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Geological framework of ancient oceanic crust in northwestern British Columbia and southwestern Yukon GEM 2 Cordillera

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Foreword

The Geo-mapping for Energy and Minerals (GEM) program is laying the foundation for sustainable economic development in the North. The Program provides modern public geoscience that will set the stage for long-term decision making related to investment in responsible resource development. Geoscience knowledge produced by GEM supports evidence-based exploration for new energy and mineral resources and enables northern communities to make informed decisions about their land, economy and society. Building upon the success of its first five-years, GEM has been renewed until 2020 to continue producing new, publically available, regional-scale geoscience knowledge in Canada's North.

During the summer 2015, GEM program has successfully carried out 17 research activities that include geological, geochemical and geophysical surveying. These activities have been undertaken in collaboration with provincial and territorial governments, northerners and their institutions, academia and the private sector. GEM will continue to work with these key collaborators as the program advances.

Introduction

The Cache Creek terrane (Fig. 1) comprises an imbricated stack of carbonate, chert, basalt, gabbro and ultramafic rocks that are exposed from southern British Columbia to southern Yukon. Its components have been variably interpreted to represent fragments of accreted seamounts, ophiolites and rifted arc complexes. Some of these are associated with Tethyan fauna-bearing limestone that is exotic to Laurentia (e.g., Monger 1977a; Monger and Ross 1971). The apparent entrapment of exotic Tethyan fauna between the less exotic Stikinia and Quesnellia terranes has guided the development of the tectonic models for the evolution of the northern Cordillera far beyond the boundaries of the Cache Creek terrane itself (e.g., Mihalynuk et al. 1994 and references therein). Although the individual tectonostratigraphic units are locally well characterized, their regional distribution remains poorly constrained. This knowledge gap

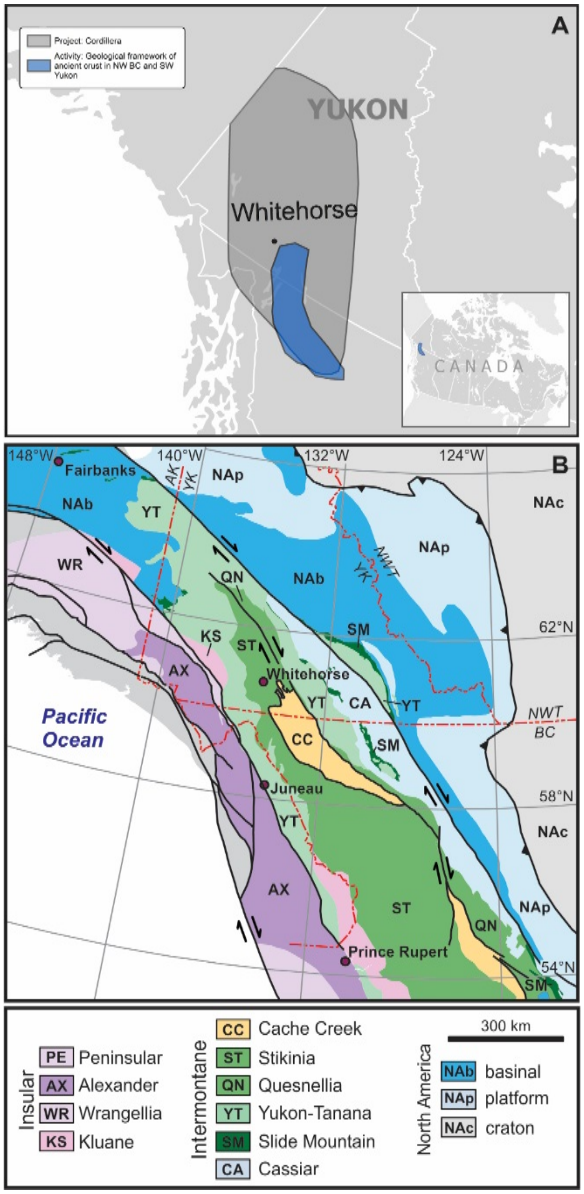


Figure 1 A. Cordillera project footprint.Terranes of the Northern Cordillera (from Colpron and Nelson, 2011).

precludes detailed tectonic reconstructions of the Cache Creek terrane that are necessary to understand the distribution and significance of mineral deposits within Cache Creek and adjacent terranes.

The *Geological framework of ancient oceanic crust in northwestern British Columbia and southwestern Yukon* activity aims to develop an updated regional geologic framework for the Cache Creek terrane in southern Yukon and northern British Columbia (Fig. 1). This framework will address the origin of individual tectono-stratigraphic units and their mineral potential, the history of associated sedimentary basins, and the accretionary history that brought the various tectono-stratigraphic units together. The proposed project area contains superb large-scale exposures that provide ample opportunities to study the larger tectonic processes that occur during formation of oceanic terranes and associated syn- and epigenetic mineral deposits.

Geological background

The Cache Creek terrane is recognized to be a composite terrane along its entire length (Fig. 2). The northern Cache Creek terrane exposed in the Cry Lake and Dease Lake areas (NTS 104I, J), is divided into two major units: the Cache Creek Complex and the Kutcho Assemblage (Fig. 2; Gabrielse 1998). The Nahlin Fault separates the two and, in most places, marks the southwest limit of the Cache Creek complex. The Kutcho assemblage to the southwest is interpreted as an Early to Middle Triassic rifted arc complex (e.g., Childe and Thompson 1997; Gabrielse 1998; Schiarizza 2011), and hosts the Kutcho Creek volcanogenic massive sulphide deposit. Located in the hanging-wall of the King Salmon Fault, Kutcho assemblage comprises felsic to mafic volcanic and hypabyssal rocks and associated epiclastic sediments; all are unconformably overlain or structurally imbricated with the Jurassic Inklin Formation. Kutcho correlatives (Fig. 2) are reported to the northwest in the Nakina (English et al. 2010; Mihalynuk et al. 2003) and Marsh Lake areas (Bickerton 2013).

The Cache Creek Complex contains conspicuous slabs of variably serpentinized ultramafic rocks up to 60 kilometres in length (Fig. 2) that are structurally juxtaposed with mafic volcanic, mafic hypabyssal and sedimentary rocks including limestone, ribbon chert and fine-grained siliciclastic rocks ranging in age from Carboniferous to Jurassic. During

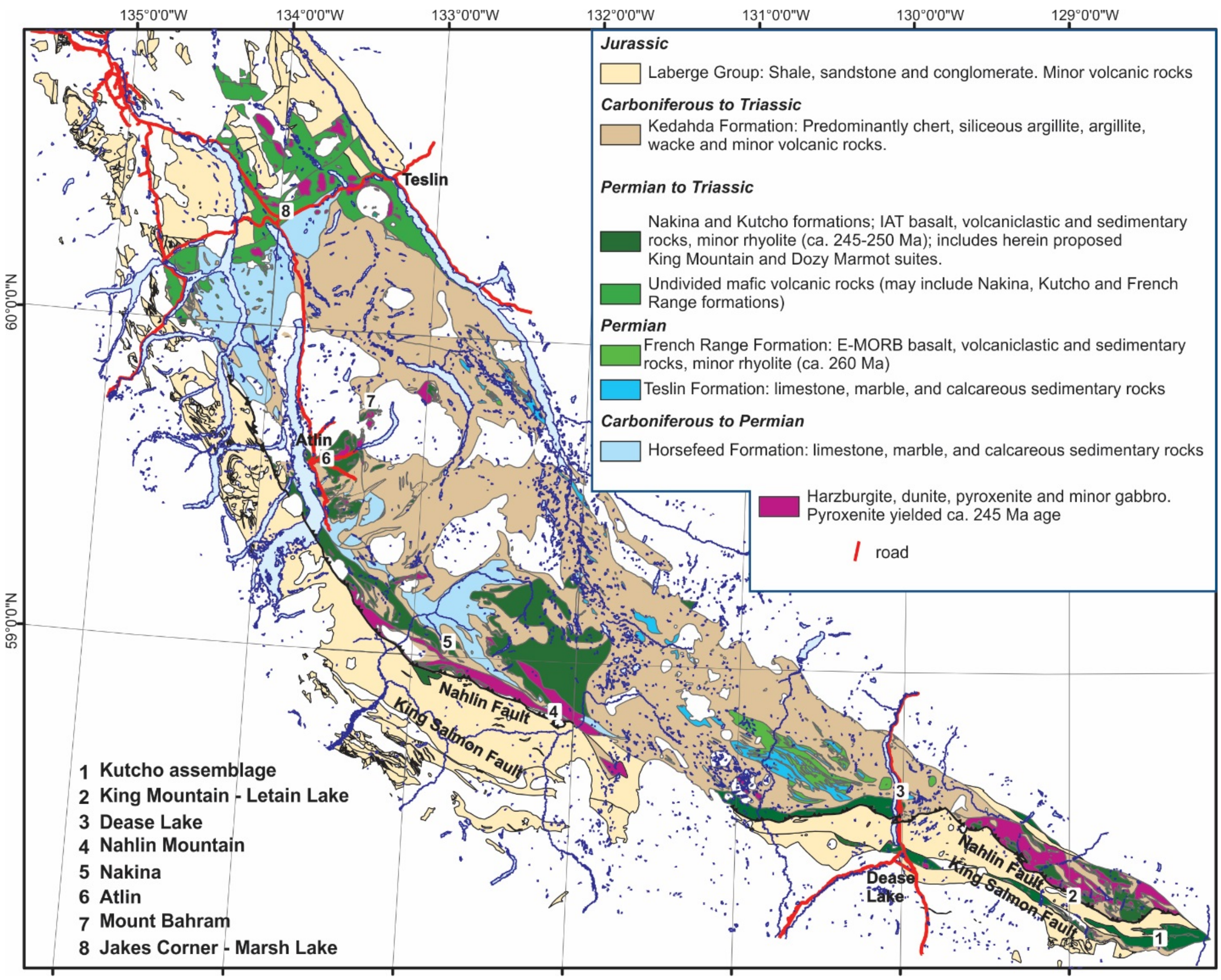


Figure 2 Simplified geology of the northern Cache Creek terrane showing the distribution of various tectono-stratigraphic units (simplified from Massey et al. 2005 and Colpron 2015).

initial studies of the mafic-ultramafic rocks, they were interpreted as ophiolite segments (i.e. spreading centre; e.g., Terry 1977) and/or a seamount (i.e. ocean island/plateau with carbonate atoll; e.g., Monger 1977b) that were in part coeval with and overlain by deep water basin strata characterized by chert and fine-grained siliciclastic rocks. Subsequent workers followed these interpretations and noted that ophiolitic components were predominant (e.g., Ash 1994; English et al. 2010; Gabrielse 1998; Mihalynuk et al. 1994); however, a consistent tectono-stratigraphy has not been developed across the northern Cache Creek terrane. As such, the relationship between interpreted seamount and ophiolite components remains enigmatic, as does their relationship to the abundant mantle tectonites and rare crustal cumulates.

Goals and objectives

Resolution of tectono-stratigraphy and structural relationships between the tectonic panels is key to reconstructing the geological history of the Cache Creek terrane and its mineral deposits. Several priority areas and transects were identified based on 2014 field results. These areas were selected to (i) fill in gaps in map coverage of mantle and lower crustal lithologies, (ii) constrain the relationship between mantle and crustal lithologies; (iii) determine the existence/extent of classical ophiolite pseudostratigraphy (Penrose-style: Anonymous, 1972); (iv) test/expand 2014 identification of extensional ophiolitic core complexes, and (v) identify the extent of arc-derived detritus in associated sedimentary units such as the Kedahda Formation.

Preliminary results

Mantle rocks

Variably serpentinized ultramafic rocks are present throughout the northern Cache Creek terrane, although the largest exposures occur in the hanging wall of the Nahlin Fault (Fig. 2). They are mainly composed of mantle harzburgite tectonite with variably abundant foliation-concordant orthopyroxenite layers and rare discordant dykes (Fig. 3a). Dunite dykes, layers and pods are common but volumetrically minor (Fig. 3b). A single U-Pb age from an ultramafic body in southernmost Yukon constrains their age as 245.4±0.8 Ma (Gordey et al., 1998). Following Terry (1977), we include these ultramafic rocks in the Nahlin suite.

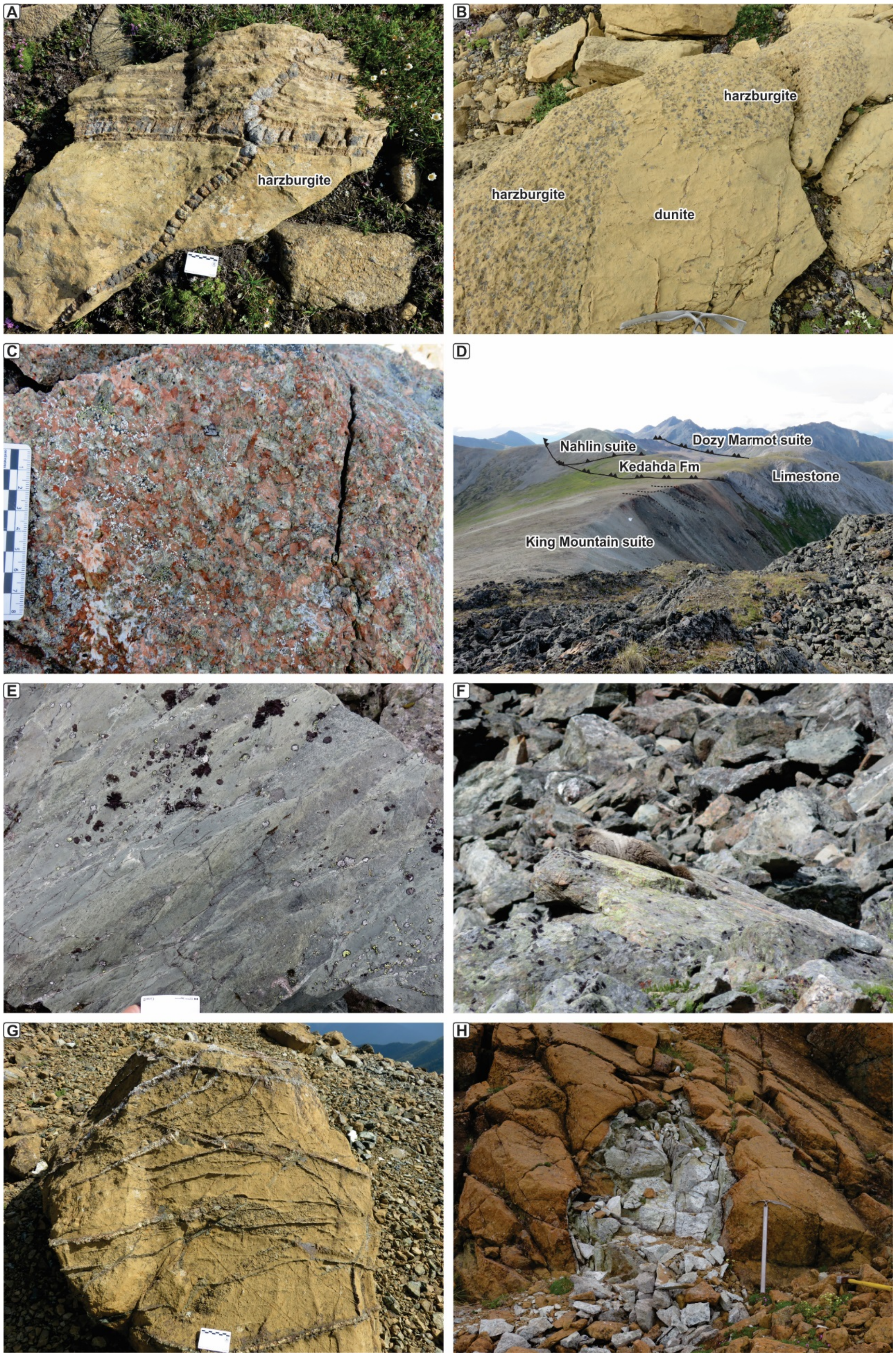
Geochemical investigations of the Nahlin suite (this study; Babechuck et al., 2010; Canil et al., 2006) indicate that the majority of samples have <2% Al_2O_3 and plot among fore-arc mantle sources that arise from high degrees of melting. The vast majority of samples have TiO_2 <0.05%. Primitive mantle (PM) normalized profiles are extremely variable within individual massifs. The most depleted samples have Yb between 0.1 and 0.01PM values, with MREE as low as 0.001PM. Most profiles show some degree of LREE-Th-LILE enrichment indicating derivation by flux melting above a subduction zone. The most depleted samples have significantly lower abundances of REE than Thetford Mines forearc peridotites which are interpreted to have been generated by high degree partial melting and interaction with boninite melts (Page et al., 2009). These characteristics appear to preclude a MORB seafloor spreading center as a viable model for the Cache Creek terrane mantle; rather, supra-subduction zone origin is likely (cf. Ash, 1994; Mihalynuk et al., 2003).

Layered gabbro and peridotite

Crustal cumulate rocks are volumetrically minor but have been previously documented in the King Mountain (Gabrielse, 1998; Zagorevski et al., 2014), Nahlin Mountain (Terry, 1997) and Nakina River map areas where diorite yielded a U-Pb zircon age of 261.4 ±0.3 Ma and a hornblende $^{40}Ar/^{39}Ar$ cooling age of ~265 Ma (Mihalynuk et al., 2003). A cirque exposure of layered, foliated to granular-textured gabbro is well exposed at King Mountain (Zagorevski et al., 2014) and extends to the adjacent ridges. $^{40}Ar/^{39}Ar$ dating of hornblende in hornblendite veins at King Mountain yielded ca. 250 Ma preliminary cooling ages (N. Joyce, unpublished data). Additional exposures of layered coarse grained gabbro have been identified and sampled during the 2015 field season: east of King Mountain as well as northeast of Letain Lake where gabbro and ultramafic cumulate rocks (harzburgite, dunite and websterite) are locally interlayered (Fig. 3c,d). Some of the gabbroic rocks in the King Mountain area were previously mapped as basalt (Gabrielse, 1998) and included in the volcanic-dominated Nakina Formation (Massey et al., 2005). The deep crustal nature of the gabbro and association with ultramafic cumulates is incompatible with their inclusion in a volcanic-dominated formation. We suggest that these rocks be assigned to a separate regional lithodeme: King Mountain suite.

Hypabyssal rocks

Fine-grained, massive to fragmental mafic rocks occur throughout the northern Cache Creek terrane. Massive mafic rocks have been generally mapped as volcanic flows, even though extrusive textures were lacking (e.g., Gabrielse, 1998). In 2014, exposures in the King Mountain area were identified as sub-parallel basalt and gabbro dykes comprising a sheeted dyke complex (Zagorevski et al., 2014). A trondhjemite dyke cutting the sheeted dyke complex yielded ca. 252 Ma preliminary crystallization age (U-Pb titanite, N.


A
harzburgite
B
harzburgite
harzburgite
dunite
C
D
Nahlin suite
Dozy Marmot suite
Kedahda Fm
Limestone
King Mountain suite
E
F
G
H

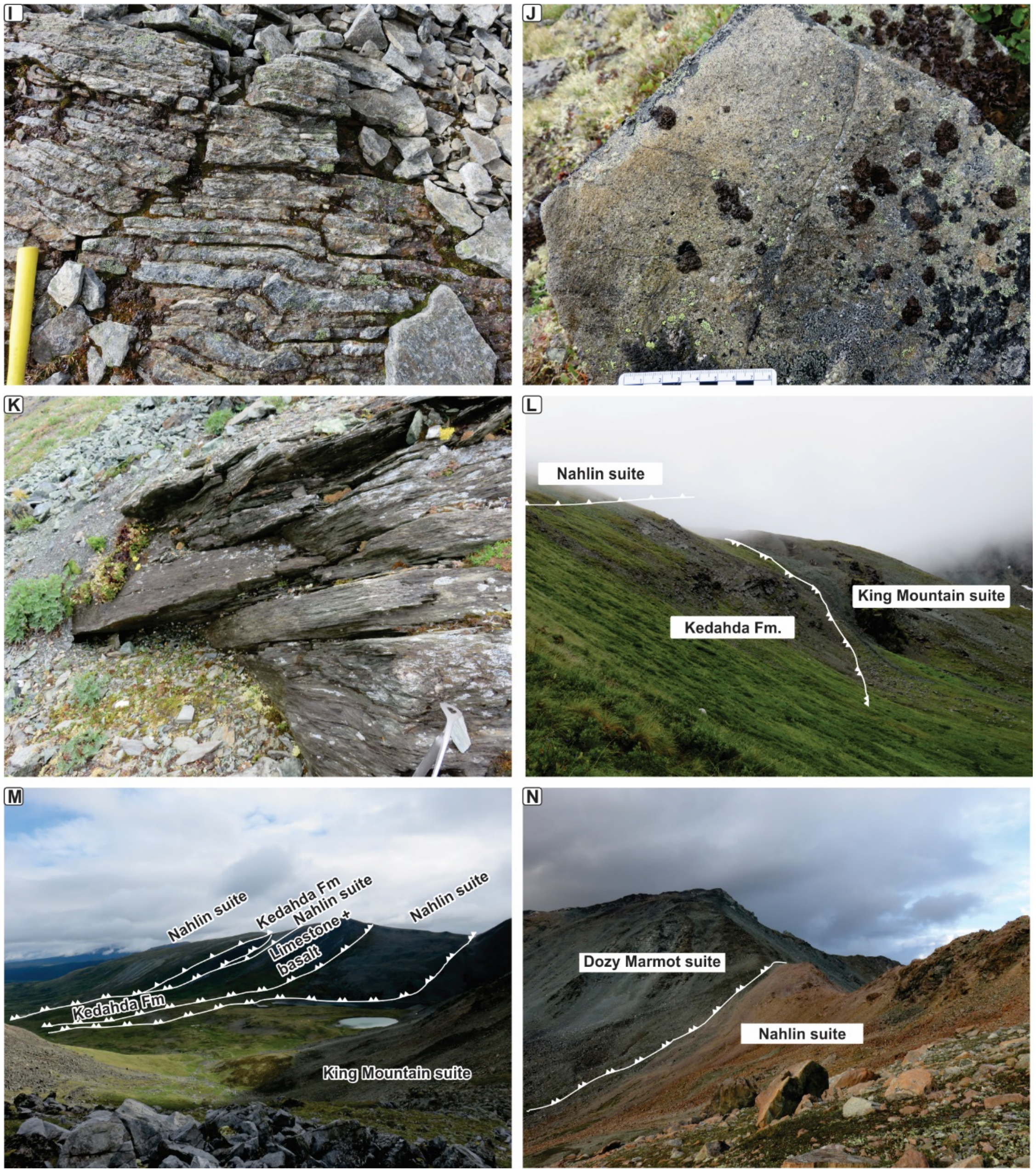


Figure 3 Representative photographs of the Cache Creek terrane. A. Late orthopyroxenite dyke cutting foliation-parallel orthopyroxenite layers in mantle tectonite harzburgite, Nahlin suite. B. Dunite channel cutting mantle hazburgite, Nahlin suite. C. Coarse-grained wherlite, King Mountain suite. D. Relationships between Kedahda Formation and Nahlin, King Mountain and Dozy Marmot suites. D_1 thrusts (single barb) emplace ophiolitic rocks onto Kedahda Formation and limestone (Teslin Formation?). D_2 thrusts (double barb) re-imbricate the sequence. Dotted lines in the King Mountain suite denote cumulate layering between wherlite and dunite. E. Sheeted dyke contacts in Dozy Marmot suite. F. Boulder field derived from sheeted dyke complex. Individual boulders typically and internally homogeneous because fracturing occurs along the sheeted dyke contacts. Marmot for scale. G. Reticulated gabbro veins of the King Mountain suite in mantle peridotite of the Nahlin suite. H. King Mountain suite gabbro boudin (light) in Nahlin suite peridotite. I. Typical ribbon chert of the Kedahda Formation. In the King Mountain area Kedahda Formation appears to be structurally below the ophiolite. J. Coarse-grained, quartz-bearing, arc-derived Kedahda Formation sandstone near Teslin Lake. K. Mylonitic Kedahda Formation below D_1 thrust (see Fig. 3l for location). L. D_1 thrust emplaces Nahlin suite over Kedahda Formation. D2 thrust emplaces Kedahda Formation and Nahlin suite over King Mountain suite. M. D_2 imbrication of D_1 thrust stack results in young-over-old and shallow-over-deep emplacement. N. D_2 thrust emplaces shallower Dozy Marmot suite over deeper Nahlin suite.

Joyce, unpublished data). Additional exposures of sheeted dyke complex have been identified between Letain Lake and Blick Creek (not shown), northeast of King Mountain (Fig. 3e,f), and as far north as Mount Bahram. We suggest that these rocks be assigned to a separate regional lithodeme: Dozy Marmot suite (Fig. 3f).

Crust-mantle relationships

Crust and mantle lithologies are commonly imbricated and cut by late faults, obscuring primary relationships. In many localities, upper crustal lithologies (i.e. hypabyssal, volcanic and sedimentary rocks) lie structurally above mantle rocks with no intervening lower or middle crust rocks (Fig. 4a; e.g., Mihalynuk et al., 2003; Zagorevski et al., 2014). This relationship is consistent across the entire northern Cache Creek terrane from King Mountain to Teslin area. Variably serpentinized ultramafic rocks are commonly dissected by fine to coarse-grained gabbroic dyke swarms. Dykes range from centimeter to decameter scale. Some gabbroic bodies are emplaced at the transition between serpentinized mantle and upper crustal lithologies. These gabbro intrusions are strongly varitextured, and range from fine to pegmatitic on a decimeter scale. Detailed mapping of gabbroic intrusions at various localities confirmed intrusion into peridotite. Gabbro locally forms reticulated vein and dyke swarms (Fig. 3g) suggestive of a low confining pressure due to pre-intrusion exhumation of the mantle peridotite. However, gabbro dykes may locally display ductile dismemberment into isolated pods and boudins within spinel- and plagioclase-bearing peridotite (Fig. 3h). Although exhumed to plagioclase crystallization depth, the gabbro-peridotite massif behaved in a ductile manner, indicating a steep geothermal gradient consistent with rapid exhumation below a detachment.

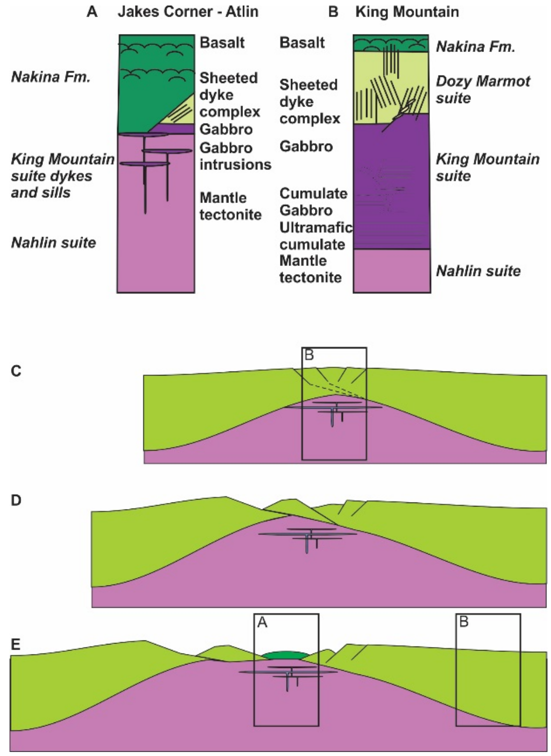


Figure 4 Comparison of ophiolitic pseudo-stratigraphy in the Cache Creek terrane and schematic tectonic model for the observed relationships. A. Pseudo-stratigraphy in the Jakes Corner and Atlin area indicates excision of middle to lower crust. B. Pseudo-stratigraphy in the King Mountain area suggests Penrose-style ophiolite. C-E. Development of oceanic core complex by rifting of an ophiolitic spreading centre where extension is accommodated by emplacement of vertical sheeted dykes and listric normal faults (C). E. Extension is localized along a fault and is tectonically accommodated. Magma emplacement continues. F. Mantle is exhumed onto the sea floor. Continued magmatism results in eruption of Nakina Formation basalt directly onto the sea floor.

Kedahda Formation

Kedahda Formation is a lithologically distinctive and aerially extensive unit characterized by thinly bedded chert (Fig. 3) and pelite, commonly termed “ribbon chert”. These units are locally interbedded with limestone and sandstone and conglomerate containing abundant volcanic and hypabyssal fragments and lesser amounts of plagioclase, mafic minerals, argillite chips and quartz (Fig. 3j; e.g., Monger, 1975; Mihalynuk et al., 2003). Conodonts and radiolaria generally yield Mississippian to Early Jurassic ages, with Middle Triassic ages predominating (e.g., Gordey et al., 1991; Mihalynuk et al., 2003, 2004). In general, provenance of the sandstone and conglomerate is unconstrained. In the Nakina area, granitoid-bearing conglomerate yielded ca. 244 Ma ages (M. Villeneuve, unpublished data; Mihalynuk et al., 2003). Samples of volcanic-derived conglomerate from the Dease Lake and King Mountain areas yielded U-Pb zircon ages consistent with Late Triassic to Early Jurassic deposition (<210 and <192 Ma) and characteristic Stikinia and Kutcho provenance (ca. 210 to 220, 250, 320 Ma; N. Joyce unpublished data). Additional sandstone and conglomerate samples were collected in 2015 from Teslin, Atlin, and Nahlin areas to further constrain provenance.

Parts of the Kedahda Formation are interpreted to stratigraphically overlie ophiolitic pseudo-stratigraphy as it is at least locally intercalated with the Nakina Formation basalt; however, contacts between Kedahda Formation and adjacent units are commonly separated by faults, obscuring primary relationships (e.g., Mihalynuk et al., 2003; McGoldrick et al., in prep). Furthermore, Mississippian radiolaria that predate ophiolitic and arc rocks indicate that Kedahda Formation likely comprises several tectono-stratigraphic units, each with unique provenance (Mihalynuk et al., 2003). Correlatives of the Kedahda Formation occur throughout the King Mountain area (Gabrielse, 1998; Massey et al., 2005), where detailed mapping identified strongly deformed to mylonitic, structurally imbricated chert, fine grained siliciclastic rocks, limestone and basalt in the structural footwall (D_1) to the ophiolite (Figs. 3d,k,l). Although these rocks were previously included in the Kedahda and Nakina formations, limestone and basalt may form part of the Teslin and French Range formations (Gabrielse, 1998). The provenance of the sedimentary rocks is yet unknown; however, they may represent the primary sole of the ophiolite and thus may form a completely different lithostratigraphic unit(s) from the Kedahda Formation rocks that overlie the ophiolite. Further work is planned to test the applicability of this hypothesis to the northwest and identify criteria to differentiate multiple Kedahda Formation-like units (e.g., Mihalynuk et al., 2003).

Ophiolitic stratigraphy

Structurally dismembered, Penrose-style ophiolite components (Anonymous, 1972) are well exposed in the King Mountain area and include Nahlin suite mantle rocks, King Mountain suite cumulate mafic and ultramafic rocks, and Dozy Marmot suite sheeted dyke complex (Fig. 4b). Nakina Formation basalt is predominantly exposed further to the northwest. Nahlin Mountain-Nakina area does preserve some elements of the Penrose-style stratigraphy; however, King Mountain and Dozy Marmot suites are poorly represented, suggesting structural excision. Atlin and Teslin areas are dominated by Nahlin suite and Nakina Formation (Fig. 4a). The general distribution of these rocks suggests that the lower and middle ophiolitic crust was excised along an intra-oceanic detachment zone, similar to intra-oceanic core complexes (Fig. 4c-e; e.g., Ohara et al., 2003). If so, ophiolitic spreading may have been accommodated magmatically in the southeast (Fig. 4c) and tectonically in the northwest (Fig. 4e). Such a relationship could result from either: progressive rifting of a supra-subduction zone ophiolite, with intitial rifting accommodated magmatically; or by contemporaneous along-strike differences between tectonically and magmatically accommodated spreading segments that are separated by a transform fault.

Syn-and post-obduction structures

Thrust faults are recognized throughout the northern Cache Creek terrane; however, determining the generation and significance of these thrust faults is commonly difficult. Mapping in the King Mountain area revealed at least two generations of thrust faults. First generation thrust faults (D_1) are very shallowlydipping structures which emplace Nahlin ultramafic suite over chert, fine grained siliciclastic rocks, limestone and basalt presently included in the Kedahda Formation (Figs. 3d,k,l,m). These structures appear to be the primary control on the distribution of ophiolitic rocks. A second set of moderately to steeply northeast dipping thrusts (D_2) imbricates D_1 structures, resulting in interleaving of Nahlin ultramafic suite mantle and structurally underlying “Kedahda Formation” (Fig. 3m) as well as (re-)imbrication of ophiolitic stratigraphy (Fig. 5). Re-imbrication of ophiolitic stratigraphy resulted in emplacement of Dozy Marmot suite over the Nahlin ultramafic suite (Fig. 3n). Since D_2 structures in the King Mountain area displaced sub-horizontal D_1 boundaries, relatively minor displacement of D_2 structures has resulted in profound apparent displacement of units in map view. D_2 structures are parallel to the Nahlin Fault, which appears to truncate the principal sub-ophiolitic D_1 basal thrust.

Conclusions

The northern Cache Creek terrane in part comprises components of structurally dismembered ophiolite, including the Nahlin ultramafic suite mantle rocks, King Mountain suite cumulate mafic and ultramafic rocks, Dozy Marmot suite sheeted dyke complex and Nakina Formation basalt. The distribution of these components is most easily explained by magmatically-accommodated extension in the southeast and tectonically-accommodated extension in the northwest. Tectonically-accommodated extension resulted in juxtaposition of upper crustal and mantle lithologies in an intra-oceanic setting along a detachment. The significance of ophiolitic components is being tested through petrological, geochemical and geochronological investigations (Corriveau, McGoldrick, Bedard, Canil). Ophiolitic components were obducted onto a sequence of chert, fine grained siliciclastic rocks,

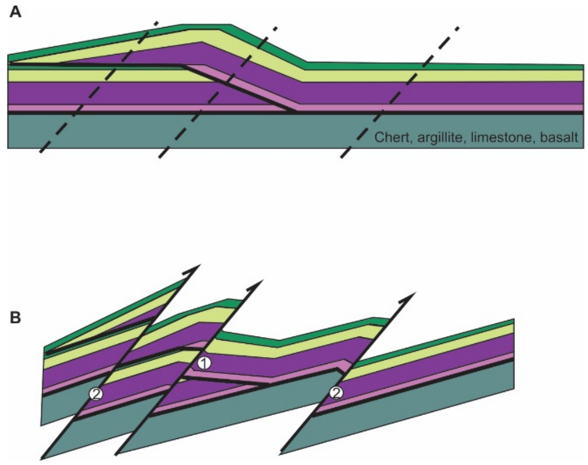


Figure 5 Schematic structural history in the King Mountain area. A. Ophiolite is emplaced above D_1 thrust fault over imbricated Kedahda, Teslin (?) and French Range (?) formations. South-west directed D_2 thrust faults re-imbricated the sequence resulting in emplacement of shallower Dozy Marmot suite over deeper Nahlin suite (1) and Kedahda Formation over the Nahlin suite mantle (2).

limestone and basalt above D_1 thrust faults. Subsequent D_2 (Jurassic?) re-imbrication of the shallow D_1 thrust faults resulted in young-over-old and shallow-over-deep relationships across D_2 thrust faults. Relationship, if any, between mapped Kedahda Formation in the footwall of the ophiolite and Kedahda Formation that overlies the ophiolite is being tested through provenance, fossil and geochemical studies (Joyce, Golding, Zagorevski). Regional compilation and reinterpretation of the tectono-stratigraphy is on-going (Zagorevski and Mihalynuk).

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