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Targeted Geoscience Initatiative - Increasing deep exploration effectiveness with next-generation science and innovation

TGI Coordination Office

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Canada

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TARGETED GEOSCIENCE INITIATIVE

Increasing deep exploration effectiveness with next-generation science and innovation

Natural Resources Canada's Targeted Geoscience Initiative (TGI) is led by a team of internationally-recognized mineral deposit researchers at the Geological Survey of Canada, with academic, provincial and territorial government and industry collaborators.

Canada

CANADA'S CHALLENGE

Canada's natural resources sector provides jobs, opportunity and prosperity for all Canadians. Although Canada has a rich mining history, in many regions the large, near-surface mineral deposits have been located and developed into mines that have a finite lifespan and are becoming depleted. It has become increasingly difficult and expensive to find new deposits, and discovery rates are dropping.

Most future mines will be in new and emerging mining districts or located deep below the surface in mature mining districts. New scientific knowledge and innovative exploration methods are necessary to locate deposits quickly and efficiently to supply Canada and the world with the minerals and metals essential for the requirements of modern lifestyles and future prosperity.

TGI seeks to understand the processes that formed Canada's mineral deposits and identify and quantify the key indicators needed to explore for them. Discovery of new deposits and mining districts supports an industry that contributes to the well-being of all Canadians, their communities and our economy.

"*When Natural Resources Canada launched the Targeted Geoscience Initiative in 2000, our goal was to develop new criteria to assist exploration and mining companies. Since then, TGI has provided new mineral system models that industry is using to guide their exploration strategies for deep mineral deposits. Each iteration of TGI has strategically refocussed on the most pressing needs of mineral exploration, stimulating significant investment and innovation in the Canadian mineral exploration industry."*

– Mike Villeneuve, Director, Geological Survey of Canada, Central Canada Division

Contents

INDUSTRY COLLABORATION

The achievements of TGI were significantly enhanced by the guidance, access and support of Canadian mineral exploration and mining companies, and service and supply companies. Between 2015 and 2019, 45 industry collaborators provided critical access to deposits, geoscience data and expertise to TGI scientists.

45 INDUSTRY COLLABORATORS

GEOLOGICAL SURVEY COLLABORATION

The Intergovernmental Geoscience Accord identifies the complementary roles of Canada's geological surveys and provides a framework for their cooperation and collaboration. TGI has strong collaboration with all provincial and territorial geological surveys, supporting public geoscience from coast to coast to coast.

ACADEMIC COLLABORATION

TGI research has been conducted in close collaboration with academics and students from Canada's universities. Between 2016 and 2019, TGI engaged with 40 academic collaborators from 24 universities.

A key goal of TGI is to train Highly Qualified Personnel (HQP) to work in the Canadian mining industry. Since 2015, TGI has trained 45 undergraduate and graduate students and nine post-doctoral fellows. These HQP are poised to become future leaders in the search for mineral deposits in Canada and worldwide.

40 ACADEMIC COLLABORATORS

24 UNIVERSITIES

45 UNDERGRADUATE & GRADUATE STUDENTS

9 POST-DOCTORAL FELLOWS

DELIVERING PUBLIC GEOSCIENCE

Geoscientists investigate the Earth's minerals, soil, water and energy resources, and examine how Earth's natural systems operated in the past, operate in the present and may operate in the future.

Public geoscience refers to geological, geophysical, geochemical and other data, maps and knowledge that governments provide at no cost as a public good. It supports decision-making on key issues such as mineral exploration, land-use planning, environmental impact assessments and public health and safety.

NEXT-GENERATION EXPLORATION MODELS

TGI is a thematic program developing next-generation ore deposit models and methods for the mineral exploration industry to discover buried mineral deposits in emerging and existing mining areas. The scientific knowledge and innovative methods generated by TGI help reduce the risks inherent to mineral exploration and enables companies to focus on and invest in areas where the probability of success is highest.

Since 2000, TGI has produced thousands of scientific papers, public reports, presentations, new models and methods and maps. These contain new knowledge about metal and fluid sources, their transport and trapping processes, the architecture of ore deposits and the clues present at and near the surface that assist with discovery.

TGI's most recent research has focussed on ore systems: sets of geological processes that lead to the formation of mineral deposits that may be suitable to mine.

THE CANADIAN MINERALS AND METALS PLAN | LE PLAN CANADIEN POUR LES MINÉRAUX ET LES MÉTAUX

TGI AND THE CANADIAN MINERALS AND METALS PLAN

Geoscience generated by TGI was instrumental in developing the strategic directions of the Canadian Minerals and Metals Plan (CMMP). This long-term plan will enhance Canada's competitiveness and develop a modern and innovative mining industry supported by world-class science and technology. By delivering public geoscience to support mineral exploration, TGI is promoting economic development and fostering Canada's role as a global leader in the mining industry. As the CMMP is implemented, leading-edge TGI research will facilitate next generation geoscience innovations and sustainable resource development.

SUCCESS

Over the past two decades, TGI has developed robust geological models that can be applied to any exploration project, established leading-edge methods to examine and target mineral deposits using a range of technologies and propelled investment and innovation in the Canadian mineral exploration industry. TGI's success stories run throughout its ore system themes, demonstrating the breadth of knowledge and innovation developed through the program, which are influencing how the mining industry is approaching exploration activities across the country.

TGI's accomplishments are recognized both domestically and internationally, but further research and collaboration are required to address the continuing issue of dwindling accessibility to new mineral resources in Canada. The continuation of collaborative studies to understand formation and preservation processes of mineral deposits will allow TGI to continue to support the mineral exploration industry through quality public geoscience products that improve exploration efficiency and effectiveness.

GOLD

Many of Canada's largest gold deposits occur in clusters, known as gold districts, which suggests that the ore deposits formed either by similar processes or from common sources, or both. Canada's richest and best-known gold districts include the Abitibi greenstone belt in the Superior Province in northern Ontario and Quebec, and the Churchill and Slave Provinces in Nunavut and the Northwest Territories. British Columbia's Cariboo District and Yukon's Klondike region are also well-known historical gold mining areas.

Even in these historic gold districts, the precise mechanisms that control the distribution of exceptional gold concentrations through space and time are not entirely understood. To develop reliable models to predict the source and distribution of gold in existing camps and identify new opportunities, TGI5 set out to close the knowledge gaps related to gold sources, transport mechanisms and concentration processes.

WORLDWIDE RECOGNITION

The Society of Economic Geologists, a world-leading scientific association, noted that the TGI synthesis gold volume published in 2015 was *"the most significant volume on the geology and genesis of gold deposits published during the past decade, providing geoscience information critical for geologists planning their exploration strategies in any environment and should be in every geologist's library."*

The Amaruq discovery exemplifies the significance and value of the data and knowledge created via governmental geoscientific initiatives in supporting exploration. GSC-driven, theme-targeted and mapping initiatives, such as the TGI program, have provided (and are still providing) priceless knowledge and tools to further aid in various aspects of mineral exploration in emerging mineral districts such as Nunavut."

– Olivier Côté-Mantha (Principal Evaluation Geologist) and Denis Vaillancourt (Exploration Manager, Canada), Agnico Eagle Mines Limited

CANADA'S NEWEST GOLD MINING DISTRICT

New public geoscience knowledge generated by TGI has helped Canada's newest gold mining district in the Kivalliq region of Nunavut to expand. Agnico Eagle Mines Limited began production at the Meadowbank mine in 2010 and in the Meliadine district in 2019. Production is expected to begin at the Amaruq deposits in late 2019.

Previous models used to predict the size, shape and grade of the deposits in this district assumed that the ore zone followed the folds of the Banded Iron Formation (BIF) host rocks; however, lower than expected gold recovery caused mine geologists to question this model.

Structural mapping and geochronology work by TGI scientists, students, and collaborators identified that the distribution of the gold in the district is controlled by a complex arrangement of faults and folds that developed over millions of years as the rocks underwent changes in pressure and temperature. This discovery improved the search criteria used to find new deposits in the district and exploration models used to look for BIF-hosted gold deposits around the globe.

JOINT RESEARCH TESTS BIG IDEAS

TGI gold research conducted with collaborators at the British Columbia and Yukon Geological Surveys is examining the relationships between gold mineralization at the Llewellyn fault in northern British Columbia and the Tally Ho shear zone in southern Yukon Territory.

New field observations coupled with high-precision geochronology indicate there are two spatially overlapping gold mineralizing events of different ages and styles. This finding matches the timing and structural framework for several gold deposits throughout British Columbia, as well as the Juneau gold camp in Alaska, suggesting a similar ore forming process. Similar features and structural controls on gold deposits are recognized elsewhere and indicate that there are fundamental, common, ore-forming processes that were repeated through time and space.

NICKEL-COPPER-PLATINUM GROUP ELEMENTS

Major nickel-copper-platinum group element (Ni-Cu-PGE) sulphide deposits, such as Canada's world-class Voisey's Bay deposit, are hosted by relatively small mafic or mafic-ultramafic intrusions that are the remnants of very large magmatic events on the scale of thousands of kilometres originating in Earth's mantle. Such high-volume magmatic events are commonly associated with the rifting and breakup of continents.

By studying the location, composition, age and shape of these mafic and ultramafic rocks and their host intrusions, their associated ore deposits in Canada and globally and their relationship to these global magmatic events, TGI scientists have built a clearer picture of when, where and how these valuable deposits form.

> *The excellent work by the GSC through the Targeted Geoscience Initiative has significantly advanced our understanding of the geology in the Ring of Fire, which ultimately helps explorers find more deposits in this incredibly well endowed mineral terrane."*
>
> \- Ryan Weston, Vice President Exploration, Noront Resources

ZOOMING IN TO ZOOM OUT

Many significant Ni-Cu-PGE deposits in Canada and around the world are a similar age. Researchers have known for decades that very large-scale magmatic activity is responsible for Ni-Cu-PGE ore deposit formation. However, the evidence linking many of these deposits in time and space was tentative and speculative and as yet unsupported with robust rock dating work.

To test these relationships, new isotopic uranium-lead dating has been completed under TGI on a linear belt of mafic-ultramafic rocks known as the Raglan Trend in northern Quebec. The dates were compared to ages of rocks from elsewhere in Canada and around the world. Ongoing geochemical, petrological and geochronological analyses will test relationships between feeder dykes, intrusive sills and lava flows to reveal the timing and spatial distribution of the magmatic plumbing systems responsible for these rich deposits.

CONNECTING CONTINENTS

TGI research has highlighted some surprising connections between the rocks that make up Canada's three-billion-year-old Superior Craton and mineral-rich cratons of similar age in southern Africa, Western Australia and the Baltic Shield.

New, high-precision dating results have redefined the stratigraphy and tectonic setting of the Circum-Superior Belt, a major mineral belt that encircles the Superior Craton from Manitoba to northern Quebec and into Labrador and the Lake Superior area of Ontario. Age data from rocks in the Circum-Superior Belt, the deformed margins of the larger Superior Craton, correlate with continental fragments elsewhere in the world that were dispersed through the processes of plate tectonics. This TGI research is helping to identify the original rifted margins, allowing for a global-scale understanding of these systems.

NEW MODEL FOR CHROMITE DEPOSITION IN THE RING OF FIRE

The Ring of Fire in northern Ontario is one of Canada's newest mineral districts, discovered in 2007. This succession of mafic to ultramafic intrusive rocks hosts world-class magmatic chromium, significant magmatic Ni-Cu-PGE and potentially economically significant, iron-titanium-vanadium mineralization. Future chromium production from the Ring of Fire region could position Canada as one of the five leading producers worldwide; however, improved scientific knowledge of the origins of these commodites is required to support exploration.

Working closely with exploration and mining companies in the area, the TGI research team has developed a new model for the formation of chromite deposits in the area. By studying the textures and geochemistry of the rocks encountered in drill cores and comparing deposits in the Ring of Fire to other significant chromite deposits elsewhere in the world, the TGI research team has proposed that the thick layers of chromite mineralization likely formed by partial melting of surrounding rock and mixing with magmas of specific chemical compositions.

DEEPER POTENTIAL IN SUDBURY

A giant meteorite impact 1,850 million years ago triggered the formation of some of the world's largest Ni-Cu-PGE magmatic sulphide deposits in the Sudbury area.

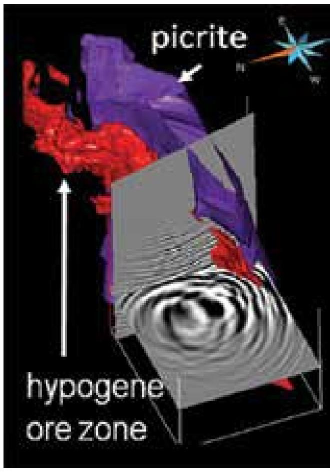
In collaboration with geologists at the Ontario Geological Survey, TGI researchers and students have enhanced geological knowledge of the Sudbury mining district. Their updated geological maps and cross sections cover the district, the deformed remnants of the meteorite impact crater and its giant melt sheet—a blanket of magma at the surface produced by the intense heat of the impact.

These new products are important because, historically, mining has targeted the base of this impact-generated melt sheet, where dense, metal-rich sulphide melts pooled and cooled into the ore deposits mined today. However, in recent years, some of the mining and exploration focus has shifted to metal-rich sulphide veins that reach deeper into fractures in the rock immediately below the melt sheet. TGI researchers suspect that the movement of the sulphide melts through these rocks can be modelled and that this sulphide melt percolation process may have repeated itself, creating veins even deeper that could be mined in the future.

PORPHYRY

Porphyry deposits are the world's most important sources of copper and molybdenum and major sources gold and silver. These enormous, low-grade deposits form in association with large intrusions, such as granite, and are usually mined as open pits over several decades. Understanding how these deposits form and their complex internal structure and developing new exploration methods are critical to finding new copper deposits to extend operations at existing mines in Canada.

NEW TECHNOLOGY EXPLORES DEEP ROOTS AT NEW AFTON



Complete porphyry systems have not been imaged from top to bottom, resulting in knowledge gaps regarding their architecture. At the New Afton copper-gold mine in British Columbia, TGI researchers and staff from New Gold Inc., the operator of the mine, completed one of the first applications of Distributed Acoustic Sensing (DAS) - Vertical Seismic Profile (VSP) for mineral exploration. The goal of this research was to create a picture of the geological structure of this copper-gold porphyry deposit below the surface, deeper than other methods are typically able to achieve.

Mining commenced at New Afton in 2012, which enabled the collection of seismic data using holes drilled underneath the mine's abandoned open pit. The TGI team used a fibre optic cable rather than traditional geophones as an innovative method to collect high-quality seismic data from the site. The 3D models developed from the seismic data, such as the one shown in the adjacent figure, provide an unprecedented view of an entire porphyry system, including its deeper levels. The ability to visualize the entire structure of the ore deposit and its relationship to surrounding rock provides clues about how mineralization occurred. The results of this leading-edge research will support future exploration activity on porphyry deposits and mining operations.

Overburden Drilling Management is uniquely positioned within our industry to see the positive effects of your research, firsthand. We can attest that your work—surficial mapping and indicator mineral research—has led to more mining companies using till sampling and indicator mineral surveys in their exploration plans."

– Don Holmes, President, Overburden Drilling Management Limited

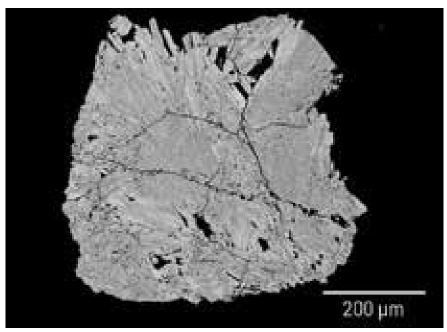
PORPHYRY INDICATOR MINERALS IN SEDIMENTS

TGI researchers are refining a cost-efficient exploration tool for finding porphyry copper deposits: indicator minerals in glacial and stream sediments. Certain minerals found in sediments on the land surface, by their chemical composition and abundance, can indicate that a porphyry copper source may be nearby. Because these copper indicator minerals are widely distributed over a large area, they create a much larger exploration target than the mineralized bedrock itself.

The minerals tourmaline, epidote and zircon were examined from samples of glacial and stream sediments collected near five porphyry copper study sites in British Columbia–Gibraltar, Mount Polley, Highland Valley Copper, Woodjam and Casino. The sediments were analysed using equipment and methods available at commercial laboratories so that the procedures can be readily adopted by industry. Once the minerals are identified, they can be traced to their source rock by following the path of glaciers or the drainage basin of streams.

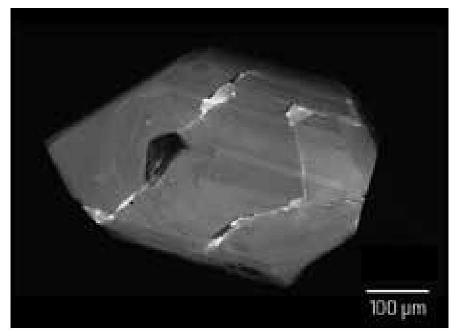
Tourmaline

MANY HIGH-PROFILE COMPANIES THAT PROVIDE GEOPHYSICAL AND GEOCHEMICAL SERVICES TO THE MINERAL EXPLORATION AND MINING INDUSTRY IN CANADA USE AND RECOMMEND THE INTEGRATED ANALYTICAL LABORATORY TECHNIQUES AND GEOPHYSICAL PROCESSING METHODS DEVELOPED UNDER TGI.



Epidote

Tourmaline and epidote may be used as indicators of undiscovered porphyry copper deposits. The epidote and tourmaline grains shown in the above images were recovered from glacial sediments near porphyry copper deposits in British Columbia. These two minerals form in the alteration zones of porphyry deposits and could make good indicator minerals, but they also form in other environments. How can we tell the difference? Preliminary results show that epidote and tourmaline associated with porphyry copper deposits have a different geochemical composition to the same minerals formed in other rocks, such as certain volcanic rocks.



Zircon

The zircon grain shown above was extracted from the intrusive rocks at the Gibraltar porphyry copper-molybdenum deposit in British Columbia. Only a small number of granite intrusions host porphyry copper mineralization, but the composition of zircon, a mineral present in intrusive rocks, can potentially be used to discriminate between fertile (potentially hosts copper mineralization) and non-fertile (unlikely to host copper mineralization) intrusions. Zircon grains recovered from glacial sediments with a positive fertility signature—such as trace amounts of certain elements—can be used to locate intrusions with a potential to host porphyry copper mineralization.

URANIUM

Canada is the world's second-largest uranium producer and all of Canada's uranium ore comes from Saskatchewan's Athabasca Basin, where the highest-grade deposits in the world are located. For decades, it was thought that Saskatchewan's uranium deposits were confined to sedimentary basins but new discoveries by TGI researchers and industry has updated uranium deposit formation models and highlighted new areas for uranium exploration underneath the basins and beyond the present-day basin margins.

> *It is exciting to have the Patterson Lake Corridor, a new exploration trend, being studied with good datasets like these. It is great to see how the GSC and TGI have responded to this opportunity to have an impact where study is needed. We look forward to seeing the results that come out of these geophysical surveys and hearing about the latest findings at workshops."*
>
> – Gerard Zaluski, Manager, Exploration Geology, Cameco Corporation

CANADIAN URANIUM

Under Canada's nuclear non-proliferation policy, Canadian uranium can be used only for peaceful purposes. While some of that uranium is used domestically for power generation at nuclear reactors in Ontario and to produce medical isotopes, most uranium mined in Canada is exported. For example, Canada contributes approximately 75% of the world's Cobalt-60, which is used to sterilize single-use medical supplies globally.

CHANGING THE WAY EXPLORERS OPERATE

TGI researchers have joined geologists and students from the Saskatchewan and Alberta Geological Surveys, eight industry partners and collaborators from three universities to update the regional geology, structural-tectonic settings and ore deposit model of the Patterson Lake corridor in Saskatchewan. Initial results reveal significant differences in uranium ore genesis that indicate changes are required to the existing exploration model applied in Proterozoic basins in Canada and abroad.

Data and knowledge generated through TGI research has been distributed publicly through annual workshops with collaborators, open file reports and data releases. In return, collaborators have helped to guide TGI researchers to new discoveries flowing from TGI studies.

UNDERSTANDING THE PATTERSON LAKE CORRIDOR

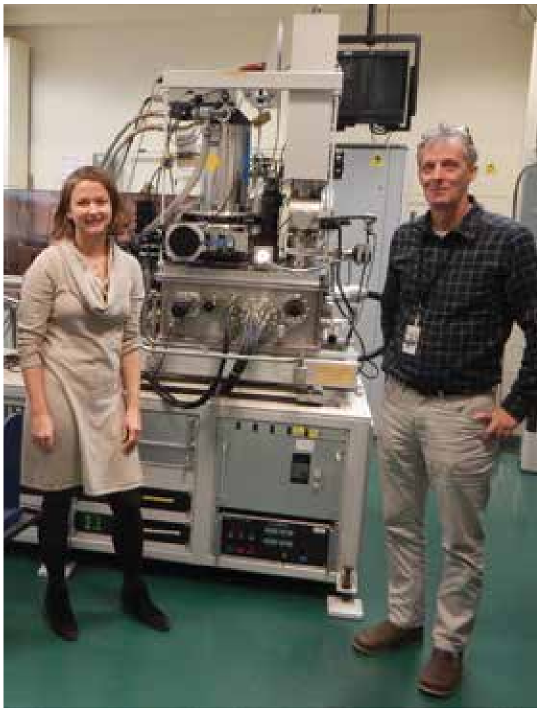
In 2012, two large, high-grade uranium deposits were discovered in basement rocks of the Patterson Lake corridor on the southwestern margin of the Athabasca Basin, Saskatchewan. Little was known about how or why these newly-discovered deposits had formed at depth outside of the basin. The companies working in the area encouraged and supported TGI researchers to acquire new data and develop new methods to understand why these deposits occur where they do.

Integration of geophysics, geochemistry and geochronology

Along the corridor, the deposits are associated with regional fault systems, so researchers used new geochemical, geophysical and geochronology methods to identify the source of the uranium, the ore fluid pathways and the causes of uranium deposition from the fluids.

One TGI study integrated visible-near infrared-shortwave infrared (VNIR-SWIR) spectroscopy, gamma-ray logs and magnetic susceptibility measurements taken on drill cores to investigate the role that reactivated faults played in the formation of these deposits.

Another study used new metal isotopes and whole rock geochemistry to improve understanding of the complex chemistry of the system and the sources of heat and metal that control ore deposition. A TGI geochronology study also used argon-argon dating, low temperature thermochronology potassium-argon dating, fission track data in apatite and hydrothermal alteration minerals to link the timing of fault movements to ore formation. Airborne and ground geophysical surveys collected new data along the corridor and western Athabasca Basin that was linked with geological, structural and geochemical data to enhance understanding of the subsurface geology and structure to depths of 50km below the surface.



BASE METALS

RE-WRITING THE TEXTBOOKS

New models developed under TGI are re-writing textbooks on base metal deposit formation in Canada. Volcanogenic massive sulphide (VMS), sedimentary exhalative (SEDEX) and hyper-enriched black shales (HEBS) are three important mineral deposit types that formed by deposition of metals on the seafloor. They are important sources of base metals, including copper, lead, zinc and other common and critical metals.

For many years, our understanding of the way these deposits formed was thought to be well understood and exploration models for these deposits were mature and rarely questioned. However, research carried out within TGI has radically changed what we know about their formation, and how and where we explore for new deposits.

A NEW MODEL FOR SEDEX FORMATION

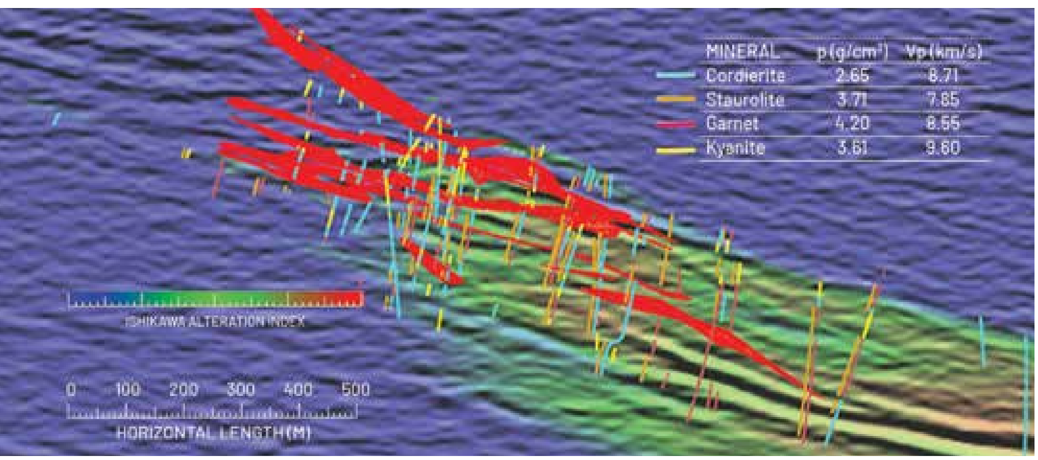
For more than 30 years, the accepted model for SEDEX deposit formation involved venting of fluids bearing lead, zinc and iron into an isolated, stagnant ocean basin with no oxygen and free hydrogen sulphide in the water. The metals bonded with the hydrogen sulphide and metal sulphides rained down to form sheet-like bodies of lead and zinc mineralization.

New collaborative research conducted by TGI involving mining and exploration companies, research organizations and universities has shown that a very different geochemical cycle is responsible for their formation. Using modern techniques to examine the geochemistry of rocks collected from the Howard's Pass District in Yukon's Selwyn Basin—a metallogenic province known for its world-class, lead-zinc SEDEX deposits—researchers discovered that they form in oxygenated waters, where mineralization formed in the subsurface muds with organic matter playing an important role in the process.

The outcomes of this research have influenced the way explorers now look for SEDEX deposits. In the past, they looked for rocks of a specific age with certain geochemical characteristics to fit the old model. Now other rocks of certain ages, geochemical compositions and tectonic settings around the world may be prospective for sedimentary-hosted lead zinc deposits

INNOVATION GENERATES NEW OPPORTUNITIES FOR VMS TARGETS

By integrating 3D seismic data with physical rock properties from drill cores, geochemistry and mineralogy of the Lalor VMS deposit in Manitoba, TGI researchers discovered that the seismic data can detect sulphide ore and the conduits of mineralized fluid that once fed metals to the deposit from beneath the ocean floor. This is remarkable, considering that multiple geological events broadly deformed and recrystallized the Lalor VMS deposit much later in its history. This innovative methodology provides industry with new opportunities for targeting VMS deposits at greater depths. The figure below shows an example of a model that combines multiple datasets from the Lalor site to allow researchers to examine the structure and formation processes of ore deposits.



CLUES TO BURIED MINERAL DEPOSITS HIDING IN FLUID INCLUSIONS

Tiny bubbles of liquid and gas, often called fluid inclusions, trapped within quartz crystals from the Windy Craggy VMS deposit in northwestern British Columbia contain fossilized samples of the mineralizing fluid. These were analyzed for their trace element contents to test the premise that magmatic products, such as fluids or vapours, contributed metals to this world-class deposit. Such information may potentially be used to find similar deposits.

TGI researchers found that the presence of a suite of certain diagnostic elements in the inclusions likely indicates magmatic input. Such information may potentially be used to explore for deposits for a particular trace element content, such as tin, indium or gold within a favourable rock package.

CRITICAL METALS IN CANADA'S YUKON

New field observations and age determinations carried out by TGI researchers and collaborators on hyper-enriched black shale (HEBS, also referred to as metalliferous shale) deposits located in the Selwyn basin, Yukon, have re-defined the accepted genetic model for these deposits in Canada and abroad.

HEBS deposits are hosted in similar rocks as SEDEX deposits: organic, carbon-rich, fine-grained, sedimentary rocks. The metal-rich rocks and their host rock stratigraphic sections are geographically widespread across northwestern Canada. Samples collected across Yukon Territory have been subject to new microanalytical techniques that produced geochemical and age data that were not possible 20 to 30 years ago.

The researchers were able to determine that all of the elements that are in HEBS or metalliferous shales, came only from seawater, and not from a meteorite impact or seafloor hydrothermal vents, as some researchers previously thought, and mineralization blanketed large areas.

Understanding the formation of these deposits, and recognizing the parameters necessary for their discovery, are vital because they can constitute a resource of so-called critical elements, such as vanadium, cobalt, molybdenum, rhenium, antimony, uranium, selenium and platinum group elements. Indeed, these elements are of paramount importance to the Canadian economy and future innovation in Canada.

For more information on the Geological Survey of Canada's Targeted Geoscience Initiative at Natural Resources Canada, please contact TGI at NRCan.tgi-igc.RNCan@canada.ca or visit the TGI webpage: https://www.nrcan.gc.ca/earth-sciences/resources/federal-programs/targeted-geoscience-initiative/10907

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> *"Public geoscience is the lifeblood of exploration."*
>
> – The Prospectors & Developers Association of Canada