, field studies, concepts, training), development of surface geochemical exploration methods (in EU funded projects) and teaching and supervision of the thesis projects.

Surficial geology, till geochemistry, and heavy mineral studies are practical exploration tools in glaciated terrains. There has been long tradition to use glacial indicators such as different glacigenic landforms and surface ore boulders for estimating ice flow directions and distances, and the elevated elements' contents and enriched heavy minerals of surface sediments, in tracing the mineralized source rocks in bedrock. Applications include all type of mineralization and the successful exploration stories cover many identified ore bodies which have led to the mining operations.

Effective use of till geochemistry and heavy minerals in ore exploration started in the 1970's in Finland by the mining companies Outokumpu and Rautaruukki as well as the Geological Survey of Finland GTK. There are many good examples of the use of these techniques in detecting the source rocks for Au, Cu, Fe and Zn ore indicators (e.g. Peuraniemi 1982). Gold exploration has been very active from the 1980's after the development of geochemical analyse method for Au, and numerous Au mineralizations have been found of which many have been led to a mining phase. There are several mines (Kittilä Mine, Pahtavaara, Pampalo etc.) opened based on that Au exploration activity. Other good example is diamond exploration, in which the heavy indicator mineral technique is used in glaciated terrains. Particularly, in the 1990's and 2020's large exploration campaigns were carried out in the eastern part of Finland (Lehtonen 2005).

In this century, numerous exploration and mining companies have been active in Finland. They have used till geochemistry and heavy minerals for searching many types of ores all around the country. In addition, the GTK has long traditions in using surface sediments and till as sample media in exploration. There are numerous reported regional and target-scale studies and sampling campaigns focusing on mineral exploration. Base metals, PGE and Au have been the most explored metals for decades, and particularly Au exploration has been based on surface geology and geochemistry, and heavy minerals' separation. One example of Au exploration is the Petäjäselkä target in Kittilä. Three different Au mineralization types were identified based on the Au-Ag ratio of Au grains in till. Deep pre-glacial weathering and elevated Au and REE contents in saprolite and glacial till have a strong positive correlation with the positive electromagnetic and radiation anomalies, caused by the sulphidic bedrock in the Mäkärä region, northern Sodankylä (Sarapää & Sarala 2013). Exploration studies revealed two REE targets in the areas: Au-hematite-quartz vein with 3 ppm Au and up to 0.4 % REE resembling ionic adsorption clays in China. Furthermore, advanced automated mineralogical identification methods (MLA, FE-SEM+EDS) have increased quality and the number of indicator minerals in heavy mineral concentrates, which is helpful in the critical minerals such as REE minerals' exploration. With the help of modern field analysers, on-site geochemical and mineralogical analyses can be now done in the field which provides a cost-effective way to study the composition of the sample materials as a part of exploration process. The same techniques are also available for characterization tailing materials in old mine sites.

Application of indicator minerals in mineral exploration in Canada

Dr. Beth McClenaghan

Research scientist at Geological Survey of Canada

Beth McClenaghan is a research scientist at the Geological Survey of Canada where she is Head of the Geochemistry Section and has worked for the past 30 years. Her research has focused on methods development for the application of till geochemistry and indicator mineral methods in mineral exploration, with particular emphasis on diamonds, and precious, base, and strategic metals. She is also an Adjunct Professor at Queen's University. Beth is a Fellow of the Association of Applied Geochemists (AAG) and is the Editor of the Association's quarterly geochemistry newsletter EXPLORE.

Boulder tracing and till geochemistry have been exploration tools in glaciated terrain for more than 60 years and their use is widespread. In the past 30 years, indicator mineral methods have expanded to become another key exploration method. This presentation describes indicator minerals methods and examples of their application to the exploration of a range of commodities in glaciated terrain, including diamonds, precious and base metals, and rare earth elements.

Historically, the focus has been on visual identification methods for indicator minerals in the sand-sized fraction of glacial sediments. Mineral identification methods now also include automated mineralogy and laser ablation ICP-MS techniques. These new analytical methods also allow us to identify and examine smaller (silt to fine sand sized) minerals in glacial sediments. Indicator minerals recovered from glacial sediments are considered to be one of two types:

1) minerals that can be directly linked to the source rocks or mineralization based on their spatial distribution in surficial sediments;

2) minerals for which mineral chemistry must be used to establish the link to the mineralization or source rock.

Numerous studies of known mineral deposits has identified indicator mineral suites, their compositional ranges, and key chemical discrimination criteria. Results of these bedrock studies are applied to the mid to heavy mineral fraction of glacial sediments. Individual mineral grains can now be analyzed to determine their major and trace element and isotopic signatures and inclusion mineralogy to identify the specific style of mineralization up ice.

Kimberlite indicator minerals (KIM) are the most widely known, well-studied and visually distinct indicator mineral suite and are used to explore for diamond-bearing kimberlite deposits. In addition to assessing diamond fertility of potential sources up ice, KIM chemistry data are used to discriminate between coalescing dispersal fans in kimberlites fields where small pipes are close together and/or in fields affected by multiple phases of ice flow.

Gold grains are one of the oldest indicator minerals and are the best indicators of their deposits. Gold grain abundance is used in tandem with grain shape and chemistry to determine the nature of the bedrock source and distance of transport from it. DiLabio's (1990) shape classification scheme for gold grains in glacial sediments has been systematically used by government and industry in North America for the past 30 years. A new scheme proposed by Girard et al. (2021) relates gold grain shape to its original form in source rocks. Gold trace element chemistry combined with inclusion mineralogy - methods initially developed for placer gold grains but applicable to gold in glacial sediments - provide insights into the specific style of mineralization in bedrock sources up ice.

Indicator minerals from other ore systems that will also be discussed include porphyry Cu, magmatic Ni-Cu-PGE, volcanogenic massive sulphide, intrusion hosted Sn-W, carbonate hosted Pb-Zn, and REE.

Day 3: Wednesday 16th of June

Mineral exploration techniques in Australia as an example of deeply weathered and covered terrain

Dr. Walid Salama

CSIRO Mineral Resources

Dr. Walid Salama is a senior research geoscientist and the leader of the Minerals and water team at CSIRO Mineral Resources in Perth, Western Australia. He joined CSIRO as a postdoc fellow in 2012. He received his PhD degree from Cairo University in Egypt in 2010. In 2007, he received a PhD fellowship from the German Exchange Academic Service (DAAD) and Joined the DFG-funded interdisciplinary research training group "Alteration and element mobility at the microbe-mineral interface") at Friedrich-Schiller university in Jena. In CSIRO, he led and involved in 20 research projects for Au, base metals and Ni-Co exploration in weathered and covered terrains in Australia and Africa. His main objective is to introduce cost-effective methods for exploration through cover.

Regolith is the entire unconsolidated and secondarily recemented cover that overlies more coherent bedrock that has been formed by weathering, erosion, transport and/or deposition of older material. It includes fractured and weathered basement rocks, saprolites, soils, organic accumulations, glacial deposits, colluvium, alluvium, evaporitic sediments and aeolian deposits. weathering causes the destruction of primary ore deposits and the dispersion of ore and pathfinder elements in the surrounding regolith. Conversely, it may also result in the supergene enrichment of some deposits and promote the formation of secondary orebodies. From a geochemical exploration perspective, it is important to understand the potential mechanisms and pathways of migration of ore and pathfinder elements in regolith and to unravel the complex superposition of events that may have occurred during regolith-landscape evolution. Many investigations have sought evidence for active dispersion from weathered mineralization in host rock through transported cover. Surface exploration using fine fraction soil, termite mounds, pedogenic carbonates and vegetation have shown a response through 2 to 20 m and rarely 30 m of transported cover in certain environments. However, in areas of deeper cover, interface sampling and indicator minerals have shown a positive response. There are two types of interfaces that may indicate mineralization. Physical interface sampling is based on the possibility of dispersion at or close to the unconformity by (i) mechanical dispersion of remnants of ferruginous duricrust, indicator minerals and gossan fragments and (ii) hydromorphic dispersion after deposition of the cover by groundwater percolating through the coarse, basal sediments, along the unconformity itself and/or the upper residual material. These mechanisms result in lateral dispersion haloes at the base of cover in which there is no evidence of upward dispersion into soil. It is this sampling medium that may provide the under-cover prospecting tool similar to surface exploration that makes use of ferruginous gravel, lag, heavy minerals or stream sediment sampling. However, understanding of palaeotopography is essential for the interpretation of geochemical data. Chemical interface sampling is based on hydromorphic dispersion in post-depositional weathering products such as iron and Mn oxide minerals formed in sediments. In places, geochemical signature of mineralization may be present, even up to ore grades of target elements.

Non- traditional stable isotopes and radiogenic isotopes in exploration

Dr. Yann Lahaye

Senior researcher at Geological Survey of Finland

Yann Lahaye received his doctoral degree at the University of Rennes in the field of Earth Sciences in 1995. He was later a postdoctoral researcher at the University of Montreal and Monash University. Yann dedicated 8 years of his research career to Goethe University in Frankfurt working as a lab manger. From 2008 until present Dr. Lahaye works as a senior researcher at GTK.

Watch a short video on GTK lab facilities here:
https://youtu.be/vLSxZUn56c8

Heavy minerals, resistant to chemical weathering, are extracted from their sedimentary formation and inherit the geochemical and isotopic signatures of their original environments. Some minerals commonly associated with mineralisation processes can be used to identify the nature and the proximity of an ore deposits, based on their isotopic composition. Classic radiogenic isotopes such as Rb-Sr, Pb-Pb and Sm-Nd are traditionally used to identify the nature of the source of the metal whether it is a hydrothermal fluid, a silicate magma, or the interaction of both. Non-traditional stable isotopes (Li, B, Fe, Cu…) could either be (i) conservative and provide similar information as radiogenic isotopes or (ii) non conservative and provide information on the processes (equilibrium or kinetic) associated with the metal circulation and precipitation. Finally, geochronological information provided by radiogenic isotopes (mainly U-Pb) are also used to identify mineralization of a specific age. The application of Isotopic measurements for fingerprinting the source of metals from heavy minerals have greatly benefited from the recent ongoing development of in situ isotopic analysis by laser ablation ICP-MS, which will be discussed in this presentation. This presentation will also illustrate the use of specific isotopic systems as well as their combination using examples taken from the literature.

Geoanalytical Techniques: Combining optical microscopy, e-beam, x-ray and laser- beam based technologies for a multi-modal, multi-scalar, & multi-dimensional approach

Prof. Alan R Butcher

Professor of Geomaterials & Applied Mineralogy at Geological Survey of Finland

Alan R Butcher obtained his PhD from the University of Manchester in 1984. He initially followed an academic career in South Africa with positions at the Bushveld Institute, University of Pretoria, then CSIR, and Rhodes University. In 1991 he was appointed a lecturer at the Camborne School of Mines (UK). In 1998, he joined the QEMSCAN development team at the CSIRO in Australia, and was later appointed Chief Scientist at Intellection Pty Ltd and more recently, Principal Petrologist at FEI Company. He is now Professor of Geomaterials and Applied Mineralogy, since 2017. Alan is both a generalist and a specialist geologist, with a keen interest in rocks of commercial importance. His lack of a single-track specialism has enabled him over the years to develop topical trends in Geoscience, including: the origins of layered intrusions in the 1980's; the development of Automated Mineralogy in the '1990's-2000's; and he is currently leading research into the geology, geometallurgy and new uses of minerals for the modern world, using a multi-scale, multi-modal, multi-dimensional, & multi-skilled approach. At GTK, Alan is also involved in the characterization and efficient processing of newly discovered battery mineral deposits in Finland, as part of the Nation's drive to attain carbon neutrality by 2035.

There have been significant advances in the way geologists examine rocks both mineralogically, petrographically, and micro-chemically since the introduction of traditional methods (light microscopy, and electron beam & laser-based techniques, such as SEM, EPMA, LA-ICP-MS). For example, cutting-edge scanning x-ray and hyperspectral imaging techniques are in now common - they allow geologists to scan drill cores at increasingly larger scales than that covered previously by a single petrographic thin section. This has allowed us to start to bridge the different scales of geological observation, from the mega- down to the nano-scale (Figure 1).

Furthermore, as geologists, we are taught to think in 3D, and yet up until quite recently, we have been mostly restricted to examining rocks in the laboratory using 2D surface techniques. But this has all changed in the last decade or so. By using workflows - borrowed and adapted from allied disciplines (including materials & biological sciences, and petroleum science & engineering) - geologists can now image rocks using powerful x-ray computed tomography-based techniques (X-CT) and focused ion beam-SEM technologies (FIB-SEM), in both 2D, 3D & more recently 4D.

These multi-scale, multi-modal and multi-dimensional workflows have opened-up a whole new world of analytical possibilities to us as a community. For the exploration geologist, it means that their valuable drill core intersections can now be examined and archived before it goes off for destruction (slicing with a diamond saw and crushing of half core for routine chemical assaying), thus digitally preserving all the contained characteristics (bedding, layering, folding, mineralisation). And for the mineral processing engineers, 3D liberation analysis is now a real possibility, something that has been requested by them for many years. And for the ore deposit geologist, it allows for a superior textural and structural understanding of mineralized rocks, all the way from the field (mega- and macro-scale) to the laboratory (micro- and nano-scale).

This workflow approach (Figure 2) is currently being implemented at the Geological Survey of Finland (GTK) in order to reduce the risks in mineral exploration; gain insights into the commercial mineralogy of ores; contribute to smarter and greener mineral processing behaviours; and to overall improve mineral deposit knowledge and understanding via an integrated 2D - 4D approach.

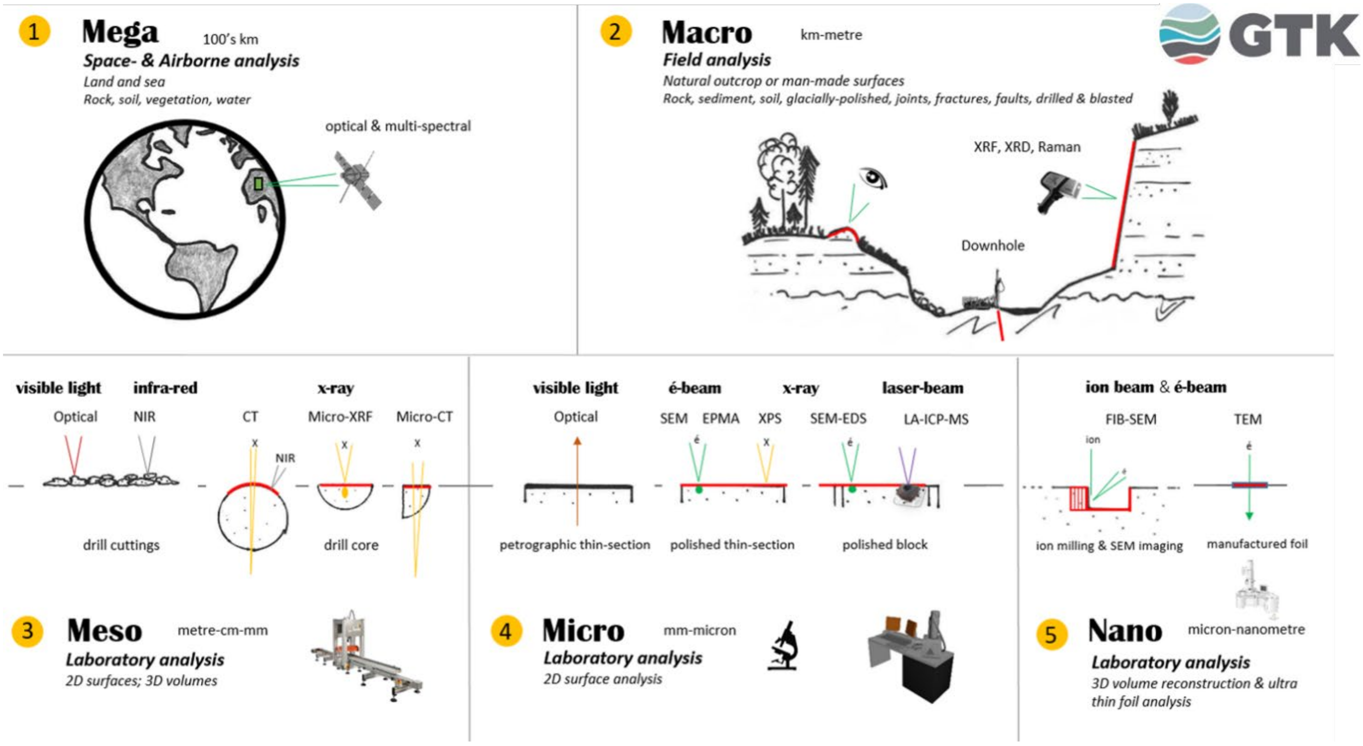


Figure 1. Generalized view of the study of geology in terms of scales of observations and technologies used to examine different features. From Butcher (2019).

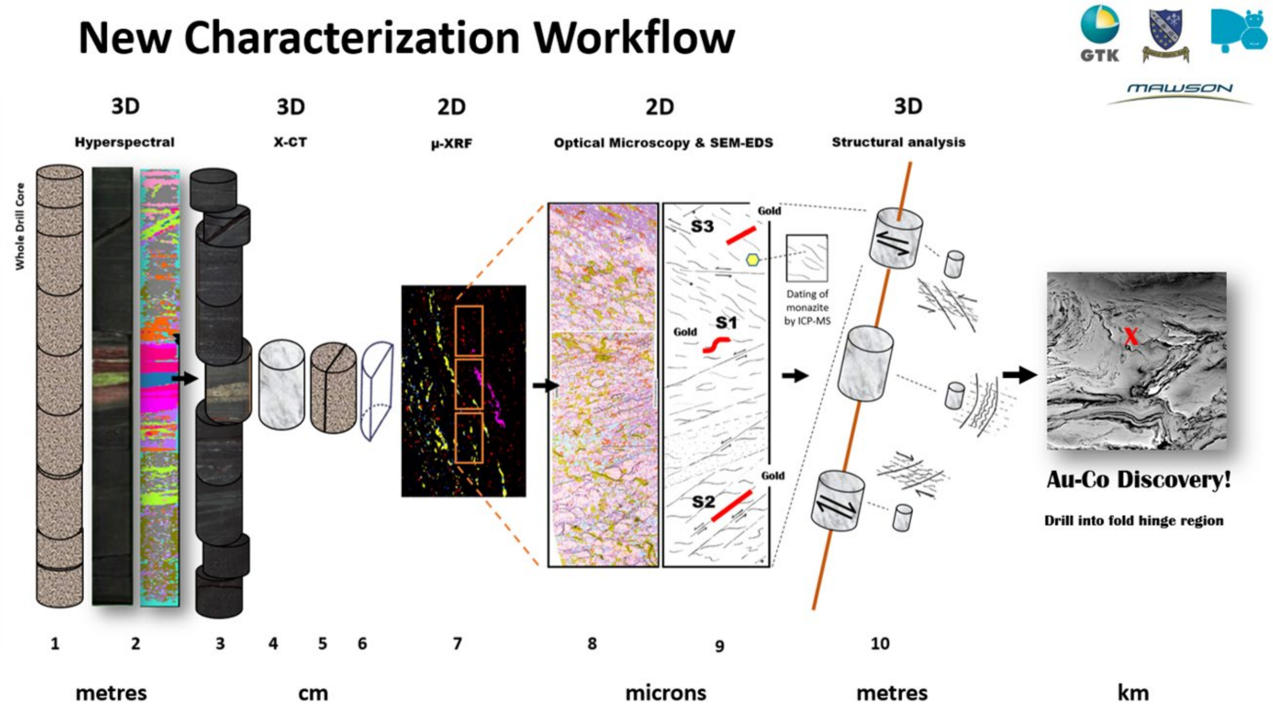


Figure 2. Multi-scale, multi-modal, multi-dimensional workflow used to characterize exploration drill core in order to optimize the discovery of gold and cobalt mineralization. Example courtesy of Mawson Resources, and developed in collaboration with Camborne School of Mines (University of Exeter), and Hippo Resources. From Butcher (2019).

REFERENCE

Butcher AR (2019) Upscaling of 2D mineralogical information to 3D volumes for geoscience applications using a multi-scale, multi-modal and multi-dimensional approach. In: ***EMAS 2019 Workshop***, *Book of Tutorials and Abstracts.* Trondheim, Norway; 19-23 May 2019. ISBN 978 90 8227 695 4.

Papers for further reading can be downloaded from here: https://we.tl/t-EHWLxefpqa

Fluid, melt and solid inclusions in mineral exploration

Dr. Sabina Strmic Palinkas (UiT The Arctic University of Norway)

Fluid inclusions are microscopic amounts of a fluid entrapped in a mineral either during its crystallization from the fluid phase (primary inclusions) or later during healing of its fractures in a presence of the fluid phase (secondary or pseudosecondary inclusions). Despite their small volume, fluid inclusions may provide a valuable set of information about temperature, pressure and chemical composition of fluids at the time of their entrapment. Therefore, fluid inclusion studies have been recognized as an essential method for understanding ore-forming processes in different types of hydrothermal mineral deposits. In contrast, fluid inclusions are rarely used as a direct tool in mineral exploration. In the MinExTarget project, we are testing a potential of fluid inclusion studies for targeting sediment-hosted Cu mineralization in Precambrian volcano-sedimentary terrains (e.g. Alta-

Kvænangen Tectonic Window, Repparfjord Tectonic Window, etc.). The study is based on comparison of fluid inclusions found in mineralized and barren quartz-carbonate veins with those found in quartz grains in the stream sediments of streams that drain the known Cu mineralization. The particular focus is given to 1) presence of specific types of fluid inclusion assemblages and 2) systematic variations in microthermometric properties of fluid inclusions hosted by mineralized and barren quartz-carbonate veins.

Melt inclusions are small droplets of parental melt entrapped by magmatic minerals during their crystallization. Similar to fluid inclusions, melt inclusions can reveal information about temperatures and pressures at which their host mineral crystalized, as well as information about the composition of parental melts. Although, melt inclusions have a well-established role in petrological studies, there have not been utilized as a tool in mineral exploration.

Presence of solid inclusions in minerals can reflect crystallization from highly saline fluids (e.g., halite, sylvite and anhydrite inclusions hosted by quartz crystals in sediment hosted Cu deposits), crystallization from melts of specific compositions (e.g. apatite inclusions in pyroxenes that crystalized from P-rich melts) or may represent a result of mineral reactions (e.g. rutile inclusions in garnets as a result of retrograde metamorphism). The phase composition of solid inclusions can be determined by transmitted and/or reflected polarized light microscopy and Raman spectroscopy but recent developments of beam analytical techniques, such as scanning electron microscopy (SEM), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and secondary-ion mass spectrometry (SIMS), allows also determination of their trace element and stable isotope composition.

Fluid, melt and solid inclusions may record information about original ore-forming processes (primary inclusions) as well as about post-crystallization fate of ore/bearing and barren mineral assemblages, but at same time, systematic studies that combine characterization of fluid inclusion assemblages and chemical and isotope characteristics of individual inclusions, can make them a useful tool in mineral exploration of different commodities, including Au in epithermal deposits, Cu and Mo in porphyry deposits, and Cu and Co in sediment hosted Cu deposits.

Day 4: Thursday 17th of June

Trace element content of pyrite: a proxy for ore-forming conditions and a potential tool for mineral exploration targeting

Dr. Paavo Nikkola

Research scientist at Geological Survey of Finland (GTK)

Paavo Nikkola works as a research scientist, specialized in mineralogy and petrology, at the Geological Survey of Finland. In 2020, he completed his doctoral thesis on the genesis of Icelandic basalts, in which he utilized trace element analyses of minerals to resolve conditions of mantle melting and magma crystallization. Now, he uses his analytical skills for the good of MinExTarget by analyzing and characterizing sulfides in till samples.

This lecture gives an overview of the application of pyrite trace element chemistry in ore genesis research and discusses how pyrite trace element contents—distinctive to various ore-forming environments—are useful in ore-exploration.

Analyzing the trace element contents of various indicator minerals in surficial sediments is an emerging tool in mineral exploration, and pyrite is a potentially useful mineral in this regard for the following reasons. Firstly, pyrite is the most common disulfide mineral, abundant in most metallic mineral deposits and rare in barren rocks. Secondly, pyrite crystals develop variable trace element contents that are distinctive of their genetic origin. Thirdly, despite their tendency to oxidize, pyrite grains are often preserved in surficial sediments.

Pyrite crystals precipitate from magmas and hydrothermal fluids under a wide variety of conditions. Additionally, pyrite forms in sedimentary diagenesis and in metamorphic replacement reactions.

Trace elements incorporate into pyrite as lattice bound substitutions for Fe and S. Also, many trace elements (e.g., Te, Bi, Au and Ag) are typically present as nano- and micro-inclusions in pyrite. Intragrain compositional variability and oscillatory growth zonation patterns in pyrite trace element contents are common and offer information of the ore genesis. Also, sector zoning patterns can be formed in response to the preferential incorporation of trace elements on the {110} lattice surface of pyrite crystals.

Sedimentary diagenetic pyrites are typically trace element rich. In turn, metamorphic pyrite, often formed in the breakdown of pyrrhotite, tends to inherit trace element characteristics from its source mineral. Magmatic pyrites typically have higher ratios of Co/Sb and Se/As in comparison to the hydrothermal pyrites for which the trace element contents vary in response to fluid temperature, pH, salinity, oxygen fugacity, sulfur fugacity, and fluid redox state. High-temperature hydrothermal environments related to porphyry copper, IOCG and orogenic gold deposits typically contain greater amounts of Co and Ni and lesser amounts of most other trace elements than pyrite formed in medium- to lower-temperature environments (i.e., epithermal, VHMS and SEDEX deposits).

Although the substantial (five orders of magnitude) variation in pyrite trace element contents related to varying crystallization conditions, data from different ore deposit types typically exhibit strong overlaps, and conventional trace element scatter plots fail to conclusively classify pyrite crystals of different origin. This has inspired researchers to use machine learning methods, that enable simultaneous comparison of multiple trace elements, in classifying pyrite trace element data. This, in turn, may open new avenues for ore-exploration at glaciated terrains by enabling trustworthy trace element-based identification of the source of a till-hosted pyrite.

Mineral trace element and isotopic footprints of orogenic gold deposits in Finland

Ferenc Molnár, Hugh O`Brien, Yann Lahaye, Sara Raic (GTK)

The formation of ore deposits can be considered as transient consequences of geological processes which operate on much larger time frames and earth-system scales than the highly focused and episodic enrichment of metals in a relatively small volume of the earth crust. The interfering processes leading to the formation of a mineral deposit affect much larger volumes of the crust than the deposit itself, and recognition of the footprints of those processes in the rocks along the migration pathways and around the orebodies is one of the major challenges in the early stages of mineral exploration projects. The footprints are recognisable by various geological and geophysical exploration methods because of the changes in properties and assemblages of minerals in rocks affected by the processes leading to ore deposition. One of the ways to recognise those footprints is the determination of trace element and isotope geochemical signatures of ore forming processes in mineral grains. If spatial distribution of those signatures shows gradual changes towards the orebodies then they can be applied to define vectors to ore.

Orogenic gold deposits are epigenetic-hydrothermal ore deposits formed most typically at mid-crustal levels in accretional and collisional orogenic belts by highly focussed flow of fluids under syn- to post-peak metamorphic conditions along fault systems of the metamorphic terrains. The peculiarity of orogenic gold mineral systems is that footprints of fluid flow are usually restricted to narrow (a few meters to a few hundred meters) zones in the wallrocks of the ore-controlling structures but can be rather extensive (e.g. up to several kilometers) along strike of these structures. However, the gold orebodies themselves are not continuous along strike of those structures, but usually occur in “lodes” or “ore shots”. In Finland, occurrences of proper structures for controlling localization of orogenic gold deposits occur in Archean and Paleoproterozoic greenstone-schist belts mostly at greenschist to amphibolite facies metamorphic grade. Many of them have valuable concentrations of gold only, but some of them, especially in the Paleoproterozoic Svecofennian orogenic belts, also have economically important concentrations of base metals, such as Cu. Co, Ni. In selected examples of these systems, our research on trace elements and isotopic properties of minerals has been focused on sulphide minerals, such as pyrite, pyrrhotite, arsenopyrite, chalcopyrite, or gangue/alteration minerals such as feldspars, carbonates, tourmaline, micas, monazite and xenotime.

The workflow of research for recognition of mineral trace element and isotopic signatures of orogenic gold deposits includes: 1) systematic sampling from distal and proximal zones of faults and orebodies, as well as from rocks unaffected by the hydrothermal processes; 2) petrographic and paragenetic characterisation of the setting of minerals of interest in those zones using polished thin sections or slabs; 3) selection of mineral grains for in situ analyses by automated and high resolution scanning electron microscopy (SEM); 4) in situ analyses by electron microprobe (EPMA) and/or laser ablation inductively coupled mass spectroscope (LA ICPMS) or other mass spectroscopic methods based on micro-sampling of minerals. The applied analytical techniques are capable to collect compositional data from polished surfaces of minerals as small as a few to tens of square micron in size. The small area of analyses even allows following compositional zoning of minerals.

The examples from orogenic gold deposits of Finland in this presentation demonstrate that trace element signatures of pyrite are applicable to make distinction between gold only and gold-base metal orogenic gold deposits, as well as between their mineralized and barren zones. The concentrations of Au, As, Sb, Ni, Co, Bi, Te, Se and their ratios and correlations in pyrite and some instances in other sulphides are sensitive records of mineralization processes. In sulphides, trace element data can be paired with sulphur isotope data from the same mineral grain or growth zones of a mineral grain which provides an additional opportunity of fingerprinting together with some understandings about origin of ore forming constituents. We also found that paired carbon and oxygen isotope data from carbonates are correlated with the concentration of gold in some gold deposits, and thus can be used for vectoring to ore. Boron isotopes together with major and trace element data of tourmaline may be used to recognise the multiple nature of hydrothermal processes and distinction of barren and gold bearing zones, as well as different sources of fluids. In the laboratories of Geological Survey of Finland, current projects also investigate the applicability of metal (e.g. Cu, Ni, Ag) stable isotopes for distinguishing barren and mineralized zones in orogenic gold deposits. Pb-rich sulphide minerals, such as galena and altaite, as well as K-feldspars are excellent target for in situ Pb isotope analyses because the structure of these minerals excludes uranium. Therefore Pb-isotope signatures of these minerals provide fingerprints of metal sources and later overprinting processes. Precise in-situ U-Pb analyses in monazite, xenotime, uraninite associated with the gold bearing hydrothermal stages are capable to define narrow time slots and thus fingerprinting of those zones of hydrothermal systems which were active during the elongated evolution of the orogen at the time of gold deposition. This is exemplified by our results of research in the Svecofennian gold only and gold-base metal deposits. Re-Os dating of sulphides (e.g. molybdenite, arsenopyrite, pyrite etc.) requires very small quantities of minerals and comparing of results of U-Pb dating of xenotime and monazite in texturally well characterised samples it is also an excellent method to recognise time-slots of ore deposition and remobilization processes.

Processing and fingerprinting of mineral trace element data by unsupervised machine learning

Dr. Sara Raič

Research Scientist at the Geological Survey of Finland (GTK)

Dr. Sara Raič received her doctoral degree at the University of Graz (Department of Petrology and Geochemistry), where she was lecturing and studying Cu-Ni-PGE-sulfide systems. Her research at the GTK is focused on the testing of new vectoring tools applied to mineral exploration of orogenic Au-deposits in Finland. To determine the vectors to ore, whole-rock geochemical datasets are combined with the trace element geochemistry and in situ sulfur isotopic analyses of indicator sulfides.

Sara Raič[1], Ferenc Molnár[1], Nick Cook[2], Mikael Vasilopoulos[3], Hugh O`Brien[1], Yann Lahaye[1]

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The trace element chemistry of sulfides has been more and more utilized in mineral exploration targeting, where it is has the capacity to define the metallogenic potential and setting of host rocks, or characterize various stages of mineralization. However, during the past years, this research was more focused on pyrite, since it is the most common sulfide mineral in many ore deposits that has a high ability to incorporate a wide variety of trace elements. Only very few studies include other base-metal sulfides as indicator minerals in this promising approach, which has great potential to become a standard vectoring tool in exploration targeting. For this purpose, a robust database of trace element chemistries from pyrite, chalcopyrite, pyrrhotite and arsenopyrite was produced in the framework of a large-scale study that covers samples from epigenetic-hydrothermal ore deposits which are classified into orogenic Au-only and orogenic Au-Cu-Co-Ni deposits in Paleoproterozoic greenstone and schist belts in northern Finland. The major aim of this research is to establish new synthetic geochemical variables for gold deposits, which have the capacity to distinguish according to element associations, as well as to the texture of the gold ore (refractory vs. free gold). Subsequently this discrimination provides the opportunity of choosing between available sulfides (not only pyrite), which will improve the metallogenic understanding of a region and may help to define future targets. The powerful technique that produces the robust databases from sulfide grains with well constrained textural and paragenetic settings in different types of gold deposits, is the in situ laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS). The benefits of this method are the fast analysis speed and the low detection limits of multi-element datasets. In order to produce meaningful results, the data acquisition includes a careful pre-processing and checking of down-hole ablation profiles for possible inclusions. The compositional data results are then treated with appropriate log-ratio transformations and used for various data visualization models (category plots, scatter plots, probability plots, etc.) and for multivariate statistical data analysis. The latter include the computation of principal components, or correlation analysis visualized by heat-maps. These methods contribute to the unravelling of subtle geochemical patterns associated with ore-forming processes and have the capacity to detect anomalous zones in the early stage of mineral exploration. Thus, the presentation also gives some theoretical background of compositional data analysis for a given trace element data set.

Introduction to data analysis techniques and the CODA approach

Prof. Dr. Peter Filzmoser

Professor of Statistics at the Vienna University of Technology, Austria*.*

He received his PhD and postdoctoral lecture qualification from the same university. He was a Visiting Professor in Toulouse, France and Minsk, Belarus. Furthermore, he has authored more than 200 research articles and several R packages and is a co-author of a book on compositional data analysis (Springer, 2018), on multivariate methods in chemometrics (CRC Press, 2009) and on analyzing environmental data (Wiley, 2008).

Geochemical data are compositional data. This statement occurs more and more frequently in publications of statistical analyses in the context of geochemical data, and it is not just a statement made by statisticians. Compositional data analysis (CODA) is also popular in other fields, such as bioinformatics, economics, or archaeology, and it makes use of relative rather than absolute information. Here, relative information refers to the (log-)ratios between the measured variables, whereas absolute information would directly process the (log-transformed) measurements. With D measured characteristics (e.g. chemical elements) one would obtain D*(D-1)/2 different log-ratios, and thus the treatment with CODA seems to complicate the problem.

However, it can be shown that all these pairwise logratios live in a space with dimension (at most) D-1, and the information contained in this space is also the basis for multivariate statistical analysis methods such as principal component analysis, cluster analysis, discriminant analysis, etc. The crucial point is how to construct this space, since the interpretation of the analysis results depends on the choice of its coordinates.

We will discuss different choices of coordinates, also in the context of different multivariate statistical methods, and demonstrate the theoretical concepts at real geochemical data by using the software environment R.

Quality assurance and quality control of surface geochemical data

Dr. (Tech) Maarit Middleton

Associate Research Professor at GTK

Dr.Maarit Middleton has graduated from Aalto university with a major in remote sensing in 2014. She has many years of experience in applying close range and remote sensing of optical data in geological and geoenvironmental studies. In addition, she has had a variety of different experiences with processing of spatial data for mineral prospectivity mapping, geoenvironmental applications, geomorphology and exploration geochemistry with plants. She was a deputy leader in the EIT Raw Materials funded project 'Upscaling deep buried exploration into European business (UpDeep) in 2017-2020. Currently she is leading the task of 'Multi-source surface geochemistry' in an H2020 funded project New Exploration technologies (NEXT).

The uncertainties of surface geochemical survey data are accumulated from natural geochemical heterogeneity of a sampling material, survey design, sampling, transportation and storage practices, and laboratory analytical procedures. Thus, external monitoring of the data quality is necessary although, nowadays, most laboratories are nationally accredited following standards of strict quality control. Geochemists and geologists should be concerned about the quality of collected data, and the quality of the laboratory results because sources of uncertainty can be various. Understanding of data quality is key for a data analyst as data analysis can only be as good as the quality of the data. In general, the surface geochemical data suffers from poorer data quality compared to e.g. whole rock geochemistry. In surface geochemistry the concentration levels can be very low expressed in ppt or ppb. This presentation outlines a five step Quality Assurance and Quality Control (QAQC) procedure by Miksova (2020) that is modified from Reimann et al. (2008). The steps are: 1) Data overview, 2) Process quality, 3) Laboratory contamination, 4) Monitoring of laboratory precision, accuracy and trends, and 5) Field precision. The procedure is specifically designed for surface geochemical data but can be applied for all geochemical survey data. The procedure also considers the data quality standards for multi-variate compositional data analysis besides the absolute elemental concentrations. The presented automatized QAQC procedure reports statistical numbers of accuracy (e.g. bias%) and precision (e.g. relative standard deviation%, precision-%) but also produces diagrams for visual interpretation such as x-charts and Thompson-Howart plots for interpretation of geochemists or geologists.

Day 5: Friday 18th of June

Integration of geochemical databases into the decision-making procedure of mineral exploration targeting

Dr. David Cohen

President of the Australian Geoscience Council

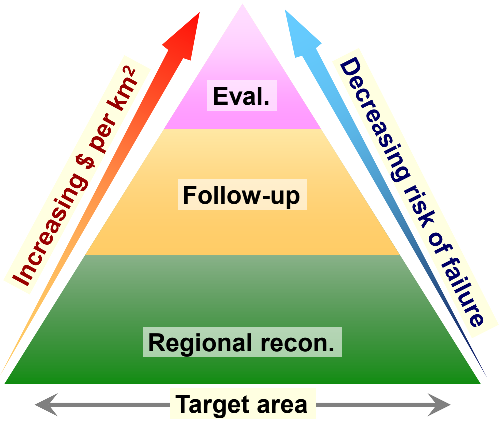
Dr. David Cohen has over 30 years' experience in exploration and environmental geochemistry research in Australia, Europe, Asia, the Middle East and North America. His areas of interest range from regional geochemical mapping programs, including use of biogeochemistry, to analytical techniques and data processing methods.

He has published over 80 papers and major reports. He has been a technical consultant to a number of exploration companies and government departments.

David is President of the Australian Geoscience Council, a Past-President of the Association of Applied Geochemists, and a fellow of the Royal Society of New South Wales. He was the 2013 Australasian Institute for Mining and Metallurgy visiting lecturer to New Zealand, and received the 2017 Silver Medal of the AAG.

Mineral exploration can be viewed in economic terms as contribution to reducing corporate risk for a mining or exploration company, a key risk being the failure to discover new mineral deposits. Uncertainty surrounding the validity of information obtained during an exploration program, the stability and integrity of data modelling, and the correct interpretation of that information, all affect the reliability of decision-making.

Most exploration programs commence with assessment of regional data – geological, geophysical and geochemical – and proceed to reduce the exploration area down to zones determined to have high mineralisation potential and the subsequent detailed evaluation of a small number of targets. As the relative expenditure per unit area increases, the risk of failure should decrease.



In exploration geochemistry, the task is not just detecting anomalous patterns that may be related to the influence of mineralisation, but to be able to rank 'anomalies' in terms of their likely importance or certainty, and to develop vectors that can assist in identifying areas for more intense investigation.

It is just as important to understand the factors that cause variations or patterns to form in geochemical data in the absence of mineralisation (i.e. background variability) as it is to examine geochemical patterns that occur in the vicinity of known mineral deposit types within various regolith-landform settings. In doing so, advantage should be made of the multivariate nature of most geochemical datasets, and the supporting geological and geophysical information, in both spatial and other statistical analysis.

The ultimate task in geochemical exploration program design is to identify the geochemical 'signals' or patterns that reflect the effects of mineralisation, and the combination of sampling, sample processing, analysis and data modelling that can most effectively detect and map such signals.

Introduction to Geochemical Databases

David Whitehead

The National Geological Survey of Denmark and Greenland

I am an exploration geologist and have worked with exploration and mining databases over several years. I have worked on projects in Scandinavia and Africa with a variety of commodities and gained useful and valuable experience working alongside experienced geologists. For the last two years, I have been at the Data and IT department at GEUS working with European mineral resource projects and with databases and GIS data from Greenland. I very much enjoy working with geological data and working out how to make best use of all the data that is available.

Geochemical databases are an important tool for managing the large amounts of geochemical data that have been collected in recent decades. Despite the fact that databases have been around for a long time, geologists often do not receive any formal training in creating and managing databases. This often leads to geologists resorting to spreadsheets to manage the data or working with databases created by others yet lack the understanding of how to manage them properly. However, geochemical databases do not need to be complex or require a detailed understanding of database management or query languages such as SQL. With careful consideration of the nature of geochemical data, database and data concepts, simple and easy to use relational databases can be created. These can prepare and present data for geologists to separate geochemical signatures resulting from geological processes from signatures caused by sample preparation and analytical procedures and biases. The creation of standardised workflows for data preparation, import, validation and export reduces the risk of systematic errors in the data although this does not entirely eliminate the risk of errors. This presentation provides a brief overview of some of the key concepts for creating a geochemical database and how to deal with some of the common issues analytical data have that require consideration from geologists.

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