British Columbia Geological Survey annual program review 2021-2022

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Executive Summary

This paper provides an overview of current British Columbia Geological Survey (BCGS) applied geoscience activities and highlights key findings from 2021 projects. Headquartered in Victoria, the Survey is part of the Mines, Competitiveness and Authorizations Division in the British Columbia Ministry of Energy, Mines and Low Carbon Innovation. The Survey generates geoscience knowledge and data to inform land use and resource management decisions, and to support the growth of British Columbia as a competitive jurisdiction for mineral exploration.

The Cordilleran Geoscience Section of the Survey conducts field and office research, including bedrock and surficial geology mapping programs, regional geochemical surveys, and targeted mineral deposit studies. The past year saw further progress of multi-year mapping and applied research across the province, boosted by the return of fieldwork from July through to late September as pandemic-related restrictions eased. Highlights included mapping in the Kitsault area in the northwest and the Kaslo Lake-Lardeau area in the south, and the deployment of remotely piloted aircraft systems (RPAS) to gather geophysical data in the central part of the province. Critical minerals, an emerging topic of importance in the context of material requirements for low-carbon technologies, provided the focus for a three-day online workshop hosted by the Survey in collaboration with the Geological Survey of Canada, the United States Geological Survey, and Geoscience Australia. The workshop attracted more than 700 participants from the geoscience community across the world and demonstrated the importance of minerals system research in evaluating critical mineral resources.

Responsible for maintaining and developing provincial geoscience databases, the Resource Information Section disseminates data online through MapPlace. Information managed by the team includes traditional geological maps together with thematic studies and reports, geochemical, geophysical, and geological databases, plus information such as MINFILE, COALFILE, Mineral Assessment Reports (ARIS), and Property File. These databases also support development of next-generation mineral potential assessments using machine learning, which is now a major focus for the Survey to support land use and resource planning initiatives.

The Mineral Development Office (MDO) provides investment intelligence to government and global business, publishing the annual Provincial Overview of Exploration and Mining in British Columbia volume, and includes three Regional Geologists who track minerals activity across the province.

1. Introduction

This paper provides an overview of current British Columbia Geological Survey (BCGS) applied geoscience activities and highlights key findings from 2021 projects. Headquartered in Victoria, the Survey is part of the Mines, Competitiveness and Authorizations Division in the British Columbia Ministry of Energy, Mines and Low Carbon Innovation. As the steward of geoscience and mineral resource information in the province, the Survey has an important role in stimulating activity, attracting investment, informing decisions through technical information, and providing continuous research based on more than a century of corporate memory.

The province is endowed with significant natural resources including metallurgical coal, base and precious metals, and industrial minerals. These deposits are intimately tied to the tectonic evolution of the Canadian Cordillera, which continued from protracted supercontinent breakup starting about 1600 million years ago to accretionary processes that operate today as Pacific Ocean crust slides beneath Vancouver Island. In the northeast part of the province, the Western Canadian Sedimentary basin hosts significant petroleum hydrocarbon resources.

The Survey is the primary repository for provincial geoscience knowledge. Maps, reports, and databases are freely available online to inform First Nations and stakeholder groups including local communities, the minerals industry, public safety agencies, environmental scientists, research organizations, and government agencies. Active Survey research programs (Fig. 1) continue to define the geological evolution and natural resources of the province, generating knowledge and data to support land use and resource management decisions that balance economic, environmental, and community interests. A particular focus is providing public geoscience to support the growth of British Columbia as a competitive jurisdiction for mineral exploration. Not only does this include supporting industry, but also providing mineral resource information that is essential for informed land use decisions by government and, increasingly, from communities. Linked to the provision

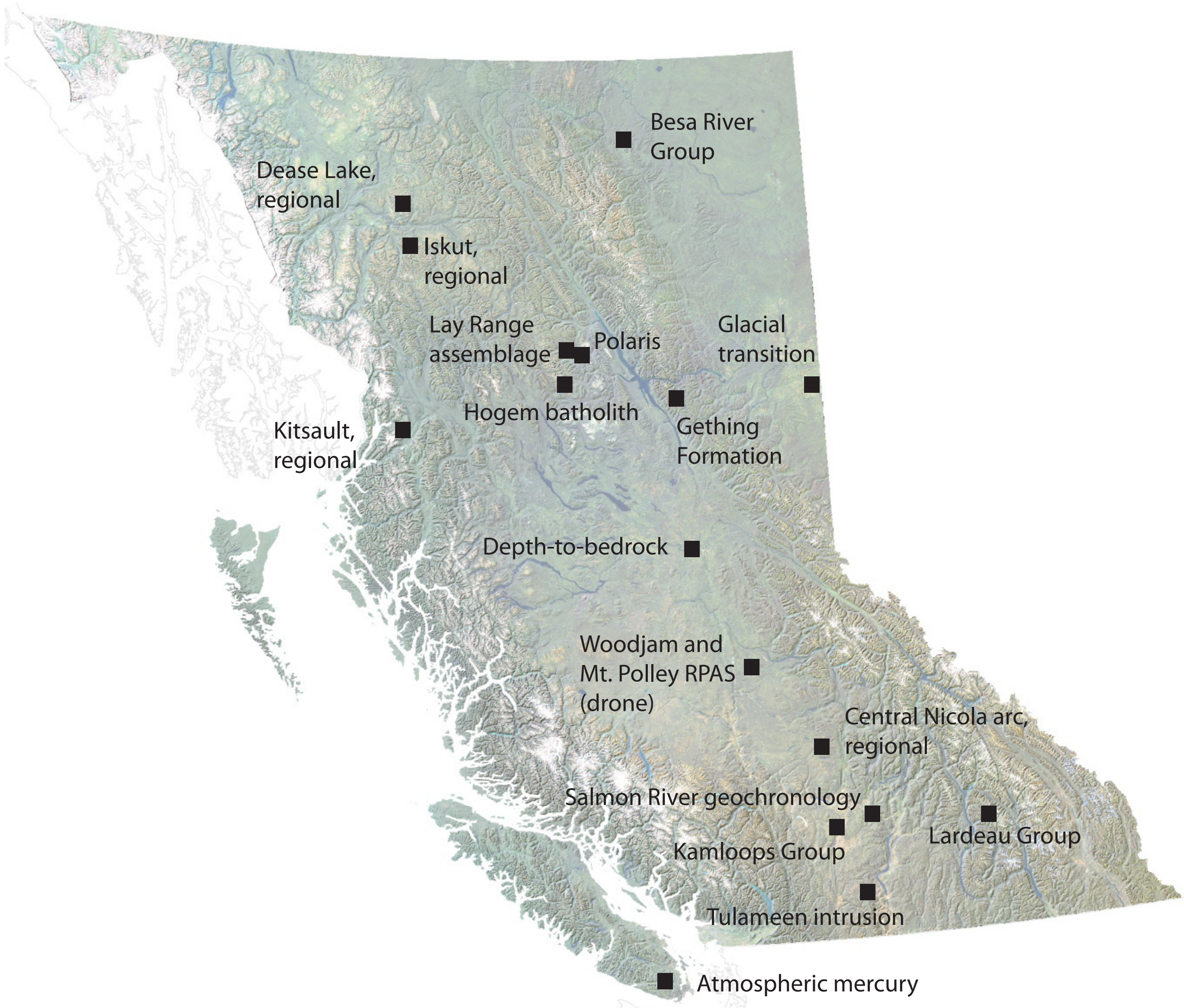


Fig. 1. British Columbia Geological Survey projects in 2021.

of geoscience information, the transformation of historic geoscience information to digital formats and databases requires coordinated effort as an ongoing, multi-year initiative.

The Survey is staffed by 35 employees, although several positions are vacant and are currently in the process of being filled. The BCGS consists of three sections: 1) Cordilleran Geoscience; 2) Resource Information and 3) the Mineral Development Office (based in a Vancouver satellite office and with Regional Geologists across the province). The Cordilleran Geoscience Section generates new knowledge through field- and desk-based research activities including bedrock and surficial geology mapping programs, regional geochemical surveys, and targeted mineral deposit studies. Section team members manage in-house laboratory facilities, curate the provincial sample archive, and build capacity through contract employment and training of geoscience assistants, typically undergraduate and graduate students. The Resource Information Section is responsible for maintaining and developing provincial geoscience databases and disseminating data online through MapPlace, the BCGS geospatial web service. The Resource Information Section is also responsible for collecting, evaluating, approving, and archiving mineral and coal exploration assessment reports submitted by industry to maintain titles in good standing. The Mineral Development Office (MDO) provides investment intelligence to government and global business, publishing the annual Provincial Overview of Exploration and Mining in British Columbia volume (e.g., Clarke et al., 2022), and includes three Regional Geologists who track minerals activity across the province (two positions are currently vacant).

The Survey welcomed Nate Corcoran as Regional Geologist for the Northeast and North Central regions in 2021. However, the Survey endured a challenging year with several retirements and resignations. Larry Jones retired as Director of the Resource Information team in August, with Yao Cui covering this position on an acting basis for the remainder of the year. In addition, the Cordilleran Section lost Graham Nixon and Janet Riddell to retirement. Larry, Graham, and Janet will be much missed by their colleagues and we wish them happy retirements after decades of service, although Graham remains connected with Emeritus status. The year also saw Deanna Miller, Sarah Meredith-Jones, and Sean Tombe leave the Survey for fresh opportunities. Jenny Boulet left for maternity leave in September and was temporarily replaced by Lisa Giesbrecht. The Survey anticipates a busy year for recruitment in 2022 as various competitions are launched to fill these vacancies.

The global Covid-19 pandemic again affected Survey operations in 2021; staff continued to work from home for much of the year. The gradual relaxation of public health restrictions in the spring and early summer allowed relatively late planning and execution of some field programs between mid July and late September. External laboratory services continued to be affected in many cases, leading to delays in analytical testing and processing of results. Despite these challenges, Survey staff maintained a full workload and publication output (Fig. 2).

2. Partnerships

The Survey adopts a collaborative approach to extend the scope and content of public geoscience while minimizing the risk of duplicative work. The Geological Survey of Canada (GSC) is an established partner; 2021 saw multiple discussions between BCGS and the GSC Geoscience for Energy and Minerals (GEM)-GeoNorth program, to align research interests and ensure coordinated engagement with First Nations in northern British Columbia. Active collaboration under GEM-GeoNorth during 2021 has focussed on provision of BCGS archive samples and expertise to support assessing the distribution of metallic mineral systems in the northern part of the province. In addition, BCGS has agreed to collaborate on a developing project that aims to examine low-temperature thermochronology to support exploration for hydrothermal ore systems at regional and deposit scales.

In collaboration with GSC, the United States Geological Survey, Geoscience Australia, and the Geological Association of Canada (Pacific section), BCGS organized and convened an online international workshop, ‘Critical minerals: From discovery to supply chain’ (Fig. 3). This three-day workshop, which attracted more than 700 participants drawn from a global audience, emphasized the important of mineral systems geoscience in developing low-carbon technologies to reduce greenhouse gas emissions and mitigate climate change. Each of the six sessions consisted of pre-recorded presentations followed by live Q&A slots that generated significant engagement with the audience, underlining the increased profile of critical minerals as a major geoscience topic.

The Survey signed an agreement with Newcrest Mining Limited in 2021 to facilitate extensive lithogeochemical analyses of 1000 igneous rock samples collected in northwestern BC and stored in the BCGS archive facility. Under the terms of the agreement, analyses will be undertaken using both total (fusion) and ‘4-acid’ digestion coupled with ICP-ES and ICP-MS techniques. The resulting dataset will be published by BCGS in 2022. This project underscores the value added to geoscience in the province by the archive facility and may provide a blueprint for future collaborative research and public-private partnerships using archived samples.

3. Cordilleran Geoscience Section

Section geologists collect fundamental geoscience data through single- and multi-year field-based programs complemented by laboratory and office studies, including regional-scale mapping, mineral deposit studies, and development of new mineral exploration methods. Expertise encompasses tectonics, structural geology, stratigraphy, petrology, metallogeny, coal deposits, Quaternary and surficial geology, critical minerals, and geochemistry.

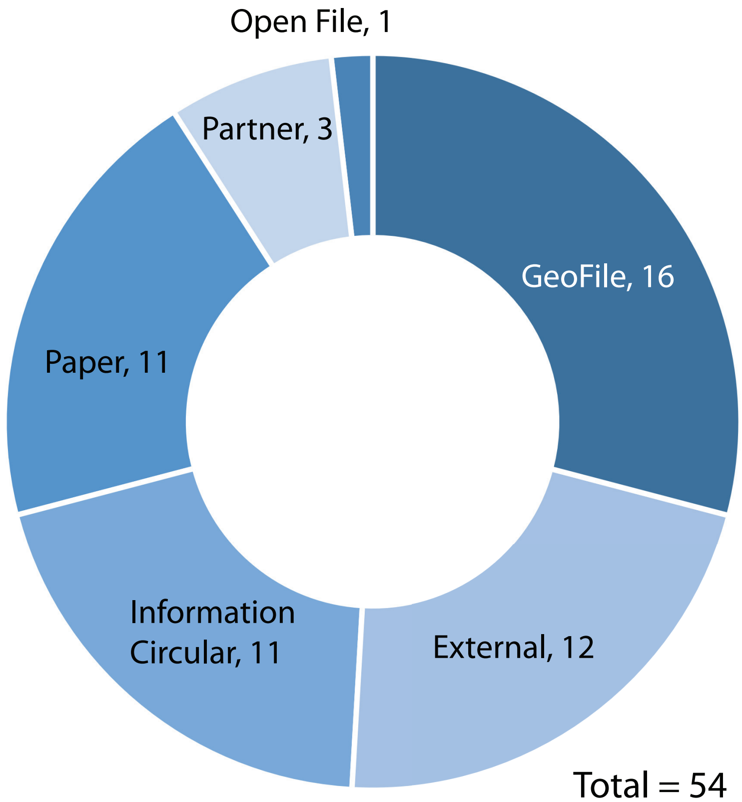
Engagement with First Nations communities is a priority for the Survey. As summer field projects are planned, liaising with First Nations is started at the earliest opportunity. During 2021, the evolving circumstances of the pandemic and wildfires across large swathes of British Columbia added extra impetus for contacting communities. As an example, planned fieldwork using a remotely piloted aircraft system (RPAS) in the Highland Valley area was suspended due to local concerns about wildfires. The project instead focussed on areas near Woodjam and Mount Polley (see section 3.2.), where discussions with the local First Nations Stewardship Forum highlighted shared interests. BCGS is committed to sharing geoscience information with all British Columbians and is expanding efforts to bring geological and mineral science to communities.

The following sections highlight ongoing and recently completed research activities aided by the partial resumption of fieldwork across the province.

3.1. Mapping, regional synthesis and compilation

Mapping is a core element of Survey and Cordilleran Section programs. The Survey delivers two key products: traditional published maps in the form of PDF files with accompanying research papers; and updates to the provincial digital geology database, which ultimately feeds into MapPlace as BC Digital Geology (Fig. 4). The digital geology database is an instrumental component of modern mineral potential assessment methods being developed by the Survey to inform land-use planning policies in the provincial government (see section 3.2.).

The past year also saw detailed planning for a multi-year project to integrate surficial geological maps from across the province into the digital geological database; work will begin in 2022 with the an inventory of published maps and data sources.



Papers*: This series is reserved for reviews and final thematic or regional works. Geological Fieldwork, our annual review of field activities and current research, is released as the first Paper of each year.

Geoscience Maps: This series is the BCGS vehicle for publishing final maps.

Open Files: These maps and reports present the interim results of ongoing research, particularly mapping projects.

GeoFiles: These publications enable rapid release of extensive data tables from ongoing geochemical, geochronologic, and geophysical work. As such, they serve the same function as data repositories provided by many journals, providing immediate access to raw data from specific projects.

Information Circulars: These publications provide accessible geoscience information to a broad audience in government, industry, and the general public. Included in the Information Circular series are the annual Provincial Overview of Mining and Exploration, **Exploration and Mining in British Columbia, and the Coal Industry Overview.

Contributions to partner publications: This category includes reports, maps, and other products published by another agency such as the Geological Survey of Canada or Geoscience BC, but have received contributions from British Columbia Geological Survey staff.

External publications: These are contributions to the peer reviewed literature and published in a recognized national or international scientific journal.

*The count refers to the total number of articles authored by BCGS personnel in a volume.

**Although five articles are included in Exploration and Mining in British Columbia, it is counted as a single volume.

Fig. 2. Types and numbers of publications produced by the British Columbia Geological Survey in 2021.

3.1.1. Northwest British Columbia

Northwest British Columbia hosts significant base- and precious-metal mineral deposits, notably in an area between Iskut and Stewart colloquially referred to as the 'Golden Triangle'. An ongoing multi-year Survey program will continue to expand regional bedrock mapping coverage to support mineral exploration; understanding the stratigraphic, magmatic, structural, metallogenic, and tectonic framework of this region continues to advance.

In support of Survey mapping programs in northwestern British Columbia, Nelson et al. (2021) provided raw U-Pb zircon datasets for 18 samples collected from between Dease

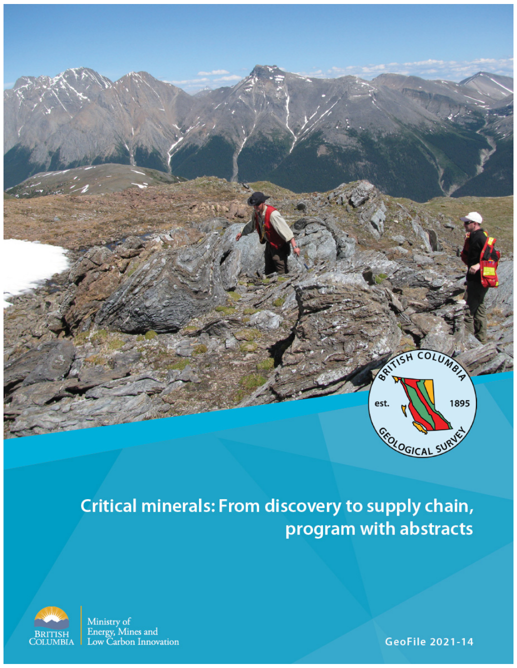


Fig. 3. Critical minerals virtual workshop held in November 2021. See British Columbia Geological Survey (2021).

Lake and Kitsault to constrain the age of intrusive and stratified protoliths, age and affinity of sedimentary sources, and timing of fault-related shearing.

Hunter et al. (2022) continued a multi-year project in the Kitsault River area, south of Stewart, presenting a detailed facies analysis of the local Hazelton Group volcano-sedimentary depositional system, providing new U-Pb zircon geochronologic data, and evaluating the implications for mineralizing systems. At the southern end of the Golden Triangle, the area hosts numerous Ag-rich volcanogenic massive sulphide (VMS) and epithermal deposits similar to those of the Eskay rift ca. 150 km to the northwest. Resolving the age and affinity of late Early to Middle Jurassic volcano-sedimentary Hazelton Group host rocks (Fig. 5) is key to understanding the metallogeny of the Kitsault area. A new U-Pb detrital zircon maximum depositional age (ca. 188 Ma) from upper Hazelton Group epiclastic rocks at the Sault Zn-Pb-Ag-Sr showing suggests that the VMS mineralization in the Kitsault River area may be slightly older than the ca. 174 Ma Au-rich VMS systems of the Eskay rift and indicates that significant precious metal-bearing VMS and/or epithermal systems formed well outside the main Eskay rift corridor in mainly volcaniclastic rocks.

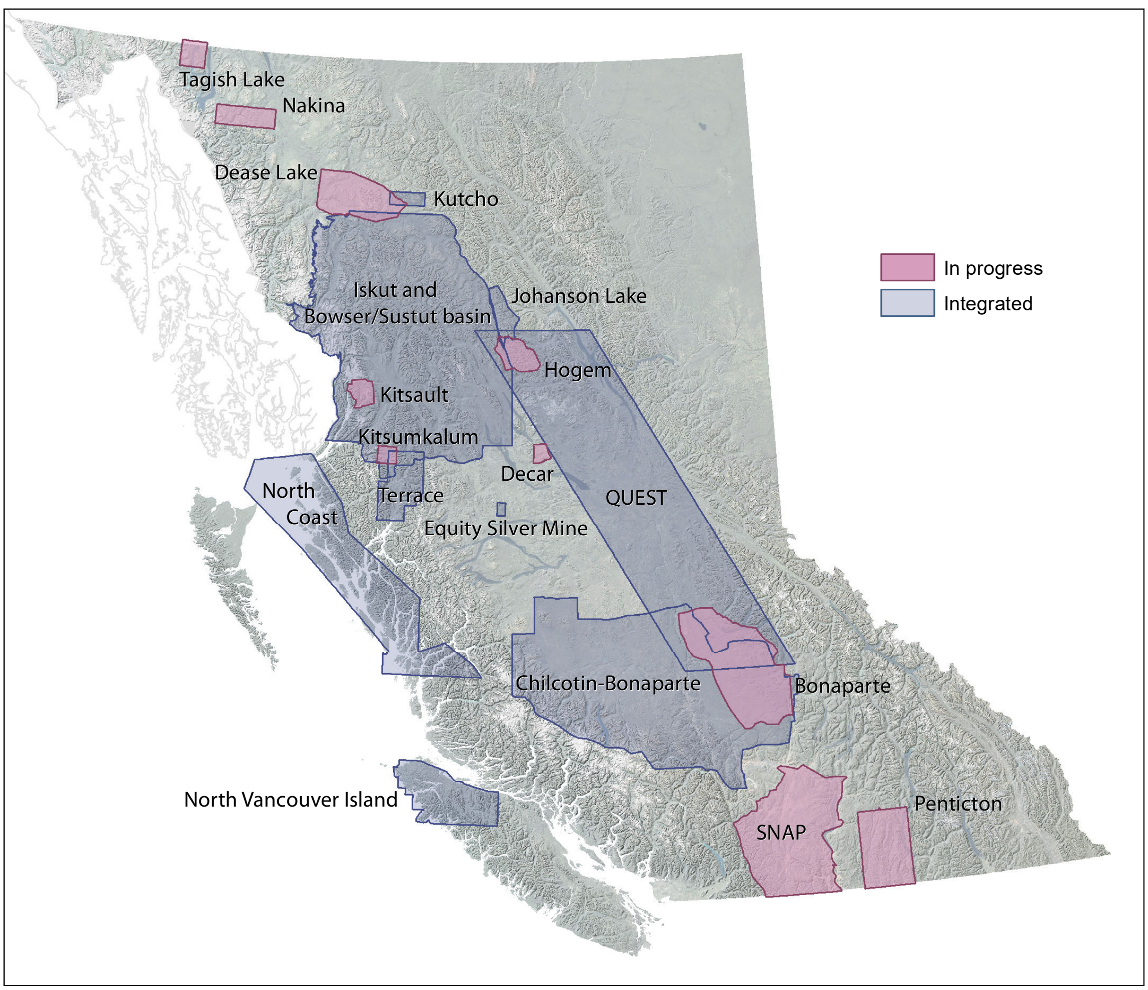


Fig. 4. BC Digital Geology, integrated and in progress.

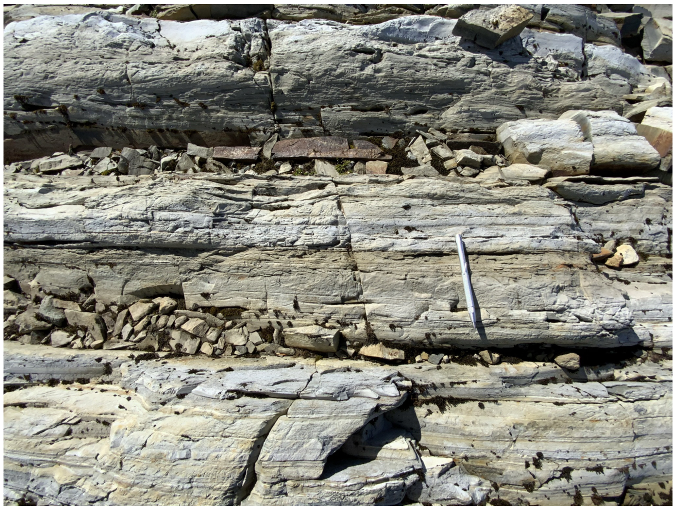


Fig. 5. Interbedded fine and course tuff from facies 6 of the upper Hazleton Group, Kitsault area. U-Pb detrital zircon analysis yielded a maximum depositional age of ca. 168 Ma. See Hunter et al. (2022).

In the Dease Lake area, ongoing activities are geared towards publication of a 1:100,000-scale Geoscience Map, a final update to the BC Digital Geology database, and a GeoFile with geochronological and lithogeochemical data. The Geoscience Map, scheduled for publication in early 2022, will show the bedrock geology of 5000 km^2 between the community of Dease Lake and the Stikine River, based on BCGS mapping carried out between 2011 and 2018. Rocks in the area are mainly in the Stikine terrane, a Paleozoic to Mesozoic island arc that was deformed in the latest Triassic to Early Jurassic before accreting to Ancestral North America in the Middle Jurassic. The area experienced repeated calc-alkalic to alkalic, arc magmatism from the Middle Triassic through the Late Jurassic. This includes Tsaybahe group volcanism (Middle Triassic), Stuhini Group volcanism (Late Triassic), and Stikine suite plutonism (Late Triassic). This magmatism was followed by latest Triassic deformation and a latest Triassic to Early Jurassic depositional and magmatic hiatus that corresponds to a significant collisional event between the Intermontane terranes. Subsequent upper Hazelton Group volcanism (Fig. 6; late Early to Middle Jurassic), Three Sisters suite plutonism (Middle Jurassic), and Snowdrift Creek suite plutonism (late Middle to Late Jurassic) formed during and after accretion of Stikinia and other Intermontane terranes to Ancestral North America. As a result of this protracted magmatic history, the area is prospective for intrusion-related magmatic-hydrothermal mineral deposits, as illustrated by the Gnat Pass porphyry copper deposit and numerous other porphyry, epithermal, and skarn prospects. Also in the Dease Lake area, Bouzari et al. (2021) examined porphyry-related advanced argillic-alteration in the Horn Mountain Formation (Hazelton Group).

Based on mapping, geochemistry, and U-Pb zircon geochronology, Stanley and Nelson (2022) recognized hitherto unappreciated Stuhini Group rocks (Fig. 7) in the past-producing Scottie gold mine area in the southern part

Fig. 6. Cliff-forming mafic volcanic rocks of the Horn Mountain Formation (upper Hazelton Group, Lower-Middle Jurassic) overlying recessive orange-weathering sedimentary rocks of the Spatsizi Formation (Lower Jurassic, upper Hazelton Group); Cake Hill pluton (Late Triassic) in foreground. Southeast of Dease Lake.

Fig. 7. Stuhini Group, lower fine-grained sedimentary-tuff unit. Interbedded argillite, plagioclase-rich, sandstone (with south-vergent fold), and limestone. See Stanley and Nelson (2022).

of the Golden Triangle, and a Hazelton Group stratigraphy that is comparable to that in the McTagg anticlinorium. The Stuhini Group volcanic rocks are highly potassic and of shoshonitic affinity, and zircons from a crystal tuff near the base of an upper volcanic unit yielded a crystallization age of ca. 214 Ma, providing new evidence of shoshonitic volcanism at the transition from main-stage Stuhini arc- back-arc activity into post-collision (Galore suite) magmatism. Zircons from a siltstone unit at the base of the Hazelton Group yielded a maximum detrital age of ca. 201 Ma, consistent with results from elsewhere in the Golden Triangle. Stanley and Nelson (2022) consider that the diverse metallogeny of the Golden Triangle resulted from collision-driven processes during Stuhini and Hazelton arc and back-arc development, drawing analogies to modern-day New Britain arc and Bismarck plate reorganization.

Colpron and Nelson (2021) published an updated review that summarized the physiography, neotectonics, crustal structure, geology, natural resources, and evolution of the northern Cordillera, and George et al. (2021) used U-Pb zircon geochronology tied to Lu-Hf isotope analysis to consider the Triassic-Jurassic magmatic and accretionary history of Stikinia and evaluate the nature and origin of basement to Stikinia.

3.1.2. Central, southern, and northeastern British Columbia

Bedrock mapping updates for the provincial database and MapPlace are ongoing for several areas of central and southern British Columbia (Fig. 4): southwest Quesnellia; Bonaparte Lake to Quesnel River; Hogem; and Decar. An update based on mapping outside of Survey programs in the Penticton area of southern British Columbia is also in preparation.

In August, a bedrock mapping project was initiated in the Lardeau area west of Kaslo Lake (Fig. 1). Rocks historically mapped as Lardeau Group (Fig. 8) are thought to have been deposited on or near the North American continental slope. In the Lardeau area, the basal unit is the Index Formation, a commonly fine-grained carbonaceous clastic package, generally considered to be Early Cambrian and overlain by mafic volcanic rocks of the Jowett Formation. In the study area, the Index Formation includes massive sulphide mineralization (Ledgend prospect) that may extend for many km, providing a regional exploration target for nickel, cobalt, and copper, all essential elements for low-carbon technologies.

Using conodont and U-Pb detrital zircon data, Schiarizza et al. (2022) document how the stratigraphic break above the Chapperon Group 50 km southeast of Kamloops includes not just a sub-Triassic unconformity but an extensive sub-Jurassic unconformity. In the Salmon River valley, an unconformity separates schists of the Chapperon Group (pre-Permian) from less deformed limestones and siliciclastic rocks previously considered entirely Triassic. Rocks above the unconformity were previously mapped as a single Triassic unit (the Salmon River succession), and the Salmon River locale was considered to be a prime example of the Permo-Triassic unconformity recognized at numerous localities throughout south-central British Columbia. Samples collected from basal limestones (Fig. 9) yielded conodonts that confirm a Late Triassic age for rocks immediately above the unconformity. However, U-Pb detrital zircon analysis of two sandstone samples indicate that the Salmon River succession is not a single Triassic unit. Detrital zircons from near the base of the siliciclastic rocks yielded a maximum depositional age of ca. 183 Ma, and a sample collected 4.5 km to the west yielded a maximum depositional age of 190 Ma. These data show that most of the Salmon River succession is Jurassic, and that a more extensive sub-Jurassic unconformity merges with the sub-Triassic unconformity. The Salmon River succession, as now defined, is tentatively correlated with the Hall Formation (Early Jurassic, Toarcian) of the Rossland Group.

Work on a multi-year mapping project in the northern part of Hogem batholith to better understand the origin and timing of batholith emplacement and base- and precious-metal mineralization continued with further $^{40}Ar/^{39}Ar$ work, a fluid inclusion study, and a detrital zircon study evaluating the nature of the basement to Stikinia. Ootes et al. (2022) present detrital zircon U-Pb, Lu-Hf isotope, and trace element data from the Lay Range assemblage, the lowest exposed lithostratigraphic unit of north-central Quesnellia. Fossil and field evidence indicates deposition of the lower sedimentary division (Fig. 10) during the Late Mississippian to Middle Pennsylvanian and of the upper mafic tuff division during the Middle Pennsylvanian to early Permian. A quartz sandstone and a polymictic pebble conglomerate from the lower part of the lower sedimentary division yielded detrital zircon U-Pb ages between 360 and 290 Ma (Carboniferous to early Permian), with a range of older detrital zircons from ca. 3600 to 890 Ma (Archean and Proterozoic). A small population of zircons ranges from 450 to

Fig. 8. Moderately dipping metamorphic rocks of the Lardeau Group (Paleozoic). The lower green-grey chlorite schist of the Jowett Formation is overlain by strongly deformed sandstone and lesser carbonate of the Badshot Formation. The contact is under the geologist's knee. The photograph was taken north of Kootenay Lake, view is to the northwest.

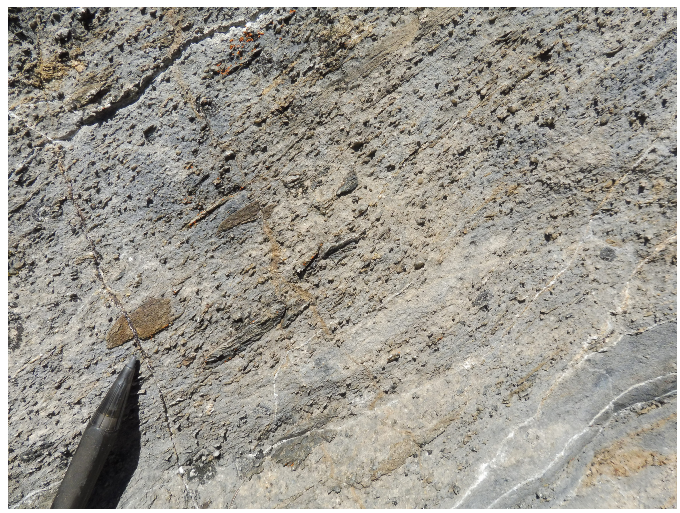


Fig. 9. 'Limestone unit' with Triassic conodonts from above the sub-Triassic unconformity with the Chapperon Group (Paleozoic), Salmon River valley. Pebbly limestone with tabular intraformational micritic limestone clasts and granules and pebbles of chert, quartz, and quartz tectonite. See Schiarizza et al. (2022).

Fig. 10. Lay Range assemblage, lower sedimentary division. At bottom of photo, sharp-based Bouma-like fining upward sequences of graded siltstones to dark grey argillites. See Ootes et al. (2022).

390 Ma (Ordovician to Devonian). The Carboniferous detrital zircons have mostly juvenile εHf(t), indicating that the parental magmas did not interact with older crust. The combined εHf(t) and trace element compositions of detrital zircons are consistent with formation in a juvenile arc during the Carboniferous. Comparison of Lay Range detrital zircon U-Pb, Hf, and trace element systematics indicate a similar timing of arc magmatism with eastern Stikinia and Wrangellia, but little relationship to ancient North America or Yukon-Tanana terrane. The older detrital zircons (Archean through Paleozoic) were sourced from a fringing landmass, possibly a continental oceanic plateau, that had little to no role in the petrogenesis of the Carboniferous magmas. The spread of ages in the Lay Range assemblage zircon distributions likely records multiple cycles of deposition, uplift, erosion, transport, and sedimentation. One possibility is that the fringing landmass was calved during rifting of the western edge of North American crust covered by Neoproterozoic through Cambrian passive margin deposits.

Field mapping of northern Hogem batholith and adjacent intrusive, volcanic, and sedimentary rocks of the Stikine and Cache Creek terranes was completed in 2019. Publication of bedrock and surficial maps is anticipated in the first half of 2022 and will be accompanied by an update to BC Digital Geology.

Van Wagoner and Ootes (2022) and Van Wagoner et al. (2021) report on the geology and geochemistry of the Kamloops Group, which forms part of a discontinuous northwest-trending belt of Eocene volcanic and sedimentary rocks that extends from central Idaho to eastern Alaska. In the Kamloops Group type area, these rocks constitute the Tranquille Formation (Fig. 11) and the overlying Dewdrop Flats Formation, each of which are divided into a number of members. Field, petrographic, and whole rock major, trace, and rare earth element data indicate that many members have comparable compositions and volcanic facies whereas others differ with geographic location, possibly reflecting various feeder vents. The volcanic rocks range from basaltic andesite to dacite; minor rhyolite occurs west of the type area in the Mount Savona Formation. The most common rock type is andesite and, although some andesites have high-Mg and adakite-like geochemical features (high Sr/Y, La/Yb), petrographic and geochemical evidence support that some of these rocks were derived from garnet-free mantle melts that mingled with garnet-free lower-crust. The geochemical features are consistent with amphibole, pyroxene, and plagioclase control resulting from mantle melts mixing with lower crust. The Kamloops study forms part of a larger project to establish the evolution of Eocene volcanism, help identify volcanic centres that may control the location of epithermal gold deposits, and estimate the contributions of volatile gases (e.g., CO_2, SO_2) to the early Eocene atmosphere.

To help steer future exploration efforts, the BCGS published a depth-to-bedrock study (Arnold, 2021) in the drift-covered area of the central Interior Plateau between the Mount Polley and Mount Milligan porphyry deposits. This project used published data including drill hole, bedrock, and surficial geology maps. Lett and Paulen (2021) published a compilation of soil and till geochemical data for two mineral properties in south-central British Columbia, the Ace, a massive sulphide and quartz vein showing, and Getty South a porphyry copper prospect.

Working in northeastern British Columbia, Ferri et al. (2021) provided a stratigraphic overview of the Liard basin and its eastern neighbour, the Horn River basin, focussing on organic-rich Upper Devonian shales of the Patry and Exshaw formations (Besa River Group) in the subsurface of Liard basin, and highlighting features that make the interval an exceptional shale gas play. Presenting whole rock, trace and rare earth element geochemistry, mineralogical, Rock-Eval, and U-Pb zircon data, Ferri et al. (2021) concluded that organic-rich Patry shales reflect establishment of anoxic bottom waters that spread across much of the Western Canada Sedimentary Basin as transgression peaked during deposition of the Exshaw Formation. Integrating aeolian landform analysis with optical dating and macrofossil radiocarbon dating, Hickin et al. (2021) examined the paraglacial to non-glacial transition following the Late Wisconsinian separation of the Cordilleran and Laurentide ice sheets in northeastern British Columbia.

Fig. 11. Hoodoos carved into andesitic to dacitic tuffs, lahars, and lacustrine volcaniclastic deposits, upper member of the Tranquille Formation (Eocene, Kamloops Group). View to the northwest; outcrop within Kamloops city limits. See Van Wagoner and Ootes (2022).

3.2. Targeted deposit studies and exploration methods

Regional mapping programs are complemented by more specific or thematic studies, typically selected to develop public geoscience knowledge and datasets in key topics that support minerals exploration or government land-use policy. Survey geoscientists test new technologies that can support future regional mapping and mineral exploration activities.

3.2.1. Deposit studies

Spence et al. (2022) describe work on the Late Triassic Tulameen intrusion, an 18 by 6 km ultramafic-mafic body in the Quesnel terrane of southern British Columbia hosted by metavolcanic and metasedimentary rocks of the Nicola Group (Upper Triassic). The intrusion is zoned with a dunite core passing outwards through olivine clinopyroxenite and clinopyroxenite to hornblende clinopyroxenite and hornblendite at the margin. Fieldwork conducted by the University of British Columbia during the summer of 2021 incorporated bedrock mapping and sampling with the assistance of remotely piloted aircraft systems (RPAS) to examine relationships between the ultramafic rock types during a period of low water in the Tulameen River. Zones of intermingled ultramafic cumulates (Fig. 12) are typical of the section and are interpreted to be the result of magma recharge and remobilization of crystal-rich magma mushes across a range of physical and rheological conditions.

Milidragovic et al. (2021) examined the chalcophile element geochemistry at the Polaris Alaskan-type mafic-ultramafic complex and concluded that two styles of PGE mineralization reflect the evolution of strongly oxidized hydrous ultramafic parental magma(s) in the absence of wall rock assimilation.

Riddell et al. (2021) reported on the analysis of ten Gething Formation coal samples from the Willow Creek mine in the Peace River coalfield of northeastern British Columbia, using the TESCAN Integrated Mineral Analyzer system to identify and quantify the mineralogy of non-carbonaceous material. Quartz, kaolinite, feldspars and siderite are most abundant; micas, other carbonate minerals, crandallite group minerals, apatite, illite and smectite, and sulphide minerals were found in trace to small amounts in most samples. Iron is most commonly hosted in carbonate minerals. Calcium occurs mainly in feldspars, phosphate minerals, and micas. Magnesium is held mainly in siderite. The ash chemistry of Willow Creek mine samples is generally similar to that of Gething Formation samples regionally, except that on average the Willow Creek mine samples contain about 50% less iron, and about 80% more phosphate.

Fig. 12. Tulameen Alaskan-type ultramafic-mafic intrusion (Upper Triassic), network of small dunite dikes with cuspate-lobate and flame-like margins projecting from a dunite enclave. See Spence et al. (2022).

Critical minerals are an important focus for the Survey, given the increasing demand for materials needed for low-carbon technologies and the accelerated pace of global investigations. L. Simandl et al. (2021) provided an overview of the implications for exploration and mining from growing demands for battery, magnet, and photovoltaic technologies. G. Simandl et al. (2021) examined the Rock Canyon Creek carbonate-hosted REE-F-Ba deposit, which has tectonic, stratigraphic, and structural similarities with Mississippi Valley-type and sparry magnesite deposits in the southeastern Rocky Mountains. In 2022, the Survey will examine critical minerals systems and develop a provincial inventory based on the federal government list (Natural Resources Canada, 2021).

3.2.2. Exploration methods

The Survey is testing remotely piloted aircraft systems (RPAS) to acquire geological data. Following up on RPAS-generated photogrammetric digital elevation models (DEMs) to support surficial geology mapping (Elia and Ferbey, 2020), work in 2021 investigated the utility of RPAS-born magnetometry and gamma-ray spectrometry devices to detect porphyry-related dispersal trains in subglacial tills.

Regional-scale till geochemistry and mineralogy surveys in British Columbia can have a low sample density (e.g., 1 sample/10 km^2) compared to other geochemical prospecting methods. Traditional magnetic and radiometric surveys can provide insight into subglacial till compositions between sample locations, but are commonly costly, time-consuming, or have a poor spatial resolution. Remotely piloted aircraft systems offer the potential to collect fast, affordable, and high-resolution data for drift prospecting studies.

The tests, the detailed results of which will be presented elsewhere, included flights totalling 155 line-km over subglacial tills in seven forestry cutblocks near the Mount Polley mine (alkalic porphyry Au-Cu) and the Woodjam developed prospect (calc-alkaline to alkalic porphyry Cu-Au). Existing geology, geochemistry, mineralogy, and geophysical datasets provide geologic control and a way of validating newly acquired RPAS-borne data. Infill till sampling supplemented these data. The RPAS flew gridded autopilot surveys at 5, 7.5, or 10 m above ground level (AGL) at 2 m/s along flight lines spaced 7.5 or 10 m apart. A GEM Systems DRONEmag potassium magnetometer was slung 2.5 m below a DJI Matrice 600 Pro (Fig. 13a) and using a 10 Hz sampling rate collected total field measurements every 20 cm on the ground. Radiation Solutions Incorporated provided a repackaged version of their

Fig. 13. a) A GEM Systems DRONEmag potassium magnetometer tethered 2.5 m below a DJI Matrice 600 Pro flying a gridded autopilot survey 7.5 m above ground level. **b)** A Radiation Solutions Incorporated RS-350 Backpack gamma-ray spectrometer, incorporating a 3”x3” NaI (Tl) crystal, retrofitted to a DJI Matrice 600 Pro. **c)** The hardware used to complete the geophysical, lidar, and photogrammetric surveys: 1. DJI Phantom 4 RTK batteries, 2. air-band handheld VHF radios, 3. magnetometer mount for DJI Matrice 600, 4. tools, VFR navigation charts, and manuals, 5. GreenValley International LiAir V70 lidar and base station, 6. laptop running GreenValley International LIDAR360 and LiAcquire software, 7. Radiation Solutions Incorporated gamma-ray spectrometer, 8. GEM Systems DRONEmag magnetometer, 9. laptop running SPH Engineering UgCS flight planning software, 10. DJI Phantom 4 RTK and base station, 11. DJI Matrice 600 Pro, 12. GSM19-G walking (base station) magnetometer, 13. DJI Matrice 600 Pro batteries, 14. RTK base station tripod, and 15. lidar base station tripod.

RS-350 backpack gamma-ray spectrometer that was mounted directly to a DJI Matrice 600 (Fig. 13b). This instrument uses a 3”x3” NaI (Tl) crystal with a 1 Hz sampling rate to collect total count data every 2 m. An SPH Engineering radar altimeter, coordinated with UgCS flight planning software, instructed the RPAS in real time to follow terrain at a constant height AGL, ensuring measured data variation was unrelated to changes in distance between the geophysical sensors and the ground. Acquired geophysical data were corrected and gridded using conventional methods for traditional airborne magnetic and radiometric surveys.

Lidar and air photo surveys were flown for the same areas at 4 m/s and 80 m AGL, using a GreenValley International Liair V70 lidar (mounted to a DJI Matrice 600 Pro) and a DJI Phantom 4 RTK. High-resolution bare Earth DEMs were produced from these data, as were orthomosaics (Fig. 14). These models and RPAS-derived digital air photo stereo pairs will supplement large-scale surficial geology mapping and be used to interpret ice-flow and till-transport histories. For example, glacially streamlined features, which indicate northwest ice flow through the Woodjam area during the Late Wisconsinan, are readily identified in RPAS lidar bare Earth models (Fig. 14a). These features cannot be mapped with confidence using RPAS photogrammetric DEMs or orthomosaics (Figs. 14b, c), and are not visible in pre-cutblock, 1:40,000-scale hardcopy air photos (Ferbey et al., 2016) in which trees obscure the subtle changes in topography that define these landforms.

The project demonstrates that commercially available hardware and software can be integrated to fly low-altitude, terrain-following RPAS geophysical surveys (Fig. 14c). The magnetic and radiometric data collected are high quality and fill a scale gap between traditional airborne and ground surveys. Furthermore, RPAS-acquired lidar data are invaluable for mapping surficial geology in forested terrain. Work

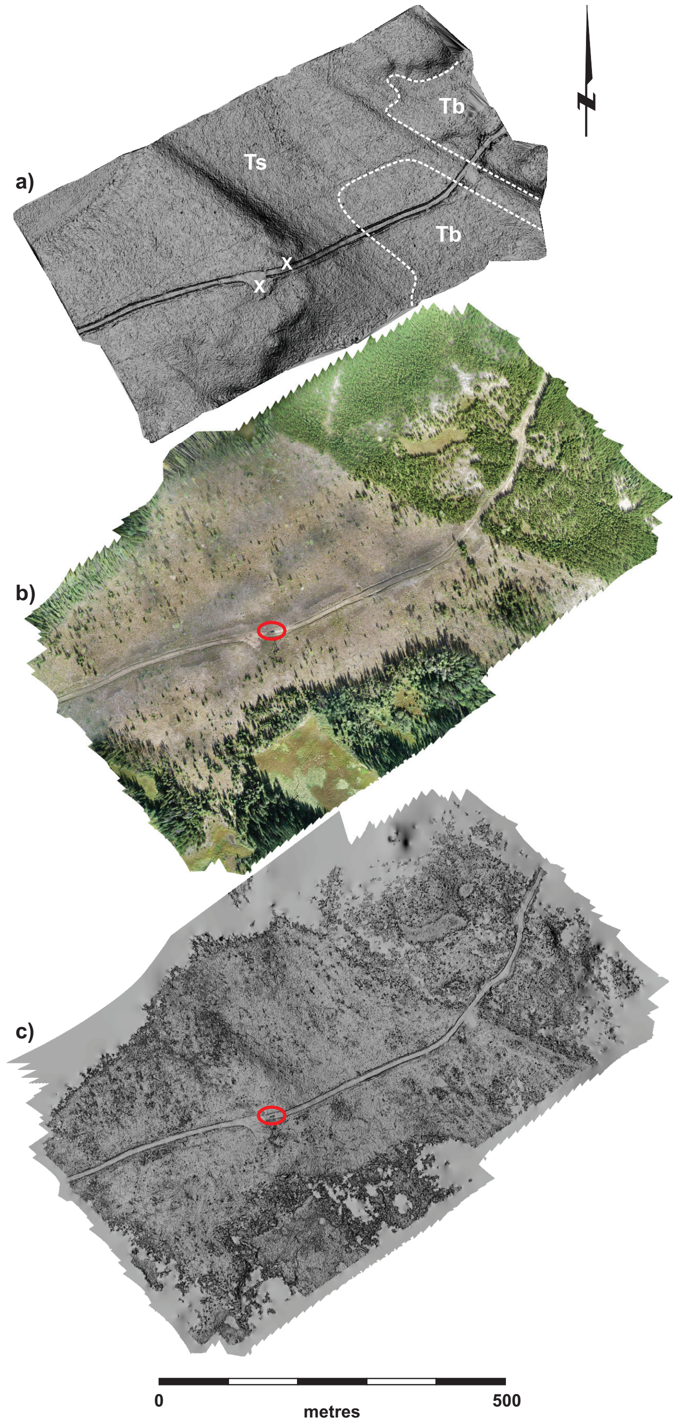


Fig. 14. a) Bare Earth digital elevation model (DEM) of a forestry cutblock west of Woodjam developed prospect, processed from lidar data acquired by LiAir V70 mounted to DJI Matrice 600 Pro. Glacially streamlined landforms (or streamlined till; Ts) indicate northwest ice flow during the Late Wisconsinan and can be differentiated from areas of thicker till (till blanket; Tb). Chilcotin Group (Miocene to Pleistocene) olivine-phyric basalt outcrops observed in the field marked with 'X'. The streamlined features are unmappable in the **b)** orthomosaic or **c)** photogrammetric DEM generated from RPAS-acquired air photos for the same area. Truck is circled in red.

planned for 2022 will continue to focus on differentiating the radiometric and magnetic signals of subglacial tills derived from potassium- and magnetite-rich porphyry systems relative to those derived from country rocks, and will investigate the ability of the method to identify subglacial tills sourced from other critical mineral hosts such as magmatic Ni±Cu±Co±PGE systems.

Based on fieldwork in the summer of 2021, Rukhlov et al. (2021, 2022) report new data from the Lara-Coronation polymetallic occurrence, southern Vancouver Island, confirming that direct and continuous analysis of gaseous elemental mercury (GEM) concentrations in near-surface air using a portable RA-915M Zeeman Hg analyzer can map sediment-covered mineralization in real time. Detailed surveys across steeply dipping, massive sulphide zones in volcanic rocks of the McLaughlin Ridge Formation (Sicker Group; Middle to Late Devonian) confirm GEM haloes in near-surface air above the mineralization. Measured GEM concentrations range from 0.61 to 251 $ng \cdot m^{-3}$ in this study, with the strongest halo (206x background Hg) above exposed mineralization. Weak haloes (1.7x background Hg) mark sediment-covered mineralized zones. Simultaneously measured meteorological and in situ soil parameters appear to have no effect on measured GEM concentrations. Real-time grid sampling of near-surface air reveals a pattern of northwest-trending GEM haloes reflecting bedrock structure, including a 224 by 30 m halo above the polymetallic VMS Coronation zone, covered by up to 22 m of overburden. This study confirms that the real-time GEM sampling of near-surface air can instantly delineate mineralized zones that are buried beneath overburden 10s of m thick. Real-time GEM sampling is a simple and effective technique for mineral exploration in overburden-covered areas.

4. Resource Information Section

The Survey collects, compiles, and disseminates provincial public geoscience information that supports effective mineral exploration, sound land use management, and responsible governance. This public geoscience includes traditional geological maps, reports, and thematic studies, province-wide digital coverage (BC Digital Geology), and databases including mineral assessment reports (ARIS), mineral inventory (MINFILE), coal information (COALFILE), geochemical and geophysical surveys, and documents donated to the British Columbia Geological Survey since the late 1880s by government, universities, industry, and individuals (Property File). The Survey operates numerous information systems to update these databases and deliver them through MapPlace, the BCGS geospatial web service, and other web portals.

Although the Survey has a long history of digitally compiling and managing geoscience, many of the information systems require modernization. As part of digital transformation efforts (Fig. 15), we are modernizing our core information systems to increase efficiency in operating and updating our geoscience

	Input	Output	Outcomes
Data	Geological mapping, field data, lab analyses, ARIS, MINFILE	Digital geology (*f_meta*) Mineral resources (*f_meta*) Mineral systems (*f_meta*)	**Framework geoscience** **Interoperable data sharing** **HTML5 compliant web services**
Process	Digitizing Updating Compiling	Automated integration Knowledge engineering	Automated transformations Mineral potential modelling
Spatial Data Infrastructure (SDI)	Geoscience Operational Database Environment (GODE)	Geoscience Application Database Environment (GADE)	MapPlace 3, OpenLayers OGC web services, OneGeology
Skills and knowledge needed	Bedrock and surficial geological mapping, geochemistry, geophysics, mineral deposits, GIS, database systems	Cordilleran geology Mineral systems Data-driven interpretation Spatial databases Data modelling	Open standards-based web services Digital cartography Geostatistics, data science

Fig. 15. Digital transformation of BCGS data.

databases, applications, and geospatial web services. This modernization will enable interoperable data sharing and applications such as mineral potential modelling.

4.1. Geoscience Spatial Data Infrastructure

Recent advancements in data science demand interoperable data sharing of framework geoscience. The Survey is identifying opportunities and prioritizing solutions to improve our digital capabilities. We are conducting a review of all geoscience databases and applications to define a system architecture and ways to implement a geoscience Spatial Data Infrastructure (SDI). The SDI will be built by following the 'FAIR' principles: Findable, Accessible, Interoperable, and Reusable. Our short-term goal is to modernize a few core information systems with a coherent operational database environment and upgraded web applications.

4.2. MapPlace

MapPlace is the BCGS geospatial web service to discover, visualize, search, and generate summary reports and maps from province-wide geoscience databases. Easy access to, and analysis of, geoscience maps and data are fundamental to inform decisions on mineral exploration, mining, environmental protection, and land use management. MapPlace provides a platform to facilitate the discovery, display, search, and analysis of geoscience information in the context of all other relevant data such as mineral titles, assessment reports, land ownership, public infrastructure, aquifers, and topographic base maps. Some of the advanced applications and user interfaces are specifically designed to enable research and analytics for mineral exploration and prospecting.

4.3. ARIS assessment reports and database

Results of mineral exploration are submitted by industry as assessment reports to the government in compliance with the Mineral Tenure Act. After a one-year confidentiality period, the assessment reports become freely available to public. The Survey manages these reports in the Assessment Report Indexing System (ARIS) database with metadata to search the locations, mineral occurrences, commodities, claims, work types, and expenditures as documented in the reports. ARIS contains more than 38,500 reports dating from 1947. The assessment reports are available online as PDF documents through the ARIS website. A version of the ARIS database for the metadata is available to download in Microsoft Access, with locations in Microsoft Excel and ESRI shapefile format. Data in formats that can be readily used, such as spreadsheets, rather than scanned .PDF files, from 620 assessment reports are available through the ARIS search application. Following work in the Interior Plateau (Norris and Fortin, 2019), the Survey continues to digitally extract assessment report-sourced surface sediment geochemical data (ARSSG), extending into northwestern British Columbia. The database currently contains more than 6.6 million determinations from more than 163,000 samples from 550 assessment reports. The data are incorporated into MapPlace and are also available on the ARSSG website, which includes sample details, geochemical results, and locations. Another project is underway to extract digital data from drillhole logs and geophysical surveys sourced from assessment reports.

4.3.1. ARIS digital data submission

Traditionally, assessment reports from mineral exploration have been submitted in hardcopy or as files such as scanned .PDF, which render data within the files difficult to extract and use. The BCGS has set up a digital data submission portal to encourage inclusion of digital files such as spreadsheets, databases, GIS maps, and grids. Explorationists will benefit because digital data can be easily retrieved, integrated, and recast for specific needs. Digital submission will also enable the Survey to better maintain province-wide databases and create derivative products that use past results to guide future exploration. Both assessment reports and digital data can be uploaded through the ARIS data submission page.

4.4. Other databases

MINFILE is a database for mineral, coal, and industrial mineral occurrences that includes information for more than 15,500 records. In the last year, more than 400 new occurrences and 2100 updates were added to the database. COALFILE includes a collection of 1040 coal assessment reports, dating from 1900. Associated data include 16,100 boreholes, 550 bulk samples, 5400 maps, 3650 trenches, and 484 coal ash chemistry analyses. Property File is a collection of more than 85,000 archived reports, maps, photos, and technical notes documenting mineral exploration activities in British Columbia from the late 1800s. The provincial geochemical databases hold field and geochemical data from multi-media surveys by the Geological Survey of Canada, the BCGS, and Geoscience BC. The databases are updated regularly and contain results from: 1) the Regional Geochemical Survey program (RGS) including analyses from more than 66,000 stream-sediment, lake sediment, moss, and water samples (Han and Rukhlov, 2020a); 2) 10,500 till surveys (Bustard et al., 2017, 2019); and 3) 11,000 lithogeochemical samples (Han and Rukhlov, 2020b). A surficial geology index map for the province (Arnold and Ferbey, 2019) is regularly updated as is an ice-flow indicator database for British Columbia and Yukon (Arnold and Ferbey, 2020).

4.5. British Columbia Digital Geology

The BCGS offers province-wide digital coverage of bedrock geology including details from field mapping, with a typical regional compilation at a scale of 1:50,000. A geospatial frame data (GFD) model is used to simplify the compilation and integration of new mapping into the BC Digital Geology database (Fig. 16, Cui, 2021). Bedrock geology is standardized with consistent stratigraphic coding, ages, and rock types to enable computations, and is available for download in GeoPackage and ESRI shapefile formats. Customized bedrock geological maps and legends can be explored, and data downloaded as KML by spatial and non-spatial queries via MapPlace. The BCGS has transformed the digital geology to the GeoSciML Lite schema and mapped the contents using the vocabularies adopted by the IUGS Commission for the Management and Application of Geoscience Information (CGI). The GeoSciML Lite-compliant digital geology is accessible via the OneGeology portal and open standard-based interface such as WMS and WFS, to enable interoperable data sharing and analytics.

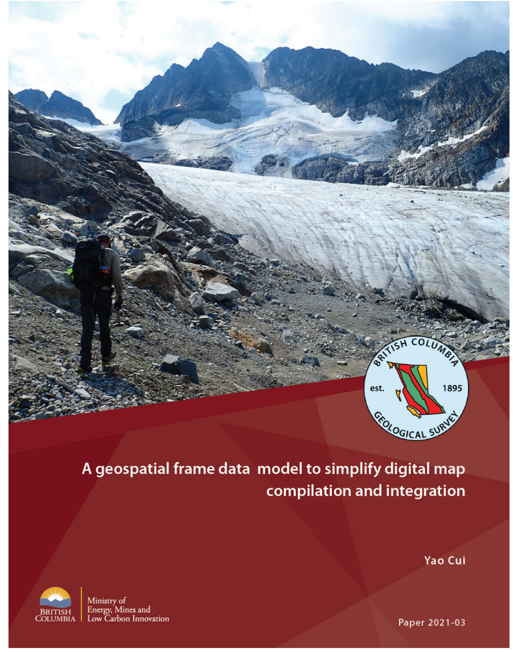


Fig. 16. The geospatial frame data (GFD) model and integration processes can be applied to any discipline that has polygons and lines to compile and produce digital map. See Cui (2021).

4.6. Mineral potential modelling

The British Columbia Geological Survey has initiated a multi-year mineral potential mapping project. The principal aim of the project is to identify areas of high prospectivity for key mineral systems across the province to assist government with land-use planning and deliver pre-competitive geoscience data to the mineral exploration industry. The initial phase of the project included a pilot study that focussed on method development in a test area. Three mineral systems were chosen for the pilot study: porphyry copper-gold; volcanic massive sulphide (VMS) copper-lead-zinc; and magmatic nickel. A weights-of-evidence method was adopted, which produced data-driven mineral potential maps for each selected mineral system. This method allowed for a comprehensive review of outputs at every stage of the modelling process to ensure that the maps were geologically sensible and statistically valid. Based on the success of the pilot study, modelling will continue into new areas and include more mineral systems in the coming years.

5. Mineral Development Office

The Mineral Development Office (MDO) is the Vancouver base of the British Columbia Geological Survey, linking the more than 800 exploration and mining companies headquartered in Vancouver to provincial mineral and coal information. The MDO distributes Survey data and provides technical information and expertise about mineral opportunities to the domestic and international investment community. The MDO monitors the activities of the mining and exploration sectors and produces the Provincial Overview of Exploration and Mining in British Columbia, an annual volume that summarizes activities in the different regions of the province (see e.g., Clarke et al., 2022).

The British Columbia Regional Geologists (Table 1) represent the provincial government on geological matters at a regional level and capture information on industry activity in their jurisdictions. Within their communities, they provide information on exploration trends, possible investment opportunities, land use processes, First Nation capacity building, and public outreach. In 2020, the Regional Geologists were repatriated to the BCGS as part of the MDO.

Acknowledgment

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Table 1. British Columbia Regional Geologists.

Regional Geologist	Office	Region
Vacant	Smithers	Northwest
Nate Corcoran	Prince George	Northeast and North Central
Vacant	Kamloops	South Central
Fiona Katay	Cranbrook	Southeast
Bruce Northcote	Vancouver	Southwest

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