Introduction and summary

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INTRODUCTION

The Geo-mapping for Energy and Minerals (GEM) program supported geological research in the northern Cordillera between 2008 and 2020. Research involved collaboration efforts between the Geological Survey of Canada (GSC), the Yukon Geological Survey (YGS), British Columbia Geological Survey (BCGS), university researchers, United States Geological Survey (Alaska), and Geoscience BC. The Cordillera project supported the research of seven postdoctoral fellows, and about thirty graduate and undergraduate projects.

In the first phase of GEM, Cordilleran research was carried out under the auspices of the Multiple Metals Northwest Canadian Cordillera project (2008–2014). This project sought to improve mineral exploration effectiveness by identifying resource-rich environments within accreted exotic and pericratonic terranes of the northern Cordillera (*see* Fig. 1). The project targeted the exotic terranes with their enclosed preaccretionary syngenetic and epigenetic deposits and the metal-rich Triassic through Paleogene magmatic arcs and associated accretion zones that resulted from the interaction between the exotic and peri-Laurentian terranes and the margin of western North America. The project was designed to balance the immediate need to support exploration decisions and reduce exploration risk, while identifying and addressing gaps in geological frameworks to support broader, long-term research objectives. Research included frontier geological mapping, thematic mapping, airborne geophysics, paleontology, isotopic studies, lithogeochemistry, and geochronology. The GEM Multiple Metals Northwest Canadian Cordillera project included the Windy-McKinley (e.g. Murphy et al., 2007, 2009), Southwest McQuesten (e.g. Colpron and Ryan, 2010; Ryan et al., 2010; Knight et al., 2013), Northern Stevenson Ridge (e.g. Ryan et al., 2013a, 2013b, 2014), Exotic Terranes and their Suture Zones (e.g. Beranek et al., 2012a, 2012b, 2013, 2014), BC North Coast (e.g. Nelson et al., 2010, 2012; Angen et al., 2014), Kutcho (Schiarizza, 2011a, 2011b), and Iskut-Sutlahini (e.g. Mihalynuk et al., 2011, 2012; Zagorevski et al., 2012, 2013) activities.

The second phase of GEM built on the results of the Multiple Metals Northwest Canadian Cordillera project. The GEM-2 Cordillera project (2014–2020) aimed to generate new geoscience knowledge of bedrock geology, regional tectonic history, and crustal architecture to support land use and exploration decisions. It involved multidisciplinary field-based activities including framework mapping, thematic studies, and geological analyses focused on areas with insufficient knowledge in western and southern Yukon and northern British Columbia. The GEM-2 Cordillera project included the Crustal Blocks (e.g. Ryan et al., 2015, 2016, 2018a; Parsons et al., 2018, 2019; van Staal et al., 2018), Porphyry Transitions (e.g. Zagorevski et al., 2014b, 2015b, 2016b, 2017b; Chapman, 2015; Martin et al., 2016; Mihalynuk et al., 2016, 2017; Milidragovic et al., 2016a, 2018; Kovacs et al., 2017; Kellett et al., 2018a; Kovacs et al., 2020), Ancient Ocean Crust (e.g. Zagorevski et al., 2014a, 2015a, 2016a; McGoldrick et al., 2017, 2018; Golding, 2018; Lawley et al., 2020), Stikine Basement (e.g. Zagorevski et al., 2017a; Zagorevski, 2018; Mihalynuk et al., 2018, 2019), Yukon Tectonic Evolution (e.g. Kellett et al., 2018b; Kellett and Iraheta-Muniz, 2019), and Crustal Structure (e.g. Cleven et al., 2018) activities.

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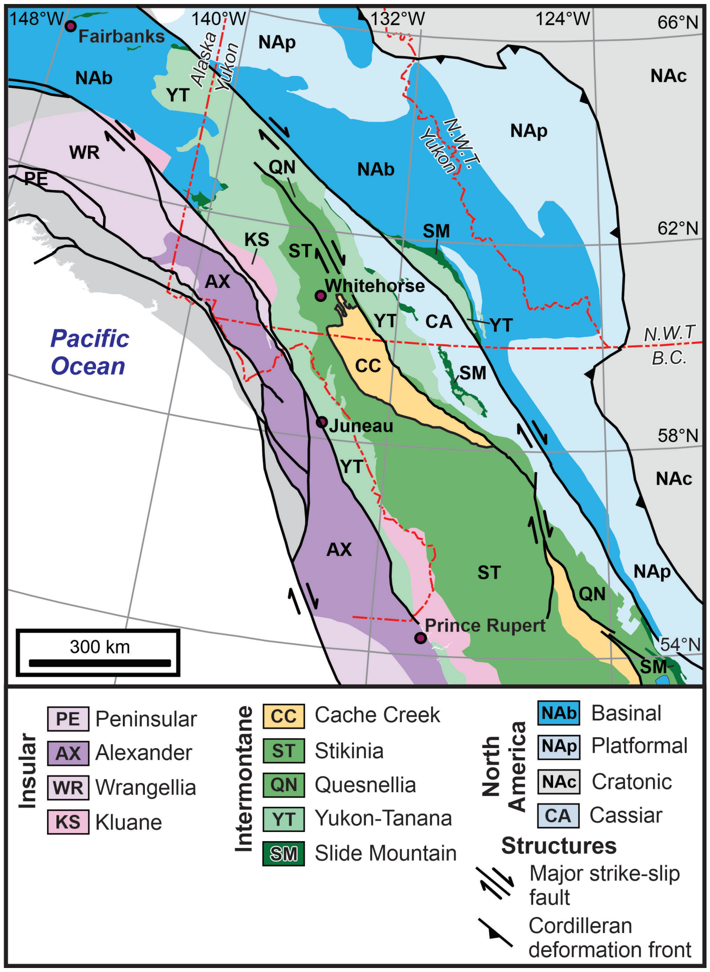

Figure 1. Lithotectonic map of northern Cordillera showing location of the superterranes and terranes (Colpron and Nelson, 2011).

Many of the regional mapping activities were supported by regional geophysical surveys (e.g. Hayward et al., 2012; Hayward and Ryan, this volume). GEM projects in the northern Cordillera produced a vast amount of analytical data including compilations of lithogeochemical (e.g. Zagorevski, 2018; Ryan et al., 2018b; Milidragovic et al., 2016b; Zagorevski, 2020), geochronological (e.g. Knight et al., 2013; Joyce et al., 2015, 2016, 2020, in press; Zagorevski et al., 2013), and microfossil (e.g. Golding et al., 2016b; Golding et al., 2017) data.

Geological Survey of Canada Bulletin 610 summarizes some significant research results and future directions from twelve years of field-based research in the northern Cordillera. The Bulletin presents five distinct, stand-alone, thematic sections: 'Oceanic terranes' (Zagorevski et al. this volume); 'Pericratonic Yukon-Tanana terrane' (Ryan et al., this volume); 'Cordilleran magmatism' (Zagorevski and van Staal, this volume); 'Overlap assemblages' (Kellett and Zagorevski, this volume); and 'Geophysical characteristics' (Hayward and Ryan, this volume). These papers are not intended to provide an exhaustive summary of all research that was carried out over the course of GEM; however, these themes, along with individual activity results (highlighted in the previous paragraphs) provide a good starting point for evaluating future research directions in the northern Cordillera.

OCEANIC TERRANES

Zagorevski et al. (this volume) present an overview of Cordilleran oceanic terranes and their significance for the tectonic evolution of the northern Cordillera. They specifically focus on ophiolite complexes, which form an important component of these oceanic terranes, are fundamental in recognizing ancient suture zones and sites of former oceanic subduction, and represent significant juvenile crust additions to continental margins. Scientific understanding of ophiolitic petrogenesis has evolved significantly since ophiolites were first interpreted as remnants of mid-oceanic ridges; however, northern Cordilleran ophiolites have generally not been evaluated in this modern framework. Zagorevski et al. (this volume) summarize the pseudo-stratigraphy, geochemistry, geochronology, and structural setting of ophiolite massifs in the northern Cache Creek, Slide Mountain, and Yukon-Tanana terranes (Fig. 1). They discuss that with rare exceptions, most ophiolites in the northern Cordillera are characterized by a non-Penrose style pseudostratigraphy of voluminous mantle tectonite, diabase, and basalt, with very minor gabbro and mafic-ultramafic cumulates. This indicates that these ophiolites formed during tectonically accommodated extension similar to modern ocean core complexes. Their data indicate that most of the northern Cordilleran ophiolites formed in Permian to Middle Triassic supra-subduction zone settings (*see also* van Staal et al., 2018; Parsons et al., 2019), and were obducted onto passive margin sequences. Zagorevski et al. (this volume) argue that previous studies incorrectly defined ‘oceanic’ terranes by grouping unrelated marine sequences and supra-subduction zone ophiolites. This led to problems in stratigraphic nomenclature, incorrect terrane definitions, and untenable tectonic reconstructions. The implications of these findings are far-ranging in the Cordillera, as they indicate that the terrane framework needs to be systematically re-evaluated.

PERICRATONIC YUKON-TANANA TERRANE

Ryan et al. (this volume) discuss the architecture of the areally extensive pericratonic Yukon-Tanana terrane (Fig. 1) and its relationship with the parautochthonous North American margin. Structural windows and metamorphic core complexes indicate that a relatively thin nappe of the Yukon-Tanana terrane structurally overlies parautochthonous North American margin, which extends southwest to the Denali Fault. The amount of overthrusting is substantial, possibly on the order of 300 to 400 km, but remains unconstrained. The Yukon-Tanana terrane and North American margin share the same pre-Carboniferous history, and Yukon-Tanana terrane is distinguished by the presence of Carboniferous to Permian magmatism. Analysis of detrital zircon populations indicates that Yukon-Tanana terrane originated from broadly the same region as the structurally underlying North American margin rocks (Cleven et al., 2019). The structural interface between them is probably a Jurassic to Cretaceous thrust, regionally referred to as the Inconnu Thrust, which locally has been reactivated as a mid-Cretaceous extensional shear zone. The earlier history of the Inconnu Thrust is obscured by poly-episodic, high-strain deformation. Distinct patterns in the timing of middle to upper amphibolite facies regional metamorphism indicate that the parautochthonous North American margin was metamorphosed in the Middle Jurassic to mid-Cretaceous, whereas the structurally overlying Yukon-Tanana terrane records Mississippian to Middle Jurassic metamorphism.

The GEM Cordillera project research demonstrates that crustal-scale structures within composite Yukon-Tanana terrane (e.g. the Yukon River shear zone) are commonly marked by discontinuous mafic-ultramafic complexes (e.g. Ryan et al., 2014). Some of these complexes represent orogenic peridotite rocks that were structurally exhumed into the Yukon-Tanana terrane in the Middle Permian, probably through extreme extension. Those Permian extensional structures appear to have been reactivated as thrust faults in the Late Triassic to Early Jurassic. The amount of intraterrane structural overlap accommodated by thrusting between the Yukon-Tanana terrane subdomains is large, probably on the order of 80 to 100 km.

CORDILLERAN MAGMATISM

The northern Cordillera is characterized by episodic magmatism that occurred prior to and following accretion of outboard Intermontane and Insular superterranes. With the exception of the Cache Creek terrane, much of the Cordilleran magmatism is associated with prolific metallotects and has been previously interpreted to be related to arc and backarc settings. This interpretation may stem from a bias imparted by the recent configuration of the North American Cordillera, where the Pacific plate has been subducting eastward beneath North America. Zagorevski and van Staal (this volume) discuss the characteristics and temporal variations of Cordilleran magmatism in Yukon and northern British Columbia, and their significance for deciphering the tectonic evolution of the northern Cordillera. Their evaluation focuses on Paleozoic within-plate magmatism in the Intermontane terranes, Permian Klondike assemblage magmatism in the Yukon-Tanana terrane, and mid-Cretaceous magmatism overlapping all terranes. They argue that through comparison to recent analogues in the western Pacific Ocean, Cordilleran development from Devonian to Triassic time and Cordilleran magmatic episodes are best explained by lithospheric extension processes rather than purely arc magmatism. They also demonstrate that many presently defined terranes are not fundamental tectonic building blocks, but likely comprise distinct tectonic elements that may not be related to each other. Proper resolution of terrane elements and correct interpretation of magmatic setting are key to progressing the understanding of Cordilleran evolution and its mineral deposits.

OVERLAP ASSEMBLAGES

Evaluation of overlap assemblages in orogenic settings can provide critical information on the tectonic evolution of an orogeny such as the timing of accretion events, extensional episodes, and changes in depositional setting. Kellett and Zagorevski (this volume) review the sediment-provenance, geochronological, and thermochronological data of the Late Triassic to Cretaceous sedimentary overlap assemblages in the northern Cordillera. The Early to Middle Jurassic Laberge Group marine silicilastic rocks overlap the Stikine, Atlin, and Cache Creek terranes in southern Yukon and northwestern British Columbia. The Laberge Group is in turn overlain by Middle-Jurassic to Cretaceous clastic units. Variations in clast composition and detrital zircon populations over time indicate major changes in sources to the overlap assemblages. The sources changed from sedimentary rock–dominated in the Sinemurian, to Pliensbachian volcanic rock–dominated, Toarcian plutonic rock–dominated, late Toarcian plutonic and metamorphic rock–dominated, and back to sedimentary rock–dominated sources in the Bajocian. Detrital zircon populations indicate minimal lag time between magmatism in the source regions and deposition into the Laberge Group, indicating contemporaneity of magmatism and basin evolution. Clast provenance and detrital zircon populations also indicate deep incision or exhumation of the Triassic Stuhini-Lewes arc, but minimal input from the Yukon-Tanana terrane. In contrast, detrital-rutile and -mica studies of the metamorphic rocks in the Laberge Group indicate punctuated, rapid exhumation of metamorphic sources in the source region, likely related to Jurassic exhumation of the Yukon-Tanana terrane. Lower-temperature zircon (U-Th)/He and apatite (U-Th)/He thermochronometers further constrain basin evolution of the overlap assemblages. These data indicate that basin thermal evolution was domainal, with at least five contrasting regional temperature-time histories represented, likely related to different tectono-thermal histories. These results indicate that detrital studies of the overlap assemblages are essential to testing and advancing tectonic models in the northern Cordillera. Future detrital studies should also incorporate additional analytical techniques, such as Hf and O isotopes in zircon, to better constrain source regions.

GEOPHYSICAL CHARACTERISTICS

The GEM Cordillera project collected approximately 230 000 km of high-resolution aeromagnetic data (e.g. Hayward et al., 2012) between 2008 and 2019. Hayward and Ryan (this volume) review the geophysical characteristics of the northern Cordillera, through a synopsis of new and existing geophysical data, as well as recent research on geophysical modelling and interpretations. Geophysical applications discussed include the provision of geological and structural interpretations and predictions in support of bedrock geological mapping, regional tectonic interpretations, and detailed studies. The paper reviews specific case studies where geophysical-data–interpretation exercises were undertaken within several regional mapping activities over the life of the Cordillera project, highlighting how this complemented the surface geological mapping, especially in remote regions with poor bedrock exposure such as parts of west-central Yukon. Beyond applications to bedrock geological mapping, Hayward and Ryan (this volume) also review how geophysical modelling, integrated with geological results, facilitates an improved understanding of the deeper crustal structure, leading to new models of the region's tectonic development, mineral deposit context, and landscape evolution to the present (e.g. Ryan et al., 2017; Hayward, 2019).

SUMMARY AND FUTURE RESEARCH

Geological research in the northern Cordillera supported by the Geo-mapping for Energy and Minerals (GEM) program used a combination of systematic and thematic mapping, stratigraphic and structural analysis, modern analytical techniques, and geophysical modelling to address the evolution of the northern

Cordillera and its mineral deposits. This has led to significant improvements in the understanding of local geology (e.g. Ryan et al., 2016; Mihalynuk et al., 2018), mineral deposits (e.g. Mihalynuk et al., 2016, 2017, 2019; Kovacs et al., 2020), regional geological relationships (e.g. Ryan et al., 2017; Hayward, 2019), and geological processes (e.g. Milidragovic et al., 2016a; Kellett et al., 2018a; McGoldrick et al., 2018). The GEM research also highlighted major knowledge gaps in the regional tectonic frameworks. For example, multiple lines of evidence indicate that traditionally defined terranes, such as the Cache Creek terrane, comprise unrelated tectonic elements and require systematic re-evaluation of the terrane components and bounding sutures (e.g. van Staal et al., 2018; Parsons et al., 2019; Zagorevski et al., this volume; Ryan et al., this volume). Regional evaluation of temporal evolution of magmatism similarly indicates that the existing interpretations are poorly supported by recent analogues, which may indicate either a composite nature of presently defined terranes or distinctly different tectonic settings of terranes (Zagorevski and van Staal, this volume). Re-evaluation of the Cordilleran terrane framework will better support future land-use and exploration decisions, and will allow better understanding of secular evolution of mineral deposits.

Provenance of terranes also needs to be re-evaluated and updated using a combination of methods. Exotic nature of terranes was mostly established on the basis of fossils such as conodonts, fusulinids, and ammonoids (e.g. Monger and Ross, 1971; Monger, 1977); however, data that support those interpretations are largely outdated and/or inaccessible. Compilation of internally consistent databases and statistical analysis of faunal assemblages (e.g. Golding, 2018) for all major fossil groups is needed in order to properly evaluate the faunal provenance of terranes. Similarly, studies of detrital zircon and metamorphic minerals from clastic sequences within terranes and their overlap assemblages is critical to constrain source regions, paleo-displacements of terranes (e.g. Cleven et al., 2019), changes in depositional environments, and changes in tectonic setting of basins and adjacent regions (e.g. Colpron et al., 2015; Golding et al., 2016a; Midwinter et al., 2016; Kellett et al., 2018a). Expansion of thematic detrital geo- and thermochronology studies to include whole-rock Sm-Nd and zircon Hf and O isotopes will be critical to evaluate evolution of the northern Cordillera. Both faunal and detrital studies will be facilitated by establishing a broader sampling and compilation framework within the accreted Cordilleran terranes, North American margin, and other potential source regions in the Pacific Ocean.

Regional geological, metamorphic, thermochronological, and structural studies have highlighted the importance of thrust imbrication and extensional tectonics regional to the 3-D distribution of terranes. For example, Yukon-Tanana terrane now forms a relatively thin nappe structurally above the parautochthonous North American margin, which is locally exposed in Late-Jurassic to Cretaceous extensional windows and core complexes (Ryan et al., this volume). Widespread Cretaceous extension in Alaska has long been recognized (Dusel-Bacon et al., 2002); however, the role of Mesozoic extensional tectonics has been generally downplayed in the northern Cordillera in favour of compressional, Andean-style models (*see* Zagorevski and van Staal, this volume). For example, early Jurassic cooling and exhumation of the Yukon-Tanana terrane, coeval with widespread magmatism and sparse deposition of metamorphic detritus in a coeval sedimentary basin, may be indicative of extensional settings. The investigation of the extent and role of extensional tectonics in magmatism and mineralization should be an important avenue of future research in the northern Cordillera.

Regional-scale geophysical modelling is integral to the understanding of the 3-D structure and 4-D evolution of the Cordillera. Specifically, integration of surface geology and geophysics can model the structure of the middle to deep Cordilleran crust (e.g. Hayward, 2019; Hayward and Ryan, this volume). Integration of tectonic frameworks and geophysical models will likely lead to improved understanding of the evolution of the crust, genesis of mineral deposits, and better tectonic reconstructions through geological time (e.g. Sigloch and Mihalynuk, 2013); however, understanding the 3-D structure and 4-D evolution of the Cordillera requires continued testing and updating of the regional geological frameworks.

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