Methods to update the digital geology of British Columbia and synopses of recently integrated mapping programs

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Abstract

The British Columbia Geological Survey (BCGS) provides digital coverage of British Columbia's bedrock geology. The standardized stratigraphic nomenclature that BCGS uses for encoding bedrock across the province resembles that specified in the North American Stratigraphic Code and includes lithostratigraphic, lithodemic, and lithotectonic units. A spatial database handles the large volume of data, rapidly integrates new data, and allows multiple users to work at the same time. The bedrock geology integrates all details from compilations of field mapping at scales from 1:50,000 to 1:250,000, maintains consistent stratigraphic nomenclature, and is free of topological errors. A new 'geospatial frame data' model simplifies integration and reduces the time needed to move from field mapping to data delivery. The data, in shapefile format, are freely available for download from the BCGS web site. The geological map is available for display and query on MapPlace 2, the BCGS geospatial web service. The most recent edition of the digital geology includes updates to the Terrace, Kutcho, QUEST, North Coast, northern Vancouver Island, and Chilcotin-Bonaparte areas. It will soon include Bowser and Sustut basins and the southern Nicola arc area.

Keywords: Bedrock geology, integration, geospatial frame data model, digital map compilation, spatial database, British Columbia, BC

1. Introduction

The British Columbia Geological Survey (BCGS) provides digital coverage of British Columbia's bedrock geology (Fig. 1). In contrast to traditional hard-copy paper compilations, this digital geology is not just a static map at a single scale. The bedrock geology of the entire province is held in a database, and people can download shapefiles to conduct computations and generate customized products. People can work in GIS software or MapPlace 2, the Survey's geospatial web service (Cui et al., 2017a). Use of the database enables computations such as geological map rendering for visualization, spatial and non-spatial queries, statistical analysis, and producing custom maps. In addition, field observations too detailed to include in the original published sources are stored in the database, enabling people to access the highest level of detail possible. As Survey geologists carry out new field mapping, their data can be easily added to the database using novel in-house techniques. This leads to efficient integration and updating.

This paper is in two parts. We first describe the spatial database, the standardized stratigraphic nomenclature used for the entire province, and our 'geospatial frame data' model. This model resolves the problems encountered when attempting to update or merge maps by different geologists working at different scales using different map units or having different interpretations. We then summarize the geology of regional compilations that were recently integrated into the database (Terrace, Kutcho, QUEST, North Coast, northern Vancouver Island, and Chilcotin-Bonaparte areas) and of areas soon to be included (Bowser and Sustut basins and southern Nicola arc). This second part emphasizes the primary sources that were used to create the database, underscoring that the digital geology of the province starts with field-based mapping.

2. A spatial database for British Columbia bedrock geology

The BCGS started compilation in the late 1980s, using Computer Aided Drafting (CAD) and, later, Geographic Information Systems (GIS) software. As part of mineral potential assessment projects from 1992 to 1996, the BCGS completed bedrock geology compilations of the entire province. Further updates led to a release in 2005 of the first province-wide digital geological map of British Columbia (Massey et al., 2005).

In 2008, the BCGS implemented a spatial database to handle the large volume of data, rapidly integrate new data, and allow multiple users to work from the database at the same time. This led to deployment of the 'Geoscience Operational Database Environment' (GODE), which consists of an operational database in PostgreSQL/PostGIS, data quality rules, desktop GIS, and a set of database applications for data quality assurance (Cui, 2011). Using GODE enables efficient data quality assurance, including detecting and fixing inconsistencies in stratigraphic nomenclature and erroneous

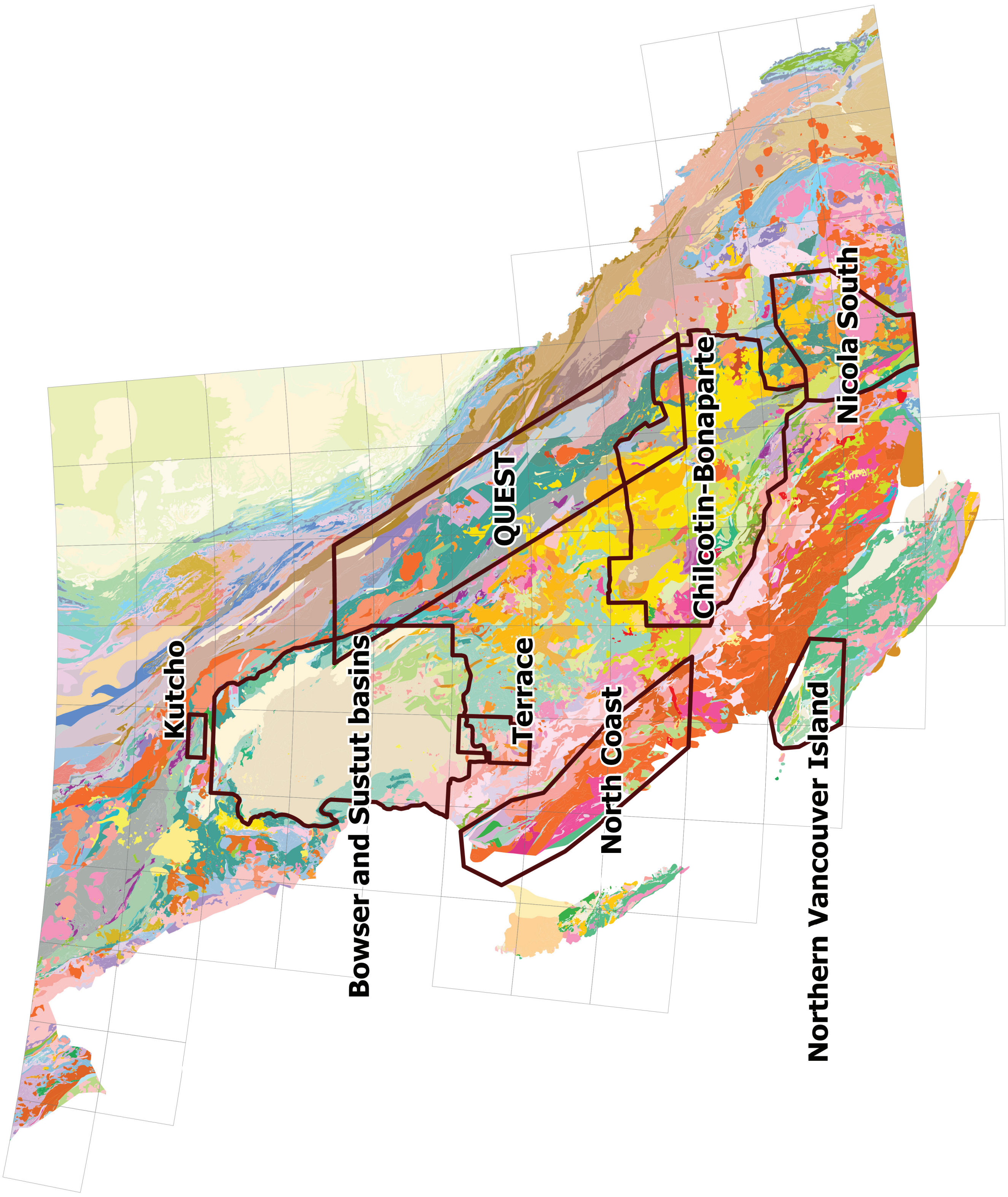

Fig. 1. Regional bedrock geology programs summarized herein.

geometries in geological contacts. Based on GODE, we developed a new way to eliminate topological errors such as overlaps, gaps, discontinuities, and slivers when maps are compiled and integrated ('geospatial frame data' model; see section 4 below).

3. Stratigraphic nomenclature and encoding

Needing a consistent scheme for the entire province, the stratigraphic nomenclature that BCGS uses for encoding resembles that specified in the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005; Rawson et al., 2002; Easton et al., 2014). Ages are adopted from the International Commission on Stratigraphy (Cohen et al., 2013; International Commission on Stratigraphy, 2017). Listings of formally named geological units in the province are available from WEBLEX Canada at (http://weblex.nrcan.gc.ca).

We distinguish three lithological categories in the British Columbia digital geology database: lithostratigraphic, lithodemic, and lithotectonic. Lithostratigraphic units are material bodies of sedimentary, volcanic, metasedimentary, or metavolcanic strata that generally conform to the Law of Superposition and are distinguished on the basis of lithic characteristics and stratigraphic position (North American Commission on Stratigraphic Nomenclature, 2005). Although formation and lithodeme are the most common fundamental map units in British Columbia, informal terms comparable to formation in rank (succession, sequence, assemblage) have also been used. Lithodemic units are material bodies of predominantly intrusive, highly deformed, and/or highly metamorphosed rocks that generally do not conform to the Law of Superposition and are distinguished on the basis of lithic characteristics (North American Commission on Stratigraphic Nomenclature, 2005). Lithotectonic units are not included in the North American Stratigraphic Code. This term is used to define units on basis of structural features, mutual relations, origin or historical evolution (North American Geologic Map Data Model Steering Committee 2004; Neuendorf, et al., 2011; European Commission, 2017). Use of the term 'assemblage' in the lithotectonic category is interchangeable with the term 'tectonostratigraphic assemblage' or 'tectonic assemblage'.

The primary goals of encoding stratigraphy in digital geology are to help maintain data in the database and to support computation, which includes: 1) creating geological maps by assigning and updating styles and symbols (e.g., line types for geological boundaries, bedrock unit colours, legends, and age symbol fonts); 2) simplifying the rendering and visualization of derived geological maps; 3) carrying out spatial and non-spatial queries to search by stratigraphic unit name, rank, age, rock type, map area, compilation, and geologist; 4) statistical analysis; and 5) generalizing bedrock units and creating custom maps at a specific scale or with a specific theme (for example all bedrock units in a specified area with high potential for porphyry deposits).

Generalized stratigraphic age and lithology are captured at the level of detail dictated by the scale of mapping. For example, a bedrock unit may simply be mapped as Triassic 'volcanic rocks' at reconnaissance scale, but referred to as 'mafic volcanic rocks' or, 'plagioclase-phyric basalts' at more detailed scales. With geochronology, petrography, and chemical analysis, the unit may be more precisely identified as Late Triassic calc-alkaline basalt.

4. Geospatial frame data model to integrate bedrock geology

Two major hurdles cause unnecessary complexity and topological errors in digital compilation. First, bedrock maps commonly depict the surface expression of quasi-planar features such as faults and unconformities using lines, and three-dimensional rock bodies using polygons. Geometric and topological errors may be inadvertently introduced along shared boundaries when such maps are revised. For example, gaps and overlaps can occur between adjacent polygons after bedrock units are subdivided and polygon geometries split. In addition, linework representing faults may be shared with polygon segments in cases where units are in fault contact, and the geometries for these shared boundaries can diverge, introducing topological errors. Second, in polygon-based maps, geometric and topological errors occur when maps are updated and merged. Commonly known as edge matching, errors occur where polygons are not aligned, resulting in overlaps, gaps, slivers, fictitious map boundary faults, and other discontinuities at map boundaries.

To reduce shared boundary problems and eliminate topological errors from updating polygons and in edge matching, the BCGS developed a geospatial frame data (GFD) model (Cui, 2014). It consists of three components: 1) centroids (points) that represent the geological units and their attributes; 2) lines that delineate the geological boundaries; and 3) data quality specifications (e.g., data consistency and integrity with respect to lines, points, and stratigraphic encoding).When updates are available or data quality issues detected, changes are applied only to the affected GFD lines and centroids. Polygons representing bedrock are not part of GFD but are generated in the finished data products.

In short, although the use of polygons to capture, theme, and display bedrock geology is attractive, it can lead to editing and merging problems that, in turn, lead to large costs when trying to integrate original source maps at the provincial level. The geospatial frame data model dispenses with polygons, resolving many of these problems.

5. Synopses of recent regional compilations

The most recent edition of the digital geology data for British Columbia (Cui et al., 2017b) includes updated compilations of the Terrace, North Coast, northern Vancouver Island, Kutcho, QUEST, and Chilcotin-Bonaparte areas (Fig. 1). The southern Nicola area and Bowser and Sustut basins will be integrated by early 2018. Emphasizing the primary sources where readers can find details, the following treatments summarize these compilations. For each area we consider the map or compilation extent, historical mapping, the rationale and sources of support for the mapping projects, geologic overviews, products delivered, and significant results, particularly those of economic importance.

5.1. Terrace

The Terrace regional mapping project (Fig. 1), in western British Columbia, was completed between 2005 and 2009. The region, includes the towns of Usk, Terrace, and Kitimat, in NTS map sheets 103I/09, southern half of 103I/16, eastern half of 103I/10 and 103I/08. Reconnaissance mapping was also completed in map sheets 103I/07 and 103I/02. The Terrace data were integrated into the digital geology in 2013.

Coastal and northwestern British Columbia have relatively poor coverage of 1:50,000 scale mapping and before this project, no 1:50,000-scale mapping was available for 103I, except in unpublished theses (i.e., Mihalynuk, 1987; Heah, 1991). The project was initiated to address this knowledge gap and stimulate exploration interest. The project was a cooperative effort between the British Columbia Geological Survey and the Resource Management Department of the Kitselas First Nation.

The area is in western Stikinia, one of the Intermontane terranes recording mainly Paleozoic through mid-Jurassic island arc magmatism (Monger et al., 1991). The area also includes the eastern fringes of the Coast Plutonic complex, a linear belt of mainly granitoid and metamorphic rocks that occupies most of coastal British Columbia. The Coast Plutonic complex is the deeply eroded and tectonically denuded roots of the mid-Jurassic to Eocene continental successor arc, which developed along the western margin of North America following accretion of the Intermontane and Insular terranes (van der Heyden, 1992; Nelson et al., 2013b).

The oldest stratified unit recognized in the map area is upper Paleozoic volcanogenic rocks and limestones, correlative with younger strata in the Stikine assemblage in the Iskut-Stikine area (Logan et al., 2000, Brown et al., 1996). Nelson et al. (2006a) proposed these rocks to be referred to as the Zymoetz Group, divided into a lower volcanic complex (Mt. Attree Formation) and an overlying, Lower Permian limestone equivalent to the Ambition Formation (Gunning et al., 1994). Above these rocks are marine strata, equivalent to the Stuhini Group (Triassic), that are in turn unconformably overlain by intermediate to felsic volcanogenic rocks in the lower part of the Hazelton Group, equivalent to the Telkwa Formation (Lower Jurassic; Tipper and Richards, 1976; Gagnon et al., 2012). The upper Hazelton Group is represented by the Smithers and Quock formations (Middle Jurassic).

Much of the map area is underlain by intrusive rocks that range from late Paleozoic to Eocene. The late Paleozoic suite was emplaced before accretion and is deformed. The Early Jurassic intrusions are mainly represented by the Kleanza suite (Nelson, 2009). Cretaceous to Paleocene plutons that are part of the Coast Plutonic complex are predominantly represented by the Kitsumkalum suit of granite, granodiorite and diorite (early Cenozoic; Nelson and Kennedy, 2007). Eocene intrusions are represented mainly by the Carpenter Creek suite of granite and granodiorite.

Three Open File maps were released from the project, including: Usk (Nelson et al., 2006a), Terrace (Nelson et al., 2007), and Chist Creek (Nelson et al., 2008a). Boudreau (2007) released her undergraduate thesis as a British Columbia Geological Survey Open File. The project produced seven British Columbia Geological Survey Geological Fieldwork articles (Barresi and Nelson, 2006; Nelson et al., 2006b; Nelson and Kennedy, 2007; McKeown et al., 2008; Nelson et al., 2008b; Angen, 2009; Nelson, 2009) and a Ph.D. thesis (Barresi, 2015) and a related journal article (Barresi et al., 2015).

The project resulted in several revelations. An extensive Paleozoic metavolcanic unit stratigraphically underlies Lower Permian limestone from Zymoetz River to Chist Creek. There is exploration potential in local occurrences of volcanogenic sulphide. Three base metal sulphide mineral showings northwest of Kitimat display characteristics of volcanogenic massive sulphide (VMS) feeder zone systems, suggesting a single belt of VMS-style mineralization, probably controlled by a penecontemporaneous seafloor structure. Two felsic marker units were identified and served to help resolve the stratigraphy of the Telkwa Formation. The Skeena River detachment fault system (Eocene) likely continues into the lowest elevations along Williams Creek, Chist Creek and the Kitimat River. The Paleozoic metavolcanic unit and its stratigraphically overlying discontinuous Lower Permian limestone extend west and southwest into the Coast Mountains in the core of a broad regional northeast-trending anticline. This anticlinal structure predates northwest-striking, northeast-side down normal faults that in turn are truncated by more northerly faults of the Kitsumkalum-Kitimat graben.

5.2. North Coast

The North Coast project (Fig. 1), also referred to as the Edges Multiple Metals-NW Canadian Cordillera project, or simply Edges, was a mapping program that ran from 2009 to 2011. The program, a contribution to Natural Resources Canada's (NRCan) first Geo-mapping for Energy and Minerals (GEM) program, encompassed an area that extends along the coast of British Columbia from north of Bella Bella to south of Prince Rupert that includes the communities of Klemtu and Hartley Bay. Mapping was completed at 1:20,000-1:50,000 and compiled to 1:150,000 in portions of NTS map sheets 103A, G, H, and J. The North Coast project data were included in the provincial digital geology in 2013.

Although the mineral potential of the northern coastal area of British Columbia had been assessed as high (Kilby, 1995), active mineral exploration was limited and the Edges project was directed at further assessing metallic mineral potential of the far-travelled terranes that make up the outer accreted margin of the Canadian Cordillera. The project was a collaboration among the Geological Survey of Canada, the British Columbia Geological Survey, and Yukon Geological

Survey, with participation by the United States Geological Survey and Canadian and American universities.

The northern coastal area was first mapped systematically as part of the Geological Survey of Canada's regional assessment of the Coast Mountains batholith and enclosed metamorphic rocks (Roddick, 1970; Baer, 1973; Hutchison, 1982). These studies concentrated on the plutonic rather than supracrustal rocks. More recent geological work focused on the structural and igneous history of the Coast Mountains (e.g., Chardon et al., 1999; Gehrels and Boghossian, 2000; Gehrels, 2001; Chardon, 2003; Butler et al., 2006; Gehrels et al., 2009).

Alexander terrane (Wheeler et al., 1991), which formed the principal focus of this project, is flanked by metamorphosed and deformed meta-sedimentary-volcanic rock units of the Gravina belt and Yukon-Tanana terrane (e.g., Gehrels and Saleeby, 1987; Gehrels et al., 1996; Rubin and Saleeby, 1992, Saleeby, 2000; Gehrels, 2001). The oldest successions mapped in project area are greenschist grade volcanic and sedimentary rocks of the Descon Formation (Early Ordovician to Late Silurian), which stratigraphically overlie the Wales Group, the oldest rocks recognized in Alexander terrane (Late Proterozoic to Cambrian) in Alaska. Plutons that are coeval (and probably cogenetic) with volcanic rocks of the Descon Formation are widespread, and range from diorite to granite. The Mathieson Channel sedimentary rocks, marble and volcanic rocks unconformably overlie the Descon Formation, the basal conglomerate of which is interpreted to represent a major phase of uplift and erosion from the Klakas orogeny (Gehrels and Saleeby, 1987). Rocks of Alexander terrane are overlain by Upper Jurassic to Upper Cretaceous turbidites and subordinate mafic volcanic rocks of the Gravina belt. These rocks can be traced, generally along the inboard margin of Alexander terrane, for the length of southeastern Alaska (Berg et al., 1972) and into northern coastal British Columbia.

Yukon-Tanana terrane underlies the western margin of the Coast Mountains and consists of high metamorphic grade marbles, quartzites, pelitic schists, and orthogneisses and greenschist to amphibolite grade metavolcanic rocks, pelitic schists, and minor marble. In northwestern British Columbia, the Ecstall belt (Gareau and Woodsworth, 2000; Alldrick, 2001; Alldrick et al., 2001), with its enclosed Devonian volcanogenic deposits, is also assigned to Yukon-Tanana terrane.

Tonalitic to granodioritic plutons of the Coast Plutonic complex, form isolated bodies in northern and western portions of the northern coastal British Columbia, and increase in extent southeastward to form continuous bodies of plutonic rock (Gehrels et al., 2009). The depth of emplacement of plutons increases eastward across the Coast Mountains. Late Jurassic bodies were emplaced at depths of ~15 km whereas the Early Cretaceous plutons were slightly deeper (~20 km) and, farther east, mid-Cretaceous plutons of the Ecstall belt were emplaced at significantly greater depths, perhaps 25-30 km (Butler et al., 2006). This increase in depth of emplacement correlates well with the eastward increase in metamorphic grade.

The two main map publications that resulted from this project include Nelson et al. (2011a; NTS 103A/8, 9, 15, and 16) and Nelson et al. (2014; parts of NTS 103-A, -G, -H, -I, and -J). These maps were augmented by five Geological Fieldwork papers (Nelson et al., 2010; Nelson et al., 2011b; Nelson et al., 2012; Angen et al., 2012; Nelson et al., 2013b), a M.Sc. thesis (Angen, 2013), and several journal articles (e.g., Colpron and Nelson, 2009, 2011; Tochilin et al., 2014.).

This project established that the southern part of Alexander terrane contains an Ordovician volcanic-sedimentary-intrusive suite of probable back-arc affinity. The Pitt VMS occurrence on Pitt Island is aligned along a major shear zone that marks the southwestern limit of mid-Cretaceous ductile shearing along the Grenville Channel fault. Chalcopyrite and sphalerite from the main Pitt showing yield lead isotopic ratios significantly lower than those of Cretaceous syngenetic and epigenetic deposits elsewhere in the Coast belt and are thus incompatible with an epigenetic origin linked to the Grenville Channel fault. Instead, they closely match lead isotopic ratios from Ordovician volcanogenic deposits of New Brunswick, Newfoundland, Quebec, and Norway. Current tectonic models place Alexander terrane near the northern end of the Caledonide chain in the early to mid-Paleozoic, implying that Ordovician volcanogenic massive sulphides in Alexander terrane may link to deposits originating in back arcs that constituted a circum-Iapetus ocean ring of fire. Mapping identified some new small sulphide occurrences within and adjacent to Ordovician rhyolites and rhyolite breccias. A suite of samples of meta-igneous rocks east of northern Grenville and Telegraph channels are Permian and represent a previously unknown, late Paleozoic volcanic-sedimentary unit with related dikes in intrusive contact with the Alexander terrane. A large tract of Late Silurian to Early Devonian orthogneiss on Porcher Island was intruded during a Caledonian-age deformational event that probably marked the amalgamation of pericratonic and primitive arc elements in the composite Alexander terrane. And finally, the mapping traced out the Grenville Channel fault for 300 km along strike with Early to mid-Cretaceous sinistral motion.

5.3. Northern Vancouver Island

The northern Vancouver Island mapping project (Fig. 1) encompassed the entire northern tip of Vancouver Island. Geological mapping was completed at 1:50,000 scale and included parts of NTS sheets 92L/03, 05, 06, 07, 10, 11, 12, and 13 as well as 102I/08, 09, and 16. Mapping began in 1992 as part of a multiyear project jointly funded by the Canada-British Columbia Mineral Development Agreement (MDA) aimed at improving the understanding of the geology and mineral potential of northern Vancouver Island (Nixon et al., 1993a, b). The project later evolved into the northern Vancouver Island integrated project that included: bedrock and surficial geological mapping; water, till and bedrock geochemistry; and alteration and mineral deposits studies (Panteleyev et al., 1996). A major focus was to provide a clearer understanding of the Bonanza volcanic rocks, and their geochemical expression and mineral potential. Final Geoscience Maps for northern

Vancouver Island (Nixon et al., 2011a-e) were included in British Columbia's integrated digital geology in 2015.

The first geological investigations of northern Vancouver Island were made by Dawson (1887) who examined Cretaceous coal-bearing strata on the north and south shores of Quatsino Sound. Subsequent studies include those of Dolmage (1919), Gunning (1930, 1932), Jeffrey (1962) and Northcote (1969, 1971). Detailed descriptions of shoreline exposures were summarized by Jeletzky (1976) who made extensive fossil collections partially identified by Tozer (1967). The regional geology of northern Vancouver Island was provided by Muller et al. (1974) and Muller and Roddick (1983). A regional geological reconnaissance mapping program in the Quatsino Sound area was initiated in 1990 by Massey and Melville (1991).

Vancouver Island is mainly underlain by Late Paleozoic to Early Mesozoic rocks of Wrangell terrane (Jones et al., 1977), which extends northwards through Haida Gwaii into southern Alaska (Wheeler and McFeely, 1991). Wrangellia was amalgamated with Alexander terrane to form the Insular superterrane as early as the Late Carboniferous (Gardner et al., 1988), and was accreted to inboard terranes of the Coast and Intermontane belts as late as the mid-Cretaceous (Monger et al., 1982) or as early as the Middle Jurassic (van der Heyden, 1992; Monger and Journeay, 1994). On northern Vancouver Island, Wrangellia is intruded to the east by granitoid rocks of the Coast Plutonic complex and fault bounded to the west by the Pacific Rim terrane and metamorphosed and intrusive rocks of the West Coast crystalline complex (Wheeler and McFeely, 1991). On Vancouver Island the Sicker and Buttle Lake groups (Devonian to Early Permian) form the basement to Wrangellia (Massey, 1995a-c).

The stratigraphy of northern Vancouver Island consists of the Vancouver and Bonanza groups, as redefined by Nixon and Orr (2007). The Vancouver Group (Middle to Late Triassic) includes the calcareous shale informally known as the 'Daonella beds' at its base, overlain by Karmutsen flood basalt (Carnian) and Quatsino limestone (Carnian to Early Norian). The basal unit of the overlying Bonanza Group (Late Triassic to Middle Jurassic) is represented by the Parson Bay Formation (Norian to Rhaetian), a mixed carbonate-siliciclastic-volcanic succession. The Parson Bay Formation is succeeded by volcaniclastic-sedimentary strata (latest Triassic to earliest Jurassic) and the main volcanic phases of the Bonanza Group, LeMare Lake (Early Jurassic; Hettangian-Sinemurian) and Holberg (Middle Jurassic; Aalenian-Bajocian) volcanic units. Coeval granitoid intrusions of the Island Plutonic suite form the plutonic component of the Bonanza magmatic arc (Northcote and Muller, 1972; DeBari et al., 1999). The distribution of Neogene volcanic centres appear to be strongly influenced by high-angle faults. The northeasterly trending Brooks Peninsula fault zone appears to coincide with the southern limit of Neogene volcanism in the region and delineate the southern boundary of an extensional regime in the Queen Charlotte basin (Armstrong et al., 1985; Lewis et al., 1997).

The project resulted in an initial compilation in 1997 (Nixon et al., 1997) and included preliminary Open File maps of Mahatta Creek (NTS 92L/5; Nixon et al., 1993b), Quatsino-Port McNeill (NTS 92L/12 and 11 west; Hammack et al., 1994), and Quatsino-Cape Scott (NTS 92L/12 west and 102I/ 8,9; Hammack et al., 1995), supported by papers in Geological Fieldwork (Nixon et al., 1993a, 1994, 1995; Archibald and Nixon, 1995). Mapping and follow-up studies on northern Vancouver Island continued with release of Geoscience Maps for Quatsino-Port McNeill (Nixon et al., 2000a, 2006b), Alice Lake (Nixon et al., 2000b, 2006f), Mahatta Creek (Nixon et al., 1993b, 2006a), Nimpkish-Telegraph Cove (Nixon et al., 2006d, 2009), and Holberg-Winter Harbour (Nixon et al., 2006c). The final set of Geoscience Maps for northern Vancouver Island capture new stratigraphic, paleontological, geochronological, geochemical, and metamorphic data (Nixon et al., 2011a-e). Several papers complementing these studies were published in Geological Fieldwork and in refereed journal articles (Nixon and Orr, 2007; Nixon et al., 2006e, 2008; Ferri et al., 2008; Greene et al., 2006, 2009, 2010).

The work on northern Vancouver Island has significant economic implications. The evolution of the Bonanza Group, as currently defined, comprises three distinct stages: an incipient arc-building phase of submarine to locally emergent, mainly basaltic to andesitic volcanism in the Late Triassic (Parson Bay Formation); the main phase of largely subaerial basaltic to rhyolitic volcanism (LeMare Lake volcanics) in the earliest Jurassic (Hettangian-Sinemurian); and the final phase of subaerial basaltic to rhyolitic arc construction (Holberg volcanics) in the early Middle Jurassic (Aalenian-Bajocian). The latter two phases of Bonanza volcanism are accompanied by coeval plutonic rocks (predominantly diorite-granodiorite) of the Island Plutonic suite. The prime Cu-Au-Mo porphyry deposits along the Island Copper-Red Dog trend are associated with the Middle Jurassic Bonanza magmatic arc north of a major fault (Holberg fault) trending through Holberg and Rupert inlets. The metallogenic potential of northern Vancouver Island is further underscored by a young suite of Late Miocene-Pliocene plutons, spatially associated with the Brooks Peninsula fault zone, that carry Cu-Mo porphyry-style mineralization; and the discovery of high-Mg basalts (Keogh Lake picrites) in the Karmutsen flood basalt succession (Late Triassic) which raises their prospectivity for magmatic Ni-Cu-PGE sulphide deposits.

5.4. Kutcho

The Kutcho update area includes about 600 km^2 of northern British Columbia, in the southeast part of NTS map sheet 104I, extending from 50 to 115 km east-southeast of the community of Dease Lake (Fig. 1). The Kutcho mapping project was carried out by the British Columbia Geological Survey in 2010 and 2011. The main goals of the program were to gain a better understanding of, and provide more detailed geological maps for, the Kutcho assemblage (Permo-Triassic) in the area where it hosts the Kutcho Creek VMS deposit (MINFILE 092I 060).

This mapping was also a contribution to the NRCan-led Edges project. The project was co-funded by the British Columbia Geological Survey, a private-public partnership agreement with Kutcho Copper Corporation, and the Geological Survey of Canada. The Kutcho data were included in British Columbia's integrated digital geology in 2013.

The regional geology of the Kutcho area is summarized by Gabrielse (1998), incorporating work carried out by the Geological Survey of Canada and British Columbia Geological Survey from 1956 to 1991, including studies of the Kutcho assemblage by Thorstad (1984) and Thorstad and Gabrielse (1986). Studies of the Kutcho Creek deposit and surrounding rocks (mainly Kutcho assemblage) are presented by Bridge et al. (1986), Barrett et al. (1996), and Childe and Thompson (1997).

The Kutcho assemblage is in the King Salmon allochthon, a narrow belt of penetratively deformed, greenschist-grade metamorphic rocks that also includes slivers of the Cache Creek complex and a Triassic-Jurassic metasedimentary succession, the Whitehorse trough, that unconformably overlies both Kutcho and Cache Creek rocks. The allochthon is separated from the main exposures of the Cache Creek complex, to the north, by the Nahlin fault and from Stikine terrane and overlying Bowser basin to the south, by the King Salmon thrust fault, which dips north. The Kutcho dextral strike-slip fault, which strikes northwest, truncates the King Salmon allochthon, and juxtaposes it against Mesozoic volcanic and plutonic rocks of Quesnel terrane.

Preliminary results from the Kutcho mapping program were presented by Schiarizza (2011a, b). The final results featured new subdivisions of the Kutcho assemblage and new radiometric ages and documented relationships with adjacent geological units (Schiarizza (2012a, b).

5.5. QUEST

The Quesnellia Exploration Strategy, or QUEST, was a collaboration of the British Columbia Geological Survey, Geological Survey of Canada and Geoscience BC. This work was also a contribution to the Edges Project of the Natural Resources Canada that, with funding from Geoscience BC, supported a number of airborne geophysical and geochemical surveys. One of the major contributions of the project was a revised bedrock geology map for the poorly exposed region from Williams Lake north through Prince George to Williston Lake (Fig. 1). The QUEST area included portions of, or complete 1:250,000 map sheets for NTS 93A, B, G, H, I, J, K, O, N and 94B, C, and D. The QUEST data were included in British Columbia's integrated digital geology in 2010.

The objectives of the project were to: 1) stimulate mineral exploration in British Columbia, particularly in the Mountain Pine Beetle infested areas of central British Columbia; and 2) provide a framework of exploration datasets for any follow-up mineral exploration work in the drift-covered areas of Quesnellia. Driven mainly by new geophysical and geochemical data acquired by Geoscience BC, the bedrock map integrated existing geological maps from the British Columbia Geological Survey and the Geological Survey of Canada, with interpretations from the geophysics. The purpose of the map revision and geophysical integration was to provide a context for porphyry mineral exploration in these covered areas. QUEST was initiated in 2007 and focused on Quesnel terrane, with the release of the hardcopy map in 2010 (Logan et al., 2010). Much of the mapping was based on the Massey et al. (2005) compilation with modifications that reflected geophysical interpretation and geological updates from Ferri and O'Brien (2003), Logan et al. (2007, 2008), Schiarizza and Macauley (2007), and Schiarizza et al. (2009).

Like Stikinia, Quesnel terrane is an island arc complex that is part of the Intermontane superterrane. The arc initiated in Late Devonian on Paleozoic basement outboard of the ancestral North American (Laurentian) margin on the eastern edge of the Panthalassa ocean (Nelson et al., 2013a; Logan and Mihalynuk, 2014). Arc construction was prolific during the Late Triassic, a particularly important period in which many Canadian Cordilleran porphyry deposits formed (Logan and Mihalynuk, 2014). By the Late Jurassic, Stikine and Quesnel arcs were accreted to the margin of ancestral North America.

5.6. Chilcotin-Bonaparte

The Chilcotin-Bonaparte compilation extends across about 73,000 km^2 of south-central British Columbia, encompassing parts of the Coast Mountains, the Interior Plateau, and the Quesnel and Shuswap highlands, and includes all or parts of NTS map sheets 92/I, J, N, O, P, and 93A, B, C (Fig. 1). It includes Paleozoic and Mesozoic rocks of Kootenay, Slide Mountain, Quesnel, Cache Creek, Cadwallader, Stikine, and Bridge River terranes, as well as metamorphic rocks, in the Coast belt, that may correlate with Yukon-Tanana terrane. The Chilcotin-Bonaparte data were included in British Columbia's integrated digital geology in 2017.

Before this compilation, the digital geology of the Chilcotin-Bonaparte area was based on the first-generation digital compilations prepared for the Mineral Potential project in the early to mid-1990s (Schiarizza et al., 1994; Schiarizza and Church, 1996). Subsequent studies in the region include several single- to multi-year mapping programs carried out by the British Columbia Geological Survey, as well as studies by the British Columbia Ministry of Energy and Mines, Oil and Gas Division, the Geological Survey of Canada, and as graduate thesis projects, mainly at the University of British Columbia. These studies introduced many substantial modifications to the original digital geology, providing motivation to undertake a new compilation.

Mesozoic rocks include late Middle Jurassic through Upper Cretaceous sedimentary successions of the Tyaughton-Methow basin in the eastern Coast Mountains, as well as Middle to Late Jurassic, Early Cretaceous, and Late Cretaceous arc volcanic successions. Eocene volcanic and local sedimentary rocks (including the Kamloops, Ootsa Lake and Endako groups), together with Neogene basalts of the Chilcotin Group, occur across most of the compilation area, and are the predominant bedrock component in many parts of the Interior Plateau. Miocene-Pleistocene volcanic rocks of the Anahim volcanic belt (Ilgachuz and Itcha groups) occur in the northwestern part of the compilation area, whereas Pleistocene and Holocene basalt related to the Wells Gray volcanic field crop out near the eastern edge of the area. Plutonic rocks include Permian, Triassic and Early Jurassic suites that are integral components of Cache Creek, Cadwallader and Quesnel terranes. Younger plutons include Late Jurassic through Eocene granitic suites that are a predominant component of the Coast Mountains, less common dioritic to granitic rocks with a similar age range scattered through the adjacent Interior Plateau, and late Early Cretaceous granite and granodiorite (Bayonne suite) that intrude Kootenay, Slide Mountain and Quesnel terranes near the eastern edge of the compilation area.

The geology of Quesnel terrane, in the eastern part of the Chilcotin-Bonaparte area, is based mainly on the maps of Schiarizza et al. (2013), which summarize six years of fieldwork, conducted between 2000 and 2008. This work introduced new, regionally significant subdivisions of the Nicola Group (Upper Triassic) and recognized several different Late Triassic-Early Jurassic plutonic suites, some with characteristic Cu-Au or Cu-Mo mineralization. The geology of the Quesnel belt also incorporates studies by Anderson et al. (2010) who recognized Early Jurassic and Middle Jurassic subdivisions of the Thuya batholith, Logan and Schiarizza (2014) who looked at the geology of the Rayfield River pluton, and Friedman et al. (2014) who provided isotopic ages for Early and Middle Jurassic intrusive rocks mapped by Beaton (2011) at the Bonaparte mine, near the southeast margin of the compilation area. In addition, the compilation incorporates the study of Schiarizza (2015), showing that the Granite Mountain batholith, host to the Gibraltar Cu-Mo porphyry deposit, is part of Quesnel terrane (rather than Cache Creek terrane, as previously inferred).

Revisions to the geology of the Interior Plateau west of the Quesnel belt are based on a geological compilation of the Taseko Lakes (92O) map area by Mahoney et al. (2013), studies west of Williams Lake by Mihalynuk and Harker (2007) and Schiarizza (2013), geologic maps covering the SE part of the Anahim Lake (93C) map area (Mihalynuk et al., 2009), an M.Sc. thesis study of the Newton Au-Ag deposit by McClenaghan (2013), and isotopic ages presented by Riddell (2010). The pre-Cenozoic geology includes: a north-south belt of rocks comprising Cache Creek terrane; a substantial area of Triassic-Jurassic Cadwallader terrane rocks to the west, locally underlain by Upper Permian bimodal volcanic and volcaniclastic rocks that correlate with the Kutcho assemblage of northern British Columbia; a large area underlain by poorly exposed mid-Cretaceous volcanic rocks, locally associated with Jurassic volcanic rocks and Upper Cretaceous sedimentary and volcanic successions, including probable correlatives of the Upper Cretaceous host to the Blackwater-Davidson epithermal Au deposit; and, in the west, a belt of Jurassic volcanic and sedimentary rocks that may, in part, correlate with upper Hazelton Group rocks of Stikine terrane.

A narrow fault-bounded belt of bimodal volcanic rocks and associated dioritic and tonalitic intrusions occurs in the eastern part of the Cache Creek belt, west and south of the town of Cache Creek. These rocks were previously assigned to the western belt of the Nicola Group (Upper Triassic), but were shown to be older, and correlated with the Kutcho assemblage (Childe et al., 1997). The Chilcotin-Bonaparte compilation was extended southward to encompass this belt, and show the revised interpretation.

Major revisions to the geology of the eastern Coast Mountains and adjacent Interior Plateau, in the southwestern part of the compilation area, are based on the geology presented by Schiarizza et al. (2002) for the Taseko Lakes-Tatlayoko Lake area. This area is underlain mainly by Middle Triassic to Middle Jurassic volcanic, plutonic and sedimentary units of Cadwallader terrane, and late Middle Jurassic to mid-Cretaceous rocks of the Tyaughton-Methow basin, and plays a prominent role in the regional definition and understanding of this terrane and basin. This improved understanding prompted revisions (mainly nomenclature and groupings of units) to the geology of the Taseko Bridge River area to the southeast, and this geology (Schiarizza et al., 1997) is also included in the compilation.

The geology of the Coast Mountains near the southwest limit of the compilation area, southwest of the Tchaikazan fault, includes Triassic rocks tentatively assigned to Stikine terrane, together with Lower and Upper Cretaceous volcanic and sedimentary rocks, structurally interleaved within the northeast-vergent eastern Waddington thrust belt (Rusmore and Woodsworth, 1993). Revisions to the geology in the southeast part of this belt are based on the thesis studies of Israel (2001), Blevings (2008), and Hollis (2009). Revisions to the northwest part of the belt are from Mustard et al. (1994).

The western end of the Chilcotin-Bonaparte compilation area incorporates major revisions to the geology of the Coast Mountains, based on maps by van der Heyden et al. (1994), Israel and van der Heyden (2006), and Israel et al. (2006). The geology of this area features undated metavolcanic and metasedimentary rocks of the Atnarko assemblage, associated migmatitic orthogneiss and amphibolite, and several distinct plutonic suites ranging from Early Jurassic to Paleocene.

The distribution of Eocene volcanic rocks was revised using maps by Mihalynuk and Harker (2007), Mihalynuk et al. (2009), Schiarizza et al. (2013), and Mahoney et al. (2013). These sources also provided updates on the distribution of the Neogene Chilcotin Group, augmenting the study of Dohaney et al. (2010), which shows the distribution of the group in the Taseko Lakes (92O) and Bonaparte Lake (92P) map areas. The northwestern part of the compilation incorporates the detailed study by Souther and Souther (1994) of the Ilgachuz Range (Anahim volcanic belt), and the eastern part shows previously unmapped outliers of Pleistocene basalt (Wells Gray volcanic field) after Schiarizza et al. (2013).

5.7. Bowser and Sustut basins

The Bowser and Sustut basins are in north-central British Columbia and include the lowlands of the Interior Plateaus and the Skeena Mountains (Fig. 1). The Sustut basin, with its relatively gently dipping strata, defines the Spatsizi Plateau (Mathews, 1986). The communities of Smithers, Hazelton and Kitwanga are along the southern margin of the Bowser basin. The Bowser and Sustut basin regional geology compilation was released by the Geological Survey of Canada in 2009 (Evenchick et al., 2009) and incorporates two decades of mapping, mainly by the Geological Survey of Canada. The mapping is slated for inclusion in the provincial digital geology in 2018.

Systematic mapping of the area underlain by the Bowser and Sustut basins began in the early 1950s as part of the Geological Survey of Canada's Operation Stikine. Although coal was known at Klappan since the 1890s (Dupont, 1900), it was only during this mapping project that these two large sedimentary basins were delineated (Geological Survey of Canada, 1957). Thematic and mapping studies were carried out in the 1970s and 1980s (e.g., Eisbacher, 1974a, b; Richards and Gilchrest, 1979; Gabrielse and Tipper, 1984; Evenchick, 1986, 1987, 1988, 1989) and continued through the 1990s and into the mid-2000s (e.g., Evenchick, 1991a,b, 1996a, b, 1997a, b, 2001, 2004, 2005; Evenchick and Green, 1990, 1995a-d, 2004a-c; Ricketts and Evenchick, 1991, 1999; Ricketts et al., 1992; Greig and Evenchick, 1993; Evenchick and McNicoll, 1993a, b; Evenchick and Porter, 1993; Evenchick and Thorkelson, 1993a, b, 1994a-c, 1995, 2004a-f, 2005; Evenchick and Parsons, 1997; Evenchick et al., 2000, 2001; Evenchick and Ritcey, 2005a, b). Mapping in the early to mid-2000s was undertaken as a federal-provincial program (Evenchick et al., 2002, 2003, 2004b, 2006, 2007a-k, 2008a-h; Hayes et al., 2004; Ferri and Boddy, 2005; Ferri et al., 2005; O'Sullivan et al., 2005; Waldron et al., 2006; Evenchick and Ferri, 2007; McMechan et al., 2007; Ricketts and Evenchick, 2007). The most recent regional compilation was completed by Evenchick et al. (2004a, 2009).

The Bowser Basin is on the northern half of Stikinia and contains greater than 5000 m of Middle Jurassic to Upper Cretaceous siliciclastic and minor volcanic rocks assigned to the Bowser Lake and Skeena groups. These sedimentary rocks were derived from erosion of mainly uplifted Cache Creek terrane rocks along the northeastern margin of the basin during and after amalgamation of Stikinia to the margin of ancestral North American (Evenchick and Thorkelson, 2005). The Bowser Lake Group represents a Middle Jurassic to earliest Cretaceous southwesterly prograding deltaic to deep-water succession that is overlain by predominantly Early Cretaceous fluvial siliciclastic rocks (Evenchick et al., 2001; Evenchick and Thorkelson, 2005). Fluvial Skeena Group (Cretaceous) siliciclastic rocks are found in southern Bowser. Both the Bowser Lake Group and Skeena Group (Cretaceous) contain significant coal deposits. The Sustut Basin, along the northeast margin of the Bowser Basin, preserves a Late Cretaceous fluvial section more than 2000 m thick that was sourced from cratonic rocks of the Omineca Mountains to the east, and eroded Bowser Lake Group rocks that were being uplifted in the emergent Skeena Fold belt. The Sustut Group was deposited as a foreland basin ahead of the Skeena Fold belt and was deformed by the advancing thrust front.

The predominant structural elements in the Bowser and Sustut basins are a series of Cretaceous northeast verging folds and thrusts that comprise the Skeena Fold belt. The southern portion of the Bowser Basin is also cut by steep normal faults, likely Cretaceous, and is cut by numerous Late Cretaceous to Paleogene intrusions. Cretaceous to Paleogene plutons of the Coast Plutonic complex intrude the western margin of the Bowser Basin.

5.8. Southern Nicola arc

This compilation integrates results from a number of regional mapping studies by the Geological Survey of Canada, and the British Columbia Department of Mines (which later became the British Columbia Geological Survey), as well as university theses and company reports (Fig. 1). Regional-scale surveys conducted by the Geological Survey of Canada include adjoining maps by Rice (1947) and Cockfield (1948), both incorporated by Monger (1989) and Monger and McMillan (1989) in the Hope (92H) and Ashcroft (92I) map sheets, respectively. Schau (1968) made the first effort to establish a stratigraphy for the Nicola Group and obtained an Early Norian fossil age in rocks mapped in the area between Iron Mountain and Nicola Lake. From 1968 to 1974 systematic mapping undertaken by geologists from the British Columbia Geological Survey moved northward from Copper Mountain (Preto, 1972), to the Aspen Grove and Nicola Mountain areas (Christopher, 1973; Christopher et al., 1974). Preto (1979) synthesized results from this program, providing the most comprehensive lithologic subdivision of Nicola rocks in southern Quesnellia. He emphasized the importance of regional faults and their influence localizing magmatism and mineralization. Furthermore, he highlighted their role in segmenting the arc and subdivided Triassic strata into three parallel structural belts, each featuring distinctive rock types. Mapping north to Nicola Lake and west to Iron Mountain (McMillan, 1981) overlapped, in part, earlier work by Schau (1968), expanding adjacent lithologic units of the Nicola Group and adding notable felsic volcanic and limestone units, containing Early Norian fossils, features that distinguish the Western belt.

The Nicola Group in southern Quesnel terrane is the focus of a compilation nearing completion that will be available as an upgrade to the British Columbia integrated digital geology in spring, 2018. The compilation area extends across 14,000 km^2 and includes the southwestern extent of Quesnel terrane.

A new perspective on the Nicola Group and evolution of the Nicola arc stems from recent British Columbia Geological Survey studies whose boundaries largely overlap the region of earlier survey work in a representative region between Merritt and Princeton (Diakow and Barrios, 2008; Southern Nicola Arc Project - 2012-2014; Mihalynuk et al., 2016). Mapping studies augmented by U-Pb isotopic ages from volcanic and sedimentary units, some of which are calibrated to conodont zones, give conclusive evidence for a two stage evolution of the Nicola arc spanning 36 million years of the Triassic. The compilation geology incorporates a revised stratigraphic framework for the Nicola Group that reflects its sequential development in southern Quesnellia. These revisions also serve as a foundation for comparison to other parts of Quesnellia.

Rocks in the Quesnel terrane record a Mesozoic history of east-directed plate subduction which generated a magmatic island arc system that presently extends as a fault-bounded belt, several thousand km long through British Columbia, north into the Yukon and south into the United States. The arc system in British Columbia is defined mainly by the Nicola Group, and co-magmatic calc-alkaline and alkalic intrusions that host economically significant porphyry Cu-Ag-Au±Mo deposits, and fewer spaced Alaskan-type ultramafic-mafic complexes that have potential for platinum metals as well as chrome, nickel, cobalt and jade.

6. Conclusions

The British Columbia Geological Survey updates the digital bedrock geology of the province and makes products available as data downloads and online on MapPlace 2. The province-wide bedrock geology uses a consistent stratigraphic nomenclature to accommodate the bedrock geology in British Columbia. The integration includes all details of maps from 1:50,000 to 1:250,000 scales. Using a ‘geospatial frame data’ model, which dispenses with polygons, and its implementation in a spatial database, the time required for map integration is reduced. This model and techniques eliminate topological errors typically associated with maps using polygons. Since the first generation of the province-wide digital map was released in 2005, large parts of the province’s geology have been updated, including the Terrace, North Coast, northern Vancouver Island, Kutcho, QUEST, and Chilcotin-Bonaparte areas.

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