British Columbia Geological Survey annual program review 2020-2021

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Executive Summary

The British Columbia Geological Survey, as the steward of provincial geoscience and mineral resource information, conducts research to define the geological evolution and natural resources of British Columbia. Part of the 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. This paper summarizes current research activity and 2020 highlights from a year that, despite the impacts of the global pandemic, realized just under 50 publications, in line with typical annual output.

The Cordilleran Geoscience Section of the Survey conducts field and desk-based research activities including bedrock and surficial geology mapping programs, regional geochemical surveys, and targeted mineral deposit studies. Despite field activity in 2020 being confined to targeted studies on Vancouver Island due to Covid-19 health restrictions and related concerns, multi-year mapping and research programs in both northwest, central, and southern British Columbia were advanced with desk-based work and laboratory analyses. Integrated bedrock mapping updates for the provincial database and MapPlace (the BCGS geospatial web service) are in preparation for several areas of the province, including: southern Quesnellia, Bonaparte Lake to Quesnel River, Hogem, Polaris, Decar, Turnagain and Tulameen. Plans are also being developed to initiate a multi-year project, starting in 2021, to integrate detailed surficial geological mapping across the province into a seamless database and MapPlace.

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

The British Columbia Geological Survey, as the oldest scientific agency in the province, has provided public geoscience services to the people of British Columbia since 1895. 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 of the province, the Western Canadian Sedimentary basin hosts significant petroleum hydrocarbon resources. 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 purpose of this paper is to provide a concise overview of current Survey research activities and highlight key findings in 2020.

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. The Survey is the primary repository for provincial geoscience knowledge. Maps, reports, and databases are freely available online, serving the interests of stakeholder groups including First Nations, local communities, the minerals industry, public safety agencies, environmental scientists, research organizations, and government agencies. Despite the extensive knowledge base provided by Survey products and archives, much work remains. The remote, rugged terrain

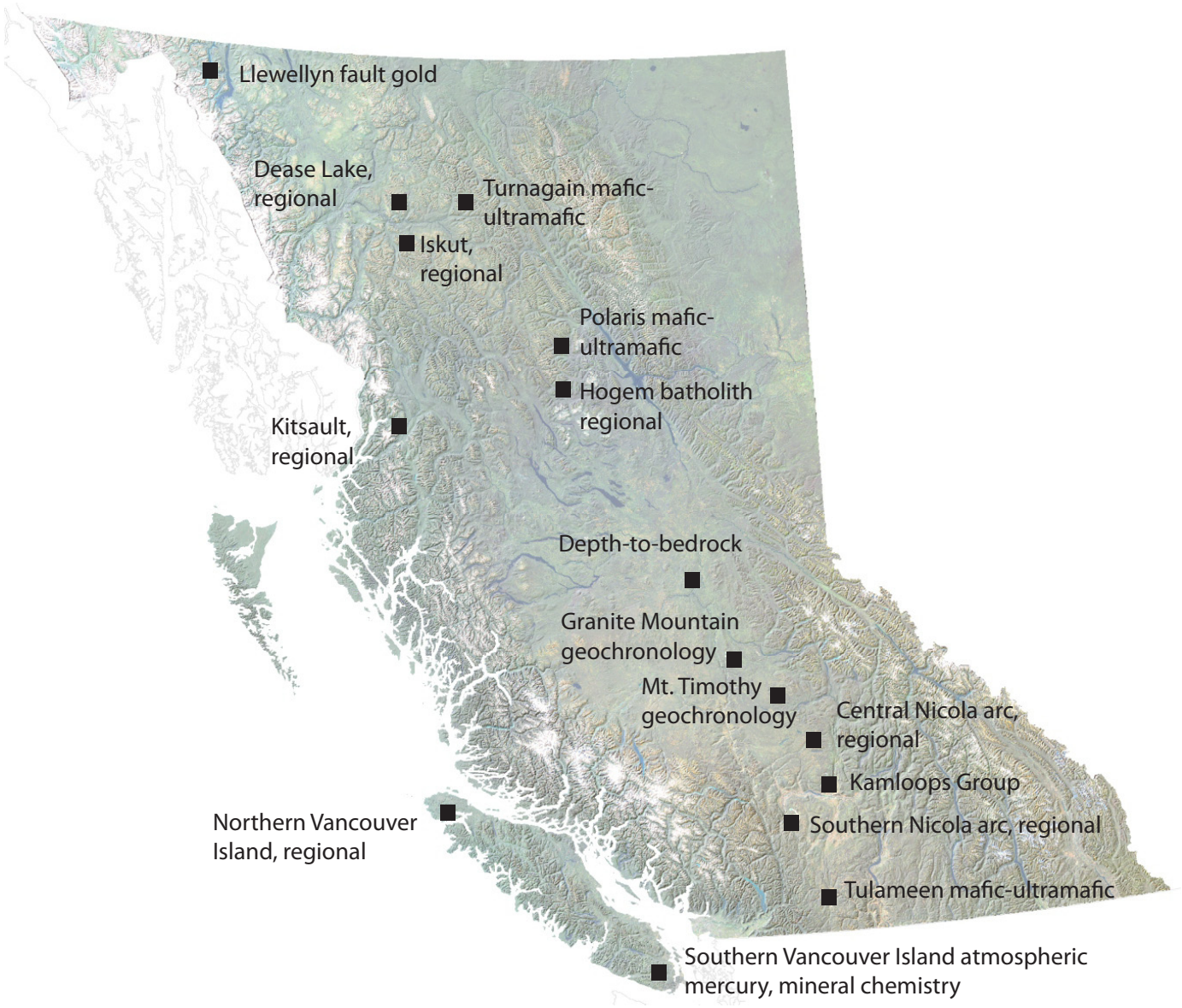


Fig. 1. British Columbia Geological Survey projects in 2020.

with harsh climatic conditions across much of the province has historically constrained Survey fieldwork. However, modern mapping techniques and technology advancements help improve the breadth and depth of geological understanding. Transformation of historic geoscience information to digital formats and databases will require coordinated effort as a multi-year initiative.

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. Staffed by 35 employees, 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., 2021), and includes three Regional Geologists who track minerals activity across the province (two positions are currently vacant).

The Survey welcomed the following new staff during 2020: Neil Wildgust (Director, Cordilleran Geoscience), replacing Fil Ferri who retired after 32 years with the Ministry; Evan Orovan, Mineral Potential Geoscientist; Bronwen Wallace, Mineral Assessment Geoscientist; Easton Elia, Geomatics Geoscientist; and Jenny Boulet, Project and Branch Coordinator. In addition, two Regional Geologists transferred from other parts of the Ministry to the Survey: Sean Tombe (Northwest Region) and Fiona Katay (Southeast Region). The past 12 months also saw Dejan Milidragovic and Pierre Landry leave the Survey ranks to pursue geoscience opportunities elsewhere in the province.

The global Covid-19 pandemic inevitably affected Survey operations in 2020. Staff were encouraged to work from home for much of the year and public health and social distancing requirements restricted summer field activity, exacerbated by concerns about local community interactions. External laboratory services were also affected in many cases, leading to delays in analytical testing and processing of results. Nonetheless, projects continued and the Survey staff maintained a full workload and publication output (Fig. 2).

2. Partnerships

The Survey adopts a collaborative approach wherever possible, extending the scope and content of public geoscience while also minimizing the risk of duplicative work. The Geological Survey of Canada (GSC) is an established partner; the two surveys have collaborated recently through the Geo-mapping for Energy and Minerals (GEM 2) and Targeted Geoscience Initiative 5 (TGI-5) programs, both completed in 2020. Research completed under these programs included: mapping of Cache Creek and Stikine terranes near Atlin (Zagorevski et al., 2021; and see section 3.1.1.); examining specialty metal deposits that host rare earth elements, lithium, tantalum, and niobium (Simandl et al., 2021; Paradis et al., 2021a, b; and see section 3.2.1.); defining a new mineral deposit model for orogenic Ni-Cu-PGE mineralization in Alaskan-type ultramafic-mafic intrusions (Nixon et al., 2020a, b); and investigating gold deposits related to the Llewellyn fault and Tally Ho shear zone in northwestern British Columbia and southern Yukon (Castonguay et al., 2020). The GSC is currently launching new multi-year phases of these programs (TGI-6 and GEM-GeoNorth) and seeking active collaboration with provincial and territorial surveys across Canada.

In collaboration with GSC, the Yukon Geological Survey (YGS) and the Geological Association of Canada (Pacific section), the Survey hosted an online workshop 'Cordilleran Geoscience: a 2020 Perspective' in October. This event included a historic perspective on the development of Cordilleran Geoscience and terrane tectonics, followed by recent research focussed on Cordilleran evolution. The workshop attracted more than 400 registrants, with at least 240 participants logged on throughout the day and contributing to lively Q&A sessions.

3. Cordilleran Geoscience Section

Section geologists collect fundamental geoscience data through single and multi-year field-based programs complemented by laboratory and desk-based studies, including regional-scale mapping, mineral deposit studies, and development of new mineral exploration methods. Expertise encompasses tectonics and structural geology, stratigraphy, petrology, metallogeny, coal deposits, Quaternary and surficial geology, critical minerals, and geochemistry. The following sections highlight ongoing and recently completed research activities, which progressed significantly in 2020 despite fieldwork being limited to Vancouver Island by pandemic concerns and associated public health orders.

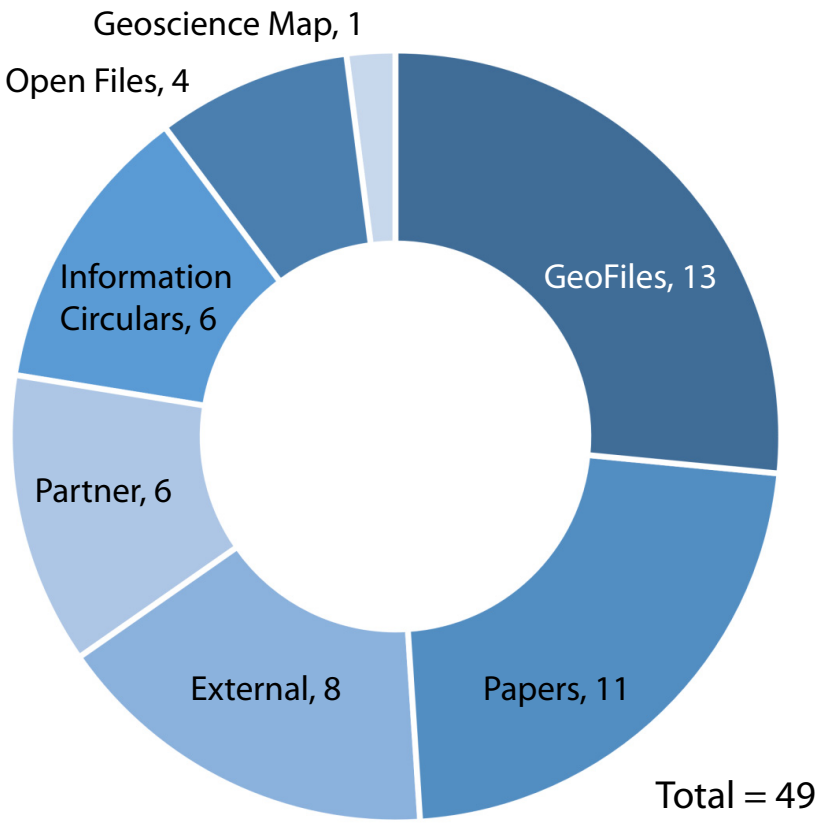
3.1. Mapping, regional synthesis and compilation

Mapping is a core element of Survey and Cordilleran Section programs, delivering two key products: updates to the provincial digital geology database that ultimately feed into MapPlace, and more traditional published maps in the form of PDF files with accompanying research papers. Both products stem from common processes including desk-based review of previous work and aerial and satellite imagery, field mapping, laboratory analyses, geological interpretation, and synthesis of these information sources into digital data formats. The resulting datasets form an essential component of modern mineral potential assessment methods being developed by the Survey to inform land use planning policies within the provincial government (see section 3.2.).

Integrated regional bedrock map updates for the provincial database and MapPlace are listed in the sections below. Plans are also being developed to initiate a multi-year project, starting in 2021, to integrate detailed surficial geological mapping across the province into MapPlace.

3.1.1. Northwest British Columbia

Northwest British Columbia hosts significant base and precious metals mineral deposits, including in an area colloquially referred to as the 'Golden Triangle' between Iskut and Stewart. An ongoing multi-year Survey program will continue to expand regional bedrock mapping coverage to support mineral exploration activity. Understanding the stratigraphic, magmatic, structural, metallogenic, and tectonic framework of this region, as recently summarized by Colpron and Nelson (2021), continues to advance through Survey research. Nelson and van Straaten (2020) described how mineralization in the Stikine volcanic island arc terrane aligns with deep crustal corridors that probably originated as fundamental zones of weakness in the pre-Devonian basement of north-central Stikinia, concluding that the exceptional mineral endowment of this region is due to a location intersecting sets of long-lived trans-crustal (probably trans-lithospheric) lineaments that provided conduits for magmas



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 2020.

and fluids during a succession of arc, back-arc, and post-arc tectonic regimes. George et al. (2021) provide new U-Pb zircon geochronologic and Lu-Hf isotopic data to address the timing of latest Triassic-Early Jurassic accretion in Stikinia, attributing regional shortening to variable along-strike interactions during end-on collision with the Yukon-Tanana terrane such that the northern apex of Stikinia saw significant crustal thickening that is lacking farther south. Pre-Devonian zircon populations,

likely multi-cyclic, differ from those of northern Yukon-Tanana terrane but resemble those of southern Wrangell terrane, and George et al. (2021) suggest that Stikinia was an independent crustal block before the onset of latest Triassic collision.

Integrated bedrock mapping updates for the provincial database and MapPlace are currently in preparation for significant areas (Fig. 3). For the Dease Lake area, ongoing activities are geared towards publication of a 1:100,000 scale Geoscience Map, a final update to the provincial database and a GeoFile incorporating geochronological, paleontological, petrographic, lithogeochemical, structural and petrophysical data. Lang et al. (2020) detailed the geology of the Gnat Pass porphyry copper deposit.

Field mapping in the Kitsault River area commenced in 2019 (Hunter and van Straaten, 2020), and a further season of mapping will be undertaken in 2021 or as soon as pandemic restrictions allow. The area is largely underlain by porphyry-epithermal- and VMS-prospective volcanosedimentary rocks of the Stuhini and Hazelton groups (Late Triassic to Middle Jurassic). To complement future regional mapping, a desktop lithogeochemical study is currently focussed on the Hazelton Group with analyses of 2015 and 2019 Survey field samples and using available exploration lithogeochemistry data from sampling in the Dolly Varden, Brucejack (Bowser Property) and Eskay Creek VMS-related deposit areas. The results of this study will be published in 2021 to identify geochemical characteristics of rock units that host VMS-style mineralization and resolve key stratigraphic questions. This project also builds on concurrent research nearby at Kinskuch Lake by Miller et al. (2020).

Included in this edition of Fieldwork is a guest paper by Greig et al. (2021), which summarizes the results of recent

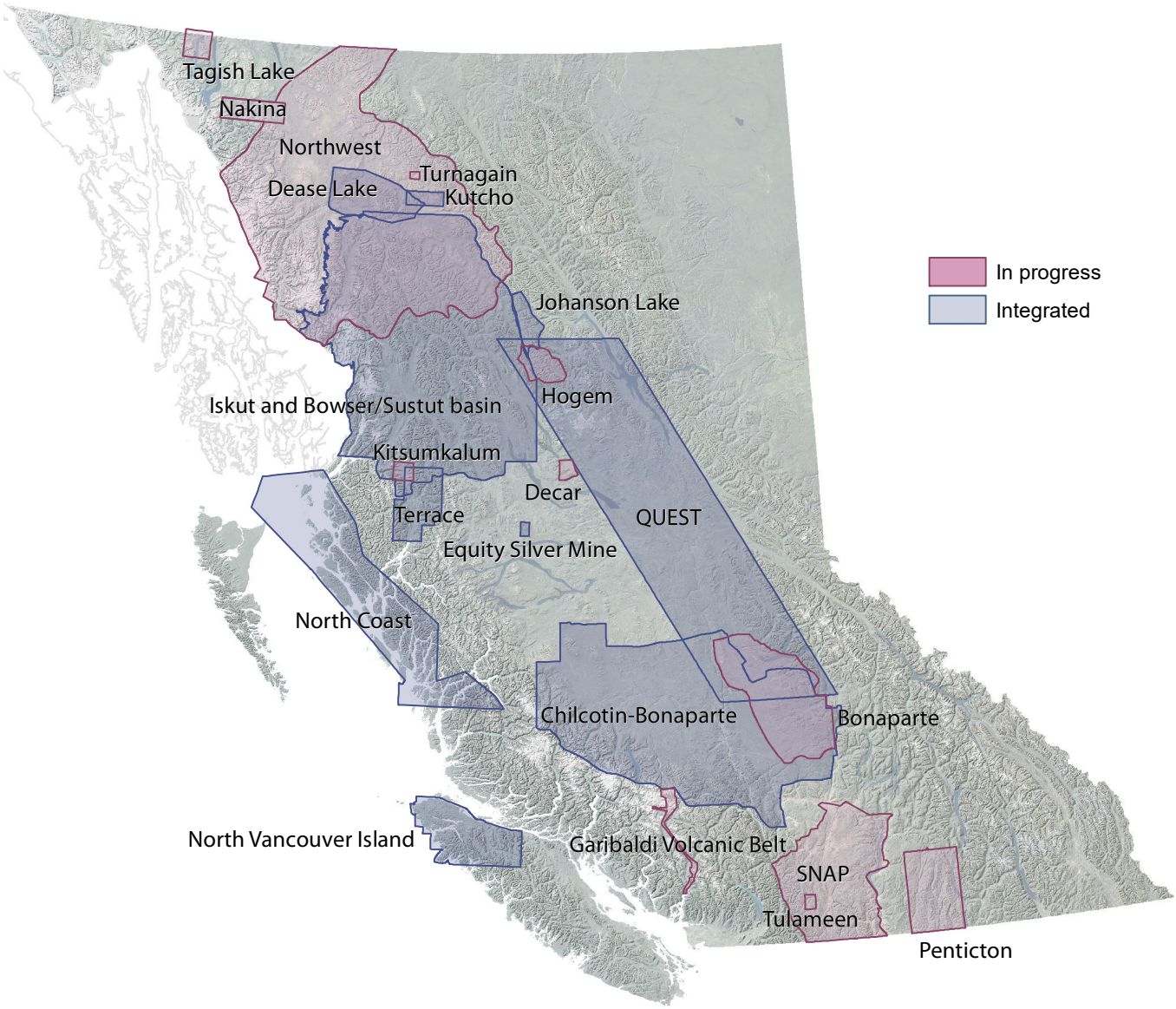


Fig. 3. Recent and planned digital geology compilation updates.

geologic mapping, new U-Pb zircon and Re-Os molybdenum geochronology, and drilling at the Tatogga property in the Iskut district. The data obtained establish the geological framework of mineralization and the timing of contraction that led to Stuhini Group deformation, uplift, and erosional stripping before deposition of the Hazelton Group (Fig. 4).

Fig. 4. Gently northwest-dipping Hazelton Group rocks underlying Tsazia Mountain, viewing west from Mount Poelzer; see Greig et al. (2021).

3.1.2. Central and southern British Columbia

Integrated bedrock mapping updates for the provincial database and MapPlace (Fig. 3) are currently in preparation for several areas of central and southern British Columbia as a result of Survey mapping and compilation projects: southern Nicola Arc, southern Quesnellia, Bonaparte Lake to Quesnel River, Hogem, Polaris, Decar, Turnagain and Tulameen. An update based on mapping outside of Survey programs in the Penticton area of southern BC is planned.

A multi-year mapping project was initiated in 2018 targeting the northern Hogem batholith and adjacent intrusive, volcanic and sedimentary rocks of the Stikine and Cache Creek terranes. New and previously unpublished geochronological data that complement bedrock mapping and geochemical studies indicate punctuated emplacement of four distinct intrusive suites during a protracted (ca. 80 Ma) interval, from 207 to 128 Ma (Fig. 5; Ootes et al., 2020; Jones et al., 2021). Bedrock mapping and geochronologic results from this study indicate that the northern Hogem batholith contains prospective rocks comparable to those that host the Lorraine and other deposits south of the present study area. Surficial geologic mapping integrated with the bedrock component indicates that the Cordilleran Ice Sheet covered the Hogem batholith area during the Late Wisconsinan glacial maximum when ice flowed east and southeast across the region (Ferbey and Elia, 2021). For most of the Late Wisconsinan, ice flow was controlled by topography, as recorded by glacially streamlined or eroded landform- and outcrop-scale indicators which are commonly aligned parallel to valleys. Valley glaciers were not entirely

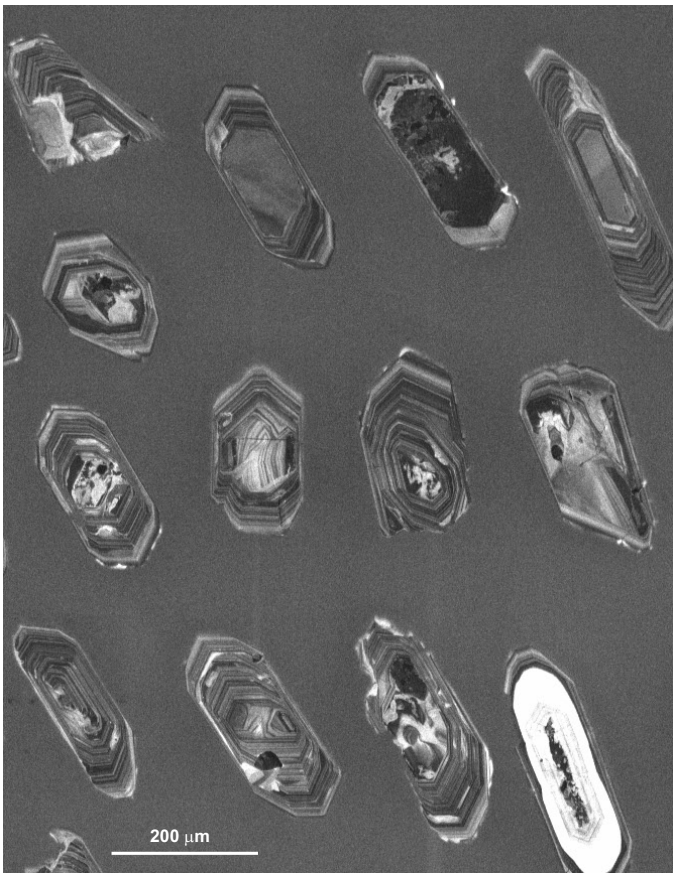


Fig. 5. Cathodoluminescent images of zircons from the Mesilinka plutonic suite (Cretaceous), Hogem batholith. All show typical prismatic igneous zircon morphology, but some show cores with rim overgrowths. The bright interior of the zircon at the bottom right reflects a relatively high U content. See Ootes et al. (2020) and Jones et al. (2021).

controlled by local topography and were thick enough to flow over low-elevation, through-valley, topographic divides transporting glacial debris into adjacent drainages. Significant volumes of glacial meltwater flowed through the valleys during deglaciation, transporting coarse-grained sands and gravels. Colluvial deposits are common along the base of steep slopes and are now vegetated and stable, but talus aprons and cones are still actively being constructed. Organic deposits occur throughout the study area, mostly as narrow transition zones between tree stands and water bodies. Subglacial till (Fig. 6), the ideal sample medium for till geochemistry and mineralogy surveys, is common in valley bottoms and lower hillslopes. Surficial geology maps of the Hogem batholith are in preparation for publication in 2021. In addition to the current mapping, Logan et al. (2020) reviewed the geology, structural setting, and porphyry deposits of the Hogem batholith.

Summarizing a long-term project in the southern Nicola arc, a region endowed with significant porphyry Cu-Au-Mo-Ag and other deposits, Mihalynuk and Diakow (2020) completed a 1:50,000 scale map depicting the geology of a 2000 km^2 area extending from southeast of Merritt to Princeton. Friedman

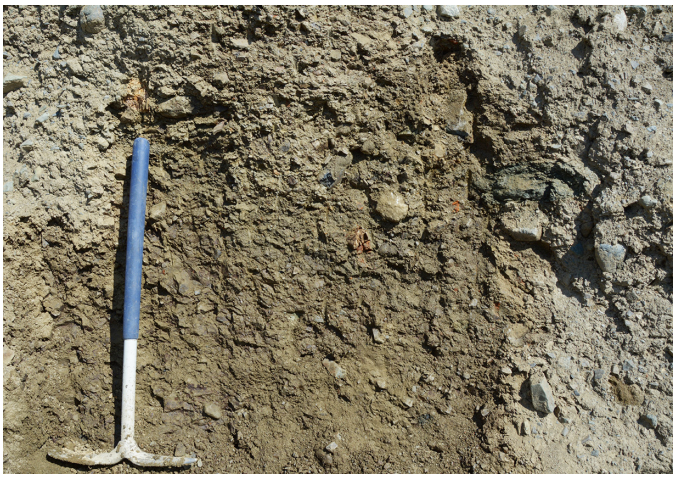


Fig. 6. A blocky, massive, overconsolidated subglacial till with a silty-sand matrix exposed on the north side of Mesilinka River valley, east of Aiken Lake; see Ferbey and Elia (2021).

et al. (2020) reported two new U-Pb zircon ages from the Nicola Group, one the oldest dated thus far (CA-TIMs, 239.99 ±0.16 Ma), the other the youngest (LA-ICPS detrital, 200.2 ±1.1 Ma; Fig. 7). van Straaten et al. (2020) reviewed the mined Gibraltar porphyry copper-molybdenum deposit and Schiarizza and Friedman (2021a) report new chronological data for the Granite Mountain batholith (Late Triassic), host to the mine. Three samples from the Granite Mountain batholith yield Late Triassic dates of 217.15 ±0.37 Ma (Granite Mountain phase leucocratic tonalite), 215.71 ±0.36 Ma (Mine phase tonalite), and 214.98 ±0.38 Ma (quartz-plagioclase porphyry dike cutting Mine phase tonalite). The Burgess Creek stock, on the northeast margin of the Granite Mountain batholith, provides dates of 222.71 ±0.39 Ma (tonalite) and 221.25 ±0.39 Ma (quartz diorite), demonstrating that it is also Late Triassic, but several million years older than the Granite Mountain batholith. To the south, the Sheridan Creek stock contains a foliation with the same orientation and characteristics as a prominent foliation in the southern part of the batholith (Fig. 8). Tonalite from the Sheridan Creek stock returns an Early Cretaceous date of 108.57 ±0.18 Ma, demonstrating that the foliation is mid-Cretaceous or younger. Work continues on the final compilation of a study (e.g., Schiarizza, 2019) in the central part of the Nicola arc.

Working in the type area of the Kamloops Group in south-central British Columbia, Van Wagoner et al. (2021) examined the physical volcanology and geochemistry of Eocene rocks that form part of the Challis-Kamloops belt which, extending for 2000 km along the length of Cordillera, records orogen-scale extension, graben formation, volcanism, and sedimentation. The area is underlain by rocks indicating subaerial to subaqueous (lacustrine) volcanism, with volcanic facies including mega pillows, hyaloclastites, pahoehoe and aa flows, domes and phreatomagmatic cones (Fig. 9). A preliminary comparison of Kamloops Group geochemistry and data from other nearby Eocene units (Princeton and Penticton groups) indicates distinct geographic differences. The Kamloops and

Fig. 7. Geochronologic sampling, Nicola Group; see Friedman et al. (2020) and Mihalynuk and Diakow (2020).

Fig. 8. Foliated Mine phase tonalite, Granite Mountain batholith, west of Gibraltar Mine; see Schiarizza and Friedman (2021a).

Fig. 9. The ridge top exposes Eocene andesitic breccias (Kissick member, Dewdrop Flats Formation, Kamloops Group) representing a dome or sub-volcanic intrusion. In the foreground are Quaternary gravel deposits. See Van Wagoner et al. (2021).

Princeton group melts may have been derived from the spinel-garnet transition zone in the subcontinental lithospheric mantle and influenced by slab-derived fluids, whereas the Penticton Group shows trends toward anhydrous enrichment and may have been derived from a different source. Farther north, Schiarizza and Friedman (2021b) resolved the age of volcanic rocks exposed on the southern slope of Mount Timothy that previously had been considered part of the Nicola Group. A sample of plagioclase-hornblende-pyroxene-phyric andesite yielded an Eocene U-Pb zircon age of 50.84 ±0.04 Ma (CA-TIMS), significantly younger than the Nicola Group.

To help steer future exploration efforts, the BCGS is continuing a regional depth-to-bedrock study in the drift-covered area of the Central Interior Plateau between the Mount Polley and Mount Milligan Cu-Au porphyry deposits. This project is using published data, including drill hole, bedrock, and surficial maps to establish the geometry of the bedrock-drift interface. Final reporting is anticipated in early 2021.The Survey is also planning to undertake remotely piloted aircraft system surveying in this region (see section 3.2.2.).

Field activity on northern Vancouver Island focussed on collecting samples of Neogene rocks for geochronology and geochemistry to better understand the spatial and temporal distribution of porphyry Cu-Mo mineralization. High-precision dating reported by Nixon et al. (2020c) linked the Klaskish Plutonic Suite (ca. 7 to 4.6 Ma) emplacement and crystallization to porphyry Cu-Mo magmatic-hydrothermal systems, representing an extensive and underexplored metallotect. Analytical results and reporting are anticipated in the first half of 2021.

3.2. Targeted deposit studies and exploration methods

Regional mapping programs as described above 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 land use policy within government. Survey geoscientists are able to trial innovative technologies that can support future regional mapping and mineral exploration activities.

3.2.1. Deposit studies

In anticipation of the next generation of mineral deposit profiles which, aided by machine learning, will guide modern mineral potential assessments, Lefebure and Jones (2020) compiled all deposit profiles developed between 1995 and 2012 into a single volume. The Survey is well positioned to advance such new methods with established databases supporting MapPlace and other applications (see section 4); 2020 saw significant effort to frame and develop mineral potential assessment for the Tahltan traditional territory in the northwestern part of the province to support land use policy discussions.

Although Alaskan-type ultramafic-mafic intrusions are gaining recognition as a global class formed at convergent margins and are also gaining global importance as an economic resource, they remain poorly understood and underexplored. Nixon et al. (2020a) reviewed magmatic Ni-Cu-PGE deposits hosted by Alaskan-type intrusions in the Canadian Cordillera, including Tulameen in south-central British Columbia and Polaris and Turnagain in the northwest. Nixon et al. (2020b) reported new U-Pb zircon and $^{40}Ar/^{39}Ar$ ages from the Turnagain intrusion, and Nott et al. (2020) published a detailed (1:15,000)

map of the Polaris intrusion that refined internal and external geological relationships. Research directed toward developing an emplacement framework for the Polaris intrusion continues.

As part of ongoing work devoted to specialty metals in southern British Columbia, Simandl et al. (2021) reported on rare earth elements in carbonates from sediment-hosted lead-zinc deposits, Paradis et al. (2021a) summarized carbonate-hosted mineral deposits (Mississippi Valley-type, magnesite, and REE-F-Ba), and Paradis et al. (2021b) examined the distribution of trace elements in pyrite from carbonate-hosted sulphide deposits. Work continues on the geochemistry of the main mineralized zone at the Rock Canyon Creek REE-Ba-F deposit and reviewing opportunities and risks associated with exploration and development of critical magnet, battery, and photovoltaics materials.

Riddell (2020) evaluated coal ash chemistry indices for predicting CSR (coke strength after reaction with CO_2) for coking coals of the Rocky Mountains (Fig. 10), concluding that correlations between measured CSR and the most commonly used predictive index (Base-Acid Ratio) are moderate to strong and thus can provide a timely and inexpensive first-order prediction for CSR, although not accurate enough for feasibility studies or product marketing. A new mineral characterization study of metallurgical coals by the Survey was initiated in 2020, beginning with sampling of the Gething Formation in the Peace River coalfield. Samples will be analyzed using an automated scanning electron microscope (SEM) to determine the mineral content, including abundance, speciation, contact association and grain size. The method is used to help design the most effective methods of processing raw coal. The data produced can also be used at the exploration phase of a project, to improve coal quality prediction.

Fig. 10. Coal core from the Gething Formation, Carbon Creek, northern British Columbia; see Riddell (2020).

3.2.2. Exploration methods

Regional geochemistry remains a major focus for the Survey. Indicator mineral chemistry enhances the provincial geochemical database by typifying potential ore deposits in prospective drainage basins. As an example and a focus during 2020, re-analysis of the archive heavy-mineral concentrate (HMC) samples using scanning electron microscopy, electron probe micro-analysis (EPMA), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and quantitative mineralogy (Rukhlov et al., 2021a) confirmed the findings of Rukhlov et al. (2020a) that yttrium-rich garnet associated with placer gold deposits at Loss Creek in the southern Vancouver Island area is the main host of 'strategic' and 'critical' heavy rare earth elements (HREE) and Ge in the HMC samples. Concentrations of up to 0.53% REE (mostly HREE) in the garnet are comparable with the top grade of the world's largest HREE producers such as the ion-adsorption clay deposits (0.05-0.5% REE) in southern China, and with eudialyte-hosted REE deposits (1.6% REE) associated with peralkaline massifs such as Ilímaussaq in southern Greenland. The significant geochemical resources of HREE, Mn, and Ge in the Loss Creek catchment basin (Rukhlov et al., 2020a) suggest that the Y-rich garnet could be a potentially source of the low-carbon energy and high-technology metals. A suite of indicator minerals, including apatite, magnetite, and epidote, recovered from samples collected in the northern Vancouver Island area in 2019 have been also analyzed for major- and trace-element concentrations using in situ EPMA and LA-ICP-MS.

Continuing long-standing Survey geochemical and mineralogical studies to define glacial dispersal systems down-ice of buried mineral deposits (e.g., Hickin and Plouffe, 2017), Lett and Paulen (2021) re-examined surface sediment and till geochemistry at the Ace mineral property using data from Survey fieldwork conducted in 2000. Much of the bedrock on the property is concealed by lodgement (basal) till, which was deposited by a southeast to northwest ice movement. The trace element dispersal profiles suggest a massive sulphide source for the anomalous metals in bedrock beneath the till at the east end of the dispersal train. Potentially, other till and soil Au and As anomalies in the western and southern parts of the survey area could have been derived from unmapped, northeast-trending gold-quartz veins**.**

Mercury vapour surveys have been used in geochemical exploration because Hg occurs in most types of endogenic ore deposits and is highly mobile. Rukhlov et al. (2020b, 2021b) measured atmospheric mercury vapour (Fig. 11) at 15 sites on Vancouver Island. To evaluate the effectiveness of the method across a range of settings, these sites include different types of known mineralized zones, barren rocks, and faults, both buried and exposed. The highest Hg concentration was above tailings at the Bentley Au occurrence, possibly due to the amalgamation technique used for fine gold extraction between the late 1800s and early 1900s. Prominent Hg vapour haloes mark shear-hosted Cu-Ag-Au sulphides at Mount Skirt (13.4x background Hg), epithermal Au-Ag-Cu at Mount Washington (8.9x background Hg), and sediment-covered polymetallic volcanogenic massive sulphide at the Lara-Coronation occurrence (4.2 to 6.6x background Hg). Basalt-hosted Cu-

Fig. 11. Simultaneous measurement of meteorological conditions (on tripod) and direct measurement of atmospheric Hg vapour concentrations using a portable RA-915M analyzer along a terrane boundary at Harling Point, Municipality of Oak Bay, Victoria; see Rukhlov et al. (2020b, 2021b).

Ag-Au sulphide zones at the Sunro past producer are marked by weak Hg vapour anomalies relative to local background. Faults, including the Leech River fault, which was active in the Quaternary, are also marked by weak Hg vapour anomalies. The study confirms that, although the Hg level is influenced by weather, the real-time Hg vapour measurement of near-surface air can delineate mineralized zones and fault structures that are buried under overburden 10s of m thick. In contrast to soil gas sampling, this simple and rapid technique can be applied to mineral exploration and geological mapping under overburden above any type of surface, including outcrops, talus, bogs, water bodies, snow, and permafrost.

Remotely piloted aircraft system (RPAS)-mountable gamma ray spectrometers are now commercially available, allowing inexpensive acquisition of K, U, and Th data above till-covered areas. The Survey is planning to use this technique to help characterize mineral potential in the Central Interior Plateau region. Phase 1 (scheduled for 2021) of this project would be a case study to prove the RPAS-borne radiometric method, in the context of till provenance and drift prospecting. The Mount Polley porphyry Cu-Au mine area is an ideal field laboratory for this case study, with mapping control on bedrock and surficial geology supplemented by matrix till geochemical and mineralogical data; forestry clear-cuts are well located for enabling RPAS surveys to be flown over subglacial tills of different provenance.

4. Resource Information Section

The Survey is the custodian of all provincial public geoscience data. This entails regularly upgrading databases and making this information, and its derivatives, easily accessible through web portals. Survey geoscientists collect fundamental geoscience information that is transferred into these online databases and used by industry to develop projects and help search for new discoveries. This information 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. All these data products are accessible through the Digital Geoscience Data page of the Survey website. Besides providing improved access to geoscience data and functionality for a range of applications and stakeholders, the availability of databases supports developing machine learning methods for future applications including mineral potential assessment.

4.1. MapPlace

MapPlace <www.MapPlace.ca> is the BCGS geospatial web service to efficiently visualize, search, report, and generate custom results and maps from province-wide geoscience databases. Some of the advanced applications and user interfaces are specifically designed to enable research and analytics for mineral exploration and prospecting. Easy access to, and analysis of, geoscience data and maps 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 in the context of all other relevant data such as mineral titles, assessment reports, land ownership, linear infrastructure, aquifers, topography and satellite imagery. Recent additions to MapPlace include: a light version for mobile devices; enhancement of topographic features; assessment report-sourced surface sediment geochemical data; and a layer to display bedrock map footprints with links to publication details and downloads.

4.2. ARIS reports and database

Results of mineral exploration programs are submitted by industry in assessment reports to the government in compliance with the Mineral Tenure Act. After a one-year confidentiality period, the reports become an open resource for mineral exploration, investment, research, land-use, and resource management. The Survey maintains these reports in the Assessment Report Indexing System (ARIS) database. This database provides information about the location, mineral occurrences, commodities, claims, work types, and expenditures as documented in the assessment reports. ARIS contains more than 38,000 reports dating from 1947. All reports are available online as PDF documents through the British Columbia Geological Survey website. Digital data, in formats that can be readily used such as spreadsheets rather than .PDF files, from 620 assessment reports are available through the ARIS search application. A version of the ARIS database is available in Microsoft Access format (.mdb) from the digital geoscience data webpage <https://www2.gov.bc.ca/gov/content/industry/mineral-exploration-mining/british-columbia-geological-survey/publications/digital-geoscience-data >.

Following the 2019 release of the assessment report-sourced surface sediment geochemical (ARSSG) database

(Norris and Fortin, 2019) work continues beyond the Interior Plateau. The database currently contains more than 5.75 million determinations from over 143,000 samples across the province. The data are incorporated into MapPlace and the ARSSG application <http://webmap.em.gov.bc.ca/arssg/arssg_home.asp>, which includes sample details and a location map. Development of an assessment report-sourced drillhole database is ongoing.

4.2.1. ARIS digital data submission

Traditionally, data in assessment reports have been embedded in paper or non-digital electronic files, such as PDF, making them difficult to extract and use. The Survey is encouraging digital data submission, which will benefit users because digital data can be easily retrieved, integrated, processed, recalculated, 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. The ARIS Data portal is now available for clients to submit both assessment reports and digital data files (up to 2 GB), such as spreadsheets, databases, maps, grids describing technical work in an assessment report. Data can be uploaded through the ARIS data submission page <http://webmap.em.gov.bc.ca/mapplace/ar_digital_submission.html>. Archives of previous assessment report data are accepted and encouraged for submission.

4.3. Other databases

COALFILE includes a collection of 1030 coal assessment reports, dating from 1900. Associated data include 16,100 boreholes, 550 bulk samples, 5400 maps, 3650 trenches, 484 coal ash chemistry analyses and links to MINFILE. COALFILE data are integrated with MapPlace.

MINFILE is a database for mineral, coal, and industrial mineral occurrences and associated details on geology and economic information for more than 15,300 records. In the last year, more than 200 new occurrences and 1250 updates were added to the database. The web-enabled MINFILE search application interacts with MapPlace, ARIS, and Property File. The MINFILE bibliography now links more than 9500 MINFILE records directly to Property File.

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. These documents are accessible in a full-text, searchable, online database. The records are spatially linked to MINFILE. The Survey accepts donations to Property File.

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). An updated geochronology database (Han et al., 2020) is anticipated to be launched in 2021. 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).

4.4. British Columbia digital geology

The BCGS offers a province-wide digital coverage of bedrock geology including details from field mapping at any scale, with a typical regional compilation at a scale of 1:50,000. BC Digital Geology regularly integrates new regional compilations. 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 interoperation and analytics of the Survey database to the exploration and mining industry. The Survey is currently focussing on integrating various compilations (see section 3) and progressing a compilation of field stations and structural measurements that will be part of the BC Digital Geology database; preliminary results will be released in 2021.

5. Mineral Development Office

The Mineral Development Office (MDO) is the Vancouver base of the British Columbia Geological Survey. It links 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., 2021).

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. Since 1993, the Regional Geologists reported to regional office directors. In 2020, the Regional Geologists were repatriated to the BCGS as part of the MDO.

Table 1. British Columbia Regional Geologists.

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

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