Spatial and temporal distribution of the Late Triassic to Early Jurassic porphyry-style mineralized plutons of the Quesnel terrane, British Columbia: inferences on tectonic controls and porphyry prospectivity

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Abstract: Middle Triassic to Middle Jurassic arc-related sequences of the Quesnel terrane, British Columbia, host numerous major porphyry deposits. In south-central Quesnel terrane, temporal and spatial distribution of deposits have been related to eastward-younging, subparallel belts of coeval, compositionally similar associated plutonic suites corresponding to shallowing of Cache Creek subduction beneath the Quesnel terrane.

Changes in alkalinity of arc magmatism is best explained by ingress of hot primitive mantle due to tectonic processes (i.e. slab rollback, tears, or break-off); however, such mechanisms are inconsistent with eastward migration of magmatism within a dominantly submergent (largely marine) arc built above east-dipping subduction. Furthermore, the plutonic belts were defined for the southern Quesnel terrane and are far less apparent farther north. Notably, the plutonic belts are defined on the oldest exposed intrusions, with their distribution correlating to the overall eastward-younging of fault-bounded country-rock panels.

In this paper, it is suggested that the axis of arc magmatism could remain largely static relative to the leading edge of the Quesnel terrane, with the observed distribution of southern Quesnel plutonism explained by post-depositional structural arrangement of fault-bounded blocks. This model raises the possibility of undiscovered early mineralization being buried beneath Rhaetian and younger sequences exposed in central and eastern Quesnel fault panels

Résumé : Dans le terrane de Quesnel, en Colombie-Britannique, des séquences du Trias moyen au Jurassique moyen apparentées à un arc renferment de nombreux gîtes porphyriques d'importance. Dans la partie centre sud du terrane de Quesnel, la distribution temporelle et spatiale des gîtes a été rattachée à des ceintures subparallèles de suites plutoniques d'âges et de compositions semblables montrant un rajeunissement vers l'est, lequel rend compte d'un exhaussement du terrane de Cache Creek subducté sous le terrane de Quesnel.

Les changements dans l'alcalinité du magmatisme d'arc s'expliquent bien par l'infiltration de manteau primitif chaud par le jeu de processus tectoniques (c.-à-d. le repli, la déchirure ou la rupture de dalles). Toutefois, ces mécanismes sont incompatibles avec la migration vers l'est de l'activité magmatique dans un arc principalement submergé (en grande partie en milieu marin), édifié au-dessus d'une zone de subduction inclinée vers l'est. En outre, les ceintures plutoniques qui ont été définies dans la partie sud du terrane de Quesnel sont beaucoup moins apparentes plus au nord. Plus spécialement, les ceintures plutoniques sont définies à partir des intrusions affleurantes les plus anciennes et leur distribution est corrélée à celle des panneaux de roches encaissantes délimités par des failles qui montrent globalement un rajeunissement vers l'est.

Dans cet article, nous suggérons que l'axe du magmatisme d'arc pourrait être demeuré en grande partie statique par rapport à la bordure externe du terrane de Quesnel, où la distribution observée de l'activité plutonique dans la partie sud de celui-ci s'expliquerait par la disposition structurale postsédimentaire des blocs délimités par des failles. Ce modèle laisse entrevoir la possibilité qu'une minéralisation précoce non encore découverte soit enfouie sous les séquences du Rhétien et de temps plus récents qui affleurent dans les panneaux délimités par des failles dans les parties centre et est du terrane de Quesnel.

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INTRODUCTION

The Quesnel terrane of British Columbia hosts numerous major porphyry and related mineral deposits, making it one of Canada's most important metallogenic belts (Fig. 1, 2). The terrane consists of Triassic to Jurassic volcanic and sedimentary rocks that are intruded by multiple calc-alkaline to alkaline magmatic pulses (Nelson and Bellefontaine, 1996; Breitsprecher et al., 2007, 2010; Logan and Mihalynuk, 2014; Mihalynuk et al., 2014, 2016; Schiarizza, 2016, 2017, 2019). Several workers have noted that these intrusions define multiple subparallel linear belts of coeval, compositionally similar plutonic suites (e.g. Parrish and Monger, 1992; Breitsprecher et al., 2010; Logan and Mihalynuk, 2014). Although the designations of these belts across the Quesnel terrane are not universally accepted (Breitsprecher et al. (2010) defined four belts, whereas Logan and Mihalynuk (2014) described three belts), the consensus is that they represent an eastward-younging progression of calc-alkaline to alkaline magmatic events, each of which extends over a 4 to 10 Ma period.

This paper examines the tectonic implications of the defined eastward progression of magmatic belts across the southern to central portion of the Quesnel terrane and assesses whether there are potential inferences that could apply to mineral prospectivity. To understand the underlying tectonic controls behind the observed distribution of plutonic suites, this paper reviews previously obtained age determinations for the Quesnel terrane, from the southern border of British Columbia to the Hogem Batholith at approximately 56.5° north (Fig. 2). The location, age, precision, method, interpretation, and source of analyses under consideration are compiled in Appendix A.

TECTONOSTRATIGRAPHIC FRAMEWORK

The Canadian Cordillera is divided into five morphological belts (from west to east: Insular, Coast, Intermontane, Omineca, and Foreland) characterized by differences in land forms, geological units, and structure (Monger et al., 1972; Gabrielse et al., 1991). These belts are composed of one or more terranes, which have been defined as fault-bounded geological entities of regional extent that are characterized by a largely coherent stratigraphy (Coney et al., 1980; Coney, 1989). The Quesnel terrane (Fig. 1, 2), along with the Cache Creek and Stikine terranes, constitute the Intermontane Belt (Coney et al., 1980; Monger et al., 1982; Silberling et al., 1992).

The prevailing tectonic paradigm for the evolution of the Quesnel terrane is that it is a Paleozoic continental block derived from the western margin of Ancestral North America

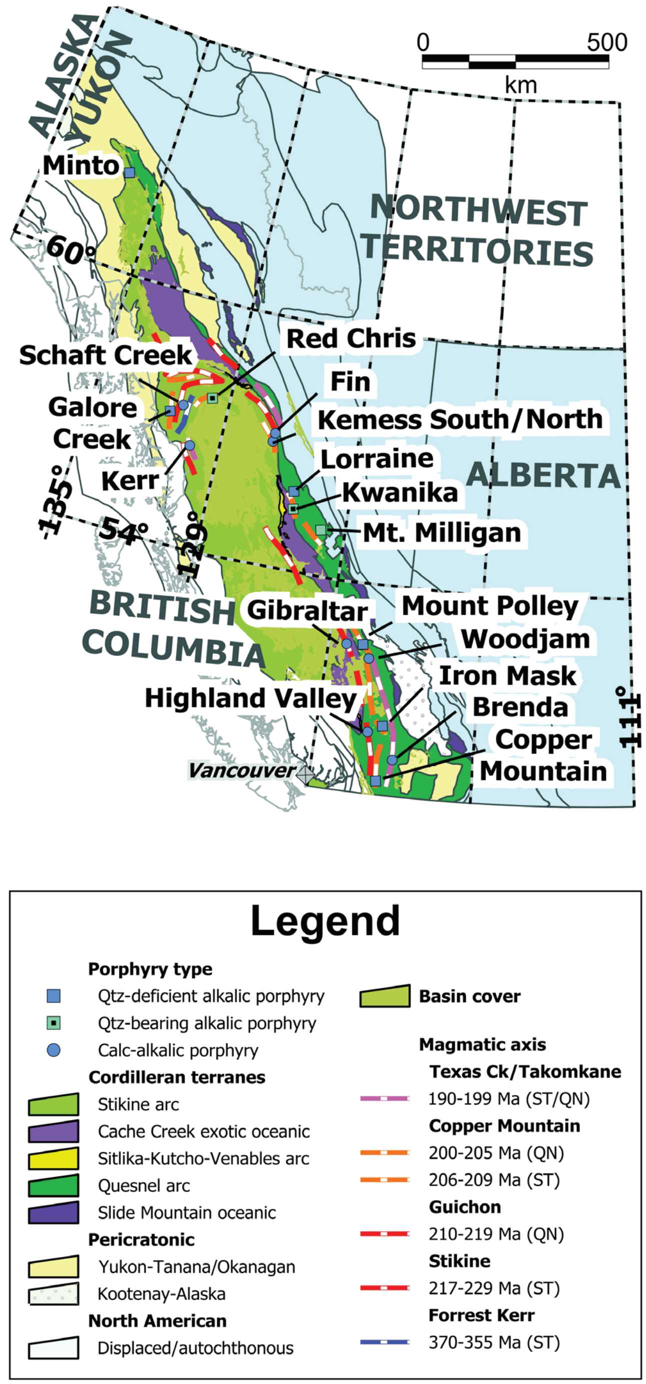

Figure 1. Major porphyry deposits of the Quesnel and Stikine terranes, Canadian Cordillera; *modified from* Logan and Mihalynuk (2014) and Mihalynuk et al. (2016).

on which a west-facing Mesozoic arc formed (Gabrielse et al., 1991). In this model, the Quesnel terrane is separated from Ancestral North America by the remnants of an oceanic tract (Slide Mountain terrane), with it becoming accreted to composite Laurentia by the Middle Jurassic (Monger et al., 1982; Mihalynuk et al., 1994). The Mesozoic arc magmatism

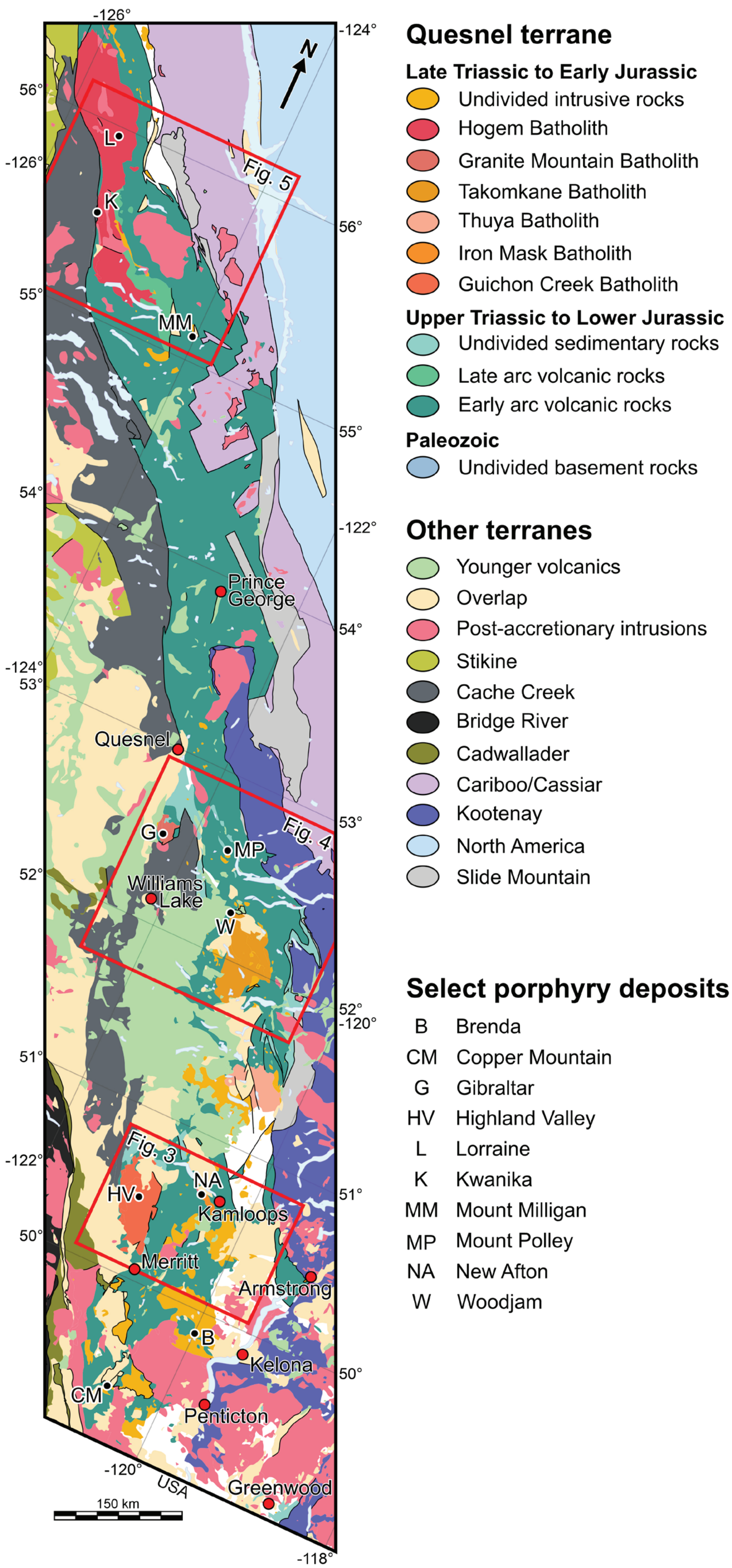

Figure 2. Simplified bedrock geology of the central portion of British Columbia between 49° and 56.5° north. Red boxes indicate the areas of more detailed bedrock geology shown in Figures 3 to 5. *Modified from* British Columbia Geological Survey's MapPlace 2 digital geology (Cui et al., 2017).

developed on the Quesnel terrane is related to the eastward (current orientation) subduction of the oceanic Cache Creek terrane. The Stikine terrane is broadly correlative to Quesnel, but is now positioned to the west of the Cache Creek terrane in British Columbia (Fig. 2). This organization of terranes has been explained by an 'enclosure' model (Nelson and Mihalynuk, 1993; Mihalynuk et al., 1994; Nelson and Colpron, 2007), whereby the Stikine terrane originated as the northern extension of the Quesnel terrane prior to wrapping around the Cache Creek terrane forming an orocline. A consequence of this model is that, through the Late Triassic to Early Jurassic, the oceanic Cache Creek terrane is experiencing concurrent eastward subduction beneath the Quesnel terrane and westward subduction beneath the Stikine terrane (current coordinates).

SUPRACRUSTAL SEQUENCES OF THE QUESNEL TERRANE

In the simplest terms, the Quesnel terrane consists of Middle Triassic to Middle Jurassic arc volcanic and siliciclastic rocks, built on Late Paleozoic sequences (Fig. 3–5). The Quesnel terrane Paleozoic sequences were allocated by Monger et al. (1991) to the Okanagan and Harper Ranch subterranes. The Okanagan subterrane is recognized only in southern British Columbia. It consists predominantly of basalt and chert, along with minor limestone and serpentinized ultramafic rocks, and was likely formed in a marginal basin, potentially related to the Slide Mountain terrane (Monger et al., 1991). In the southern part of the Quesnel terrane, the Harper Ranch subterrane is largely represented by the Late Devonian to Late Permian Harper Ranch Group (Fig. 3; Beatty et al., 2006), which consists of arc-derived volcaniclastic rocks along with limestone, argillite, chert, and clastic sedimentary rocks. Farther north in the Quesnel terrane, the Harper Ranch subterrane is represented by Carboniferous to Permian arc volcanic and sedimentary rocks of the Lay Range assemblage (Fig. 5; Nelson et al., 1993; Ferri, 1997). The composite diorite-gabbro Lounge Lizard Intrusive Complex (Nelson et al., 1993) occurs as a faulted block within Lay Range assemblage rocks. This body is classified as Paleozoic, but it is notable that Nelson et al. (1993) observed the similarity of this complex with components of the Jurassic Boundary phase of the Hogem Batholith. Furthermore, the ca. 186 Ma Polaris Ultramafic Complex occupies a very similar structural position, approximately 75 km to the north-northwest (Nixon et al., 1997).

The Triassic Slocan Group primarily outcrops along the south and central portion of the eastern margin of the Quesnel terrane, adjacent to the Slide Mountain terrane (Fig. 4; Rees, 1987; Panteleyev et al., 1996; Schiarizza et al., 2013; Schiarizza, 2016). This unit that forms a relatively narrow band to the north of Kamloops, whereas farther south it discontinuously occurs over a significantly wider area, consists mostly of dark grey to black slate and phyllite, with minor light to medium grey siltstone (Schiarizza, 2016). Previous studies recognized these sedimentary sequences as distinct (e.g. Campbell and Tipper, 1971), with Schiarizza et al. (2013) mapping them as a separate unit within the primarily arc volcanic Nicola Group. Schiarizza (2016), following Rees (1987), subsequently defined them as the distinct and discretely mappable Slocan Group.

The Nicola Group represents the dominant supracrustal sequence in the south and central portions of the Quesnel terrane (Fig. 3, 4). The equivalent stratigraphic unit in the northern part of the Quesnel terrane, and indeed the related Stikine terrane, is the Takla Group (Fig. 5). The Nicola Group largely consists of submarine volcanic, volcaniclastic, and sedimentary rocks (Preto, 1979; Mortimer, 1987; Mihalynuk et al., 2016) representing more than a dozen individual lithostratigraphic units (Mihalynuk et al., 2016). Recent age determinations indicate that Nicola magmatism occurred in several pulses during the Middle and Upper Triassic (Mihalynuk et al., 2015, 2016).

In the southern portion of the Quesnel terrane, the Nicola Group is divided between three subparallel belts separated along north-trending faults, referred to as the Eastern, Central, and Western belts (Fig. 3; Preto, 1979; Mihalynuk et al., 2016). The Western belt of the Nicola Group contains the 'lower mafic unit' that is dominated by massive, poorly-layered, oxidized to epidotized, dark green, augite-phyric calc-alkalic basaltic lava flows, interlayered with mafic tuff, and the 'upper stratified unit' consisting of variable andesitic to rhyolitic volcanic and volcaniclastic rocks interbedded with feldspathic wacke, conglomerate, siltstone and limestone (Mihalynuk et al., 2016). The Western belt includes Ladinian (ca. 238 Ma) and lower Norian (ca. 224 Ma) magmatism, as well as middle to upper Norian clastic sedimentation (ca. 210 Ma; Appendix A; Mihalynuk et al., 2016). The Central belt also contains a Ladinian magmatic pulse, along with a younger pulse in the latest Triassic/lowermost Jurassic (ca. 201 Ma). There are also Norian zircon-bearing clastic sedimentary rocks that are interpreted as the product of uplift that eroded middle Norian components (Mihalynuk et al., 2016). The Eastern belt consists mostly of well-bedded, clastic sedimentary rocks, along with (mostly) mafic volcanic units that are middle Norian to latest Triassic/lowermost Jurassic (Mihalynuk et al., 2016). This recent dating also demonstrated that the main sedimentary successions of the Eastern belt (or at the very least those exposed toward the west of this belt) are coeval to younger than the last vestiges of Nicola volcanism, and not representative of a thick turbiditic basement to arc magmatism, as previously believed (e.g. Mihalynuk et al., 2015).

Farther north, between Bonaparte Lake and the Quesnel River, the Nicola Group is separated into four lithostratigraphic assemblages (Fig. 4; Schiarizza, 2016, 2017, 2019) that at least in part demonstrate superpositional relationships.

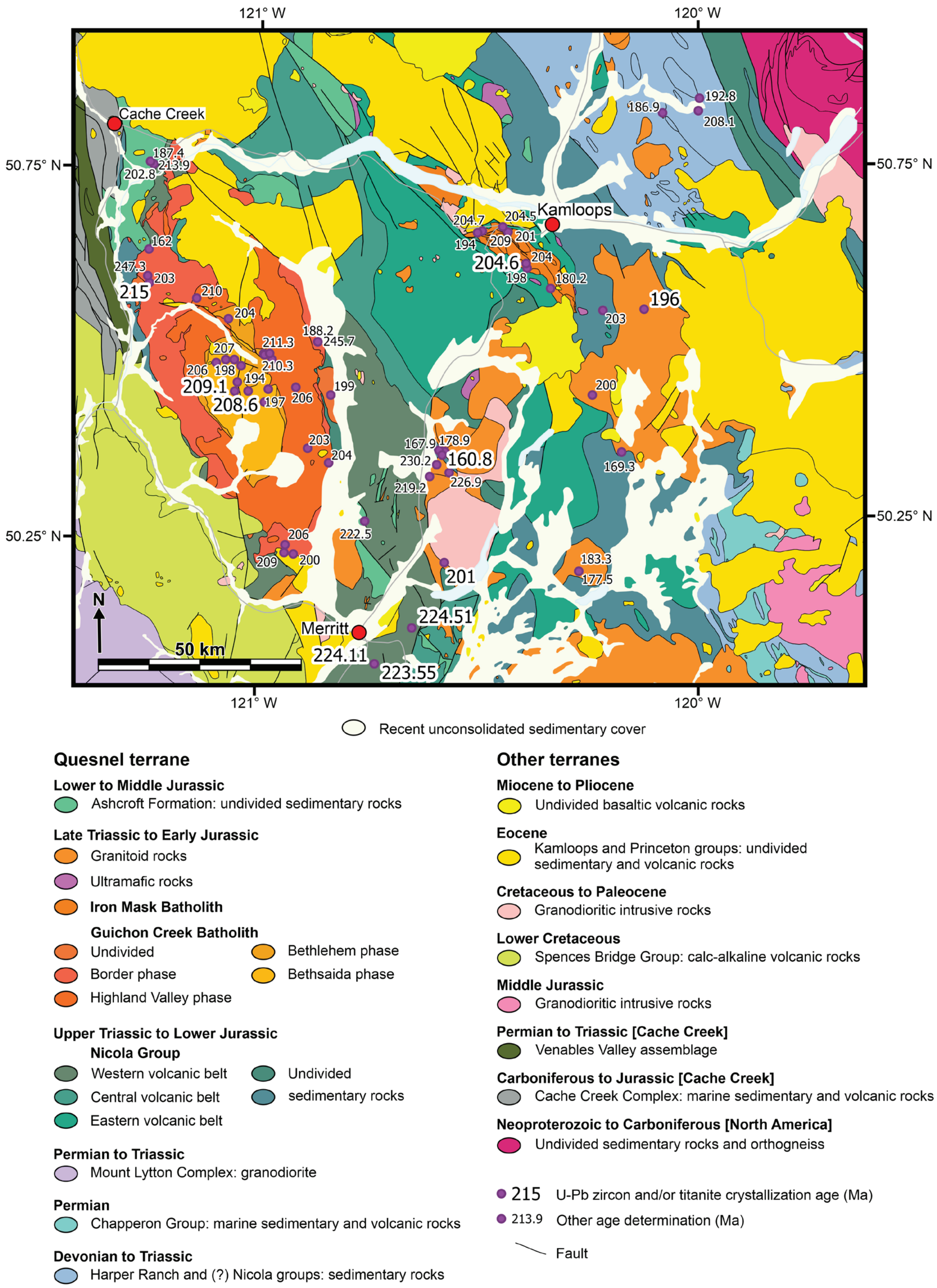

Figure 3. Bedrock geology of the Guichon Creek and Iron Mask batholith area. *Modified from* British Columbia Geological Survey's MapPlace 2 digital geology (Cui et al., 2017), in association with Beatty et al. (2006), Breitsprecher (2010), Friedman et al. (2016), Mihalynuk et al. (2016), and Whalen et al. (2017). Distribution of select Mesozoic Quesnel terrane age determinations are shown (Wanless et al., 1965, 1968; White et al., 1967; Chrismas et al., 1969; Blanchflower, 1971; Jones, 1975; Preto et al., 1979; Hunt and Roddick, 1987; Mortimer et al., 1990; Parrish and Monger, 1992; Mortensen et al., 1995; Moore et al., 2000; Erdmer et al., 2002; Friedman et al., 2002, 2016; Petersen et al., 2004; Breitsprecher et al., 2010; Whalen et al., 2017). Additional age determination data are compiled in Appendix A.

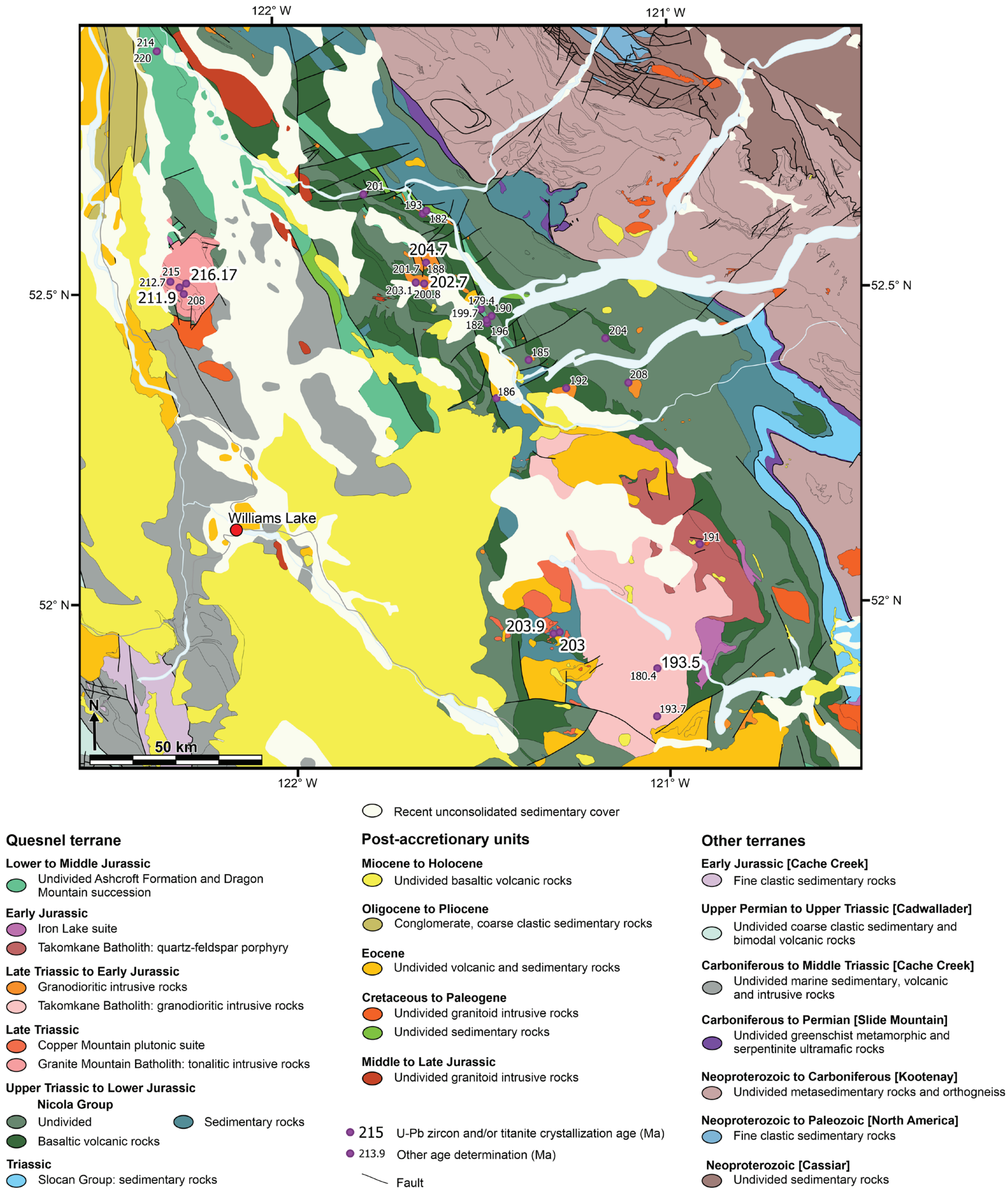

Figure 4. Bedrock geology of the Granite Mountain and Takomkane batholith area. *Modified from* British Columbia Geological Survey's MapPlace 2 digital geology (Cui et al., 2017), in association with Schiarizza (2014, 2015, 2016) and Mostaghimi (2016). Distribution of select Mesozoic Quesnel terrane age determinations are shown (Leech et al., 1963; Schink, 1974; Drummond et al., 1976; Jung, 1986; Bailey and Archibald, 1990; Mortensen et al., 1995; Panteleyev et al., 1996; Whiteaker et al., 1998; Petersen, 2001; Petersen et al., 2004; Oliver et al., 2009; R.G. Anderson, pers. comm., 2012; Mostaghimi, 2016). Additional age determination data are compiled in Appendix A.

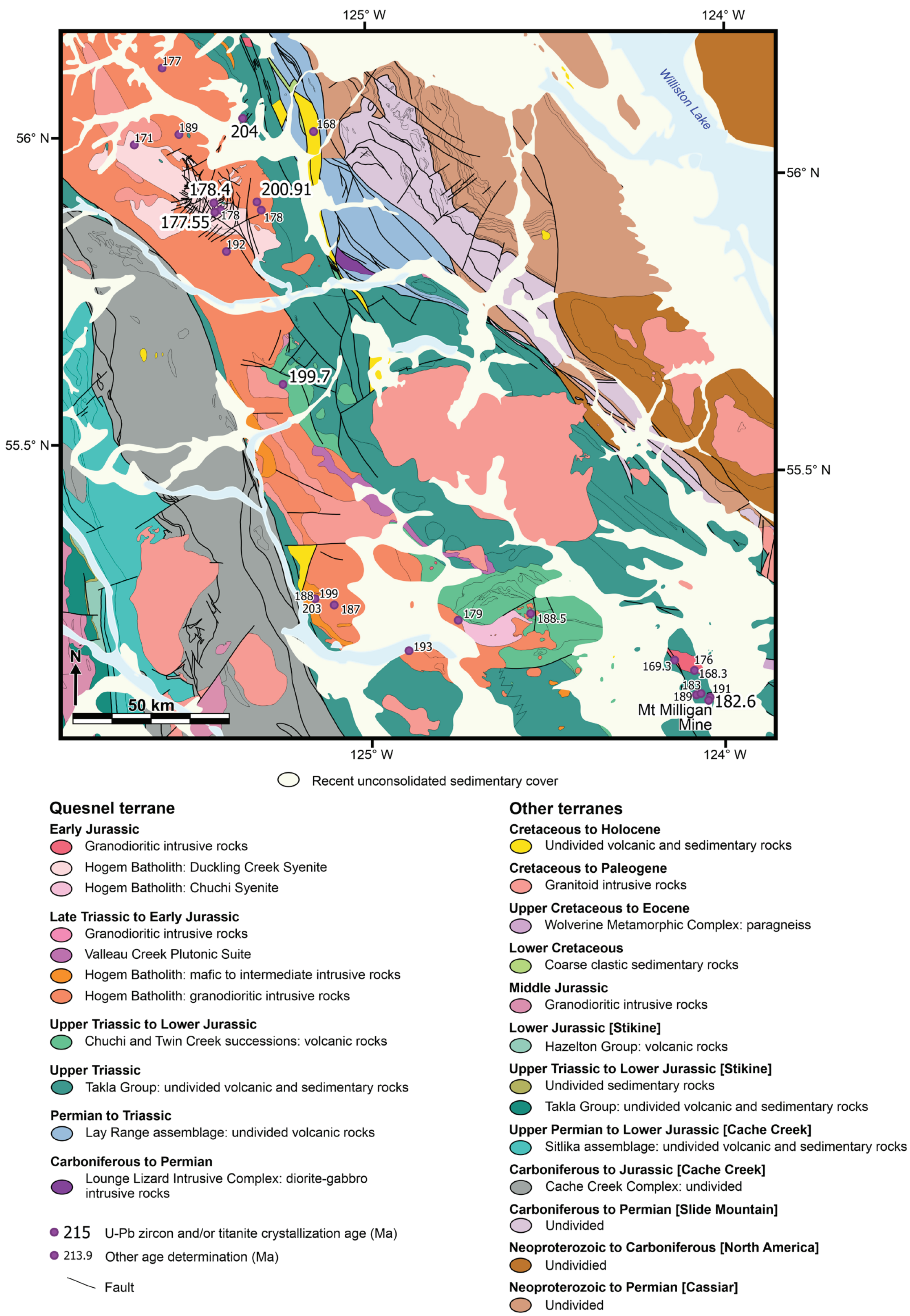

Figure 5. Bedrock geology of the Hogem Batholith area. *Modified from* British Columbia Geological Survey's MapPlace 2 digital geology (Cui et al., 2017), in association with Bath et al. (2014), Devine (2014), and Ootes (2019). Distribution of select Mesozoic Quesnel terrane age determinations are shown (Eadie, 1976; Garnett, 1978; Parrish and Tipper, 1992; Mortensen et al., 1995; Nelson and Bellefontaine, 1996; Bath et al., 2014; Devine et al., 2014). Additional age determination data are compiled in Appendix A.

Assemblage one, which is exposed in a relatively extensive and continuous zone along the east margin of the group, along with a tentatively correlated zone in the interior of the belt, consists of Middle Triassic units composed dominantly of siltstone, argillite, chert, and volcanic sandstone, along with occasional lenses of lithologically distinct pillow basalt that is interpreted as non-arc (Logan and Bath, 2006; Schiarizza, 2019). Assemblage two, which is the most widespread component of the Nicola Group in this area, largely consists of volcanic sandstone and pyroxene-phyric basalt and breccia (Schiarizza, 2019). Sparse fossil collections indicate an early Carnian to early Norian age for this assemblage (Schiarizza, 2016, 2019). Assemblage three is represented by homogeneous pyroxene-phyric basaltic rocks that form two belts defining a regional syncline, and is presumed to be Norian (Schiarizza, 2019). Assemblage four consists of a potentially unconformable set of latest Triassic to Early Jurassic conglomerate, sandstone and volcanic rocks that form the uppermost portion of the Nicola Group (Schiarizza, 2019). Assemblage four rocks are mainly exposed as the core of a regional syncline observed west of the Takomkane Batholith (Fig. 4; Schiarizza, 2016).

The Middle to Upper Triassic Takla Group of the northern Quesnel terrane (Fig. 5; Nelson et al., 1993) is lithologically similar to, and effectively coeval with, Nicola Group rocks. The oldest rocks of the Takla Group are dark grey to black shales and siltstones, with minor epiclastic and pyroclastic deposits. Younger (presumably late Carnian to middle Norian) rocks include augite-xenocrystic, lapilli-bearing volcaniclastic rocks and fine-grained, black siltstone and argillite. These are overlain, at least in part, by a thick sequence of coarse-grained, augite-xenocrystic, pyroclastic basaltic rocks, with lesser flows and minor plagioclase-dominant units and epiclastic sedimentary beds.

The Takla Group in this area is unconformably (to possibly disconformably) overlain by Lower Jurassic rocks of the volcanic Chuchi Lake and Twin Creek sequences and the clastic sedimentary Discovery Creek sequence (Fig. 5; Nelson and Bellefontaine, 1996). These rocks were originally included within the Takla Group and might correspond with the broadly coeval units that postdate the Nicola Group in the south and central portion of the Quesnel terrane (Nelson and Bellefontaine, 1996). Such units include the locally sourced conglomerate, sandstone, siltstone, grey and carbonaceous black shale, and limestone of the Ashcroft Formation (Fig. 3, 4; McMillan, 1974) and interbedded conglomerate and sandstone of the Dragon Mountain succession (Fig. 4; Logan and Moynihan, 2009). Dragon Mountain succession conglomerate is described as notably polymictic, including granitoid and Nicola Group–sourced volcanic detritus (Schiarizza et al., 2002; Logan and Moynihan, 2009; Schiarizza, 2015). It seems reasonable that the Chuchi Lake, Twin Creek, and Discovery Creek sequences are equivalent to the Early to Middle Jurassic Rossland and Ymir groups that are exposed along the southeast margin of the Quesnel terrane (in the area south of Castlegar to Nelson, British Columbia). The Elise Formation volcanic rocks of the Rossland Group overlie Sinemurian sedimentary rocks (Archibald Formation, Rossland Group) and are interpreted as largely marine, calc-alkalic to alkalic, arc volcanic rocks built on attenuated continental crust (Höy and Dunne, 1997).

LATE TRIASSIC TO MIDDLE JURASSIC QUESNEL TERRANE INTRUSIVE ROCKS

The Late Triassic to Middle Jurassic intrusions into the Quesnel terrane are the driver/source of the porphyry-style mineralization that makes this region economically important. Although individual batholiths (i.e. Guichon Creek) typically exhibit distinct pulses of magmatism, over the terrane as a whole age determinations indicate effectively continuous magmatic activity for over 50 Ma (*see* Appendix A for select age determinations). Note, this assertion assumes that Ar-Ar and K-Ar cooling and/or alteration age determinations are broadly representative of magmatic activity (although not necessarily exposed intrusive bodies) given that Middle Triassic and younger rocks of the Quesnel terrane experienced only zeolite to prehnite-pumpellyite metamorphism (Greenwood et al., 1991; Read et al., 1991).

In the southern Quesnel terrane, intrusive magmatism has been split into paired calc-alkalic to alkalic belts that migrated to the east over time in response to east-dipping subduction (Logan and Mihalynuk, 2014). Breitsprecher et al. (2010) defined the magmatic progression as i) Late Triassic (ca. 212–208 Ma) Guichon Creek suite—calc-alkaline porphyry Cu-Mo±Au mineralization; ii) latest Late Triassic (ca. 206–200 Ma) Copper Mountain suite—significant alkaline porphyry Cu-Au±Ag mineralization; iii) Early Jurassic (ca. 197–192 Ma) Wildhorse suite—local calc-alkaline porphyry Cu±Au±Mo mineralization; and iv) latest Early Jurassic (ca. 190–182 Ma) Iron Lake suite—poorly mineralized alkaline mafic to ultramafic units. Logan and Mihalynuk (2014), as well as extending the belts to the Stikine terrane, correlated the early phases of the Hogem Batholith (Mortensen et al., 1995) with the Copper Mountain suite and extended the second pulse of alkalic magmatism to ca. 178 Ma for the northern Quesnel terrane based on the Lorraine deposit ages (Duckling Creek phase of the Hogem Batholith; Bath et al., 2014; Devine et al., 2014).

Guichon Creek Batholith

The Guichon Creek Batholith (Fig. 3) is a concentrically zoned, calc-alkalic body, approximately 65 by 30 km in size, that intrudes Nicola Group rocks (McMillan et al., 2009; Anderson et al., 2012; Bouzari et al., 2016, 2017; Whalen et al., 2017). The batholith contains diorite, quartz diorite, quartz monzonite, and granodiorite components distributed between the Border, Highland Valley (consisting of the Guichon and Chataway subphases), Bethlehem (consisting of the Bethlehem and Skeena subphases), and Bethsaida phases (Casselman et al., 1995; McMillan et al., 2009). The Highland Valley porphyry Cu-Mo-Ag-Au deposits (Valley, Lornex, Highmont, Alwin, Bethlehem, and JA) are hosted within the Bethlehem and Skeena subphases and Bethsaida phase (McMillan et al., 2009; Logan and Mihalynuk, 2014). Crystallization ages determined with U-Pb zircon range between 215 and 206 Ma, with Ar ages clustering from 202 to 197 Ma and 194 to 188 Ma (Fig. 3; Appendix A).

Granite Mountain Batholith

The Late Triassic Granite Mountain Batholith occurs in a fault-bounded panel of Quesnel terrane rocks, partially enveloped by Cache Creek terrane, southwest of the main belt of Quesnel rocks in south-central British Columbia (Fig. 4; Schiarizza, 2015). The batholith, which hosts the Gibraltar porphyry Cu-Mo mine, is divided into three main units. These are, from southwest to northeast: the Border phase (diorite to quartz diorite), the Mine phase (tonalite) and the Granite Mountain phase (leucocratic tonalite). Kobylinski et al. (2020) noted that intrusive contacts are not apparent between these phases, nor are there wholly distinctive characteristics for each phase. Thus, they proposed a simpler division into copper-bearing and barren phases. In this scheme the copper-bearing tonalite contains visible chalcopyrite, whereas chalcopyrite grains are absent in the barren tonalite. Age determinations are largely between 216 and 208 Ma (Fig. 4; Appendix A), making the Granite Mountain Batholith effectively coeval with the Guichon Creek Batholith approximately 250 km to the south-southeast. Note, Kobylinski et al. (2020), following the suggestion of Ash et al. (1999), include the Burgess Creek stock (Panteleyev, 1978; Schiarizza, 2014, 2015) within the Granite Mountain Batholith, extending the range for barren rocks to ca. 229 Ma.

Iron Mask Batholith

The Iron Mask Batholith (Fig. 3), which hosts the New Afton and Ajax deposits, is a diorite–monzonite complex that outcrops as two bodies separated by a graben of Eocene rocks (Kamloops Group). The batholith is divided into the Pothook diorite, Cherry Creek monzonite, Sugarloaf diorite, and Iron Mask Hybrid phase (Logan et al., 2006, 2007). Age determinations for the Iron Mask Batholith are largely between ca. 205 and 194 Ma, although a distinctly younger ca. 180 Ma Ar determination is assigned to pegmatite associated with late mineralization (Fig. 3; Appendix A).

Takomkane Batholith

The large, Late Triassic to Early Jurassic, composite calc-alkalic Takomkane Batholith (Fig. 4; Schiarizza et al., 2013) is host to at least three mineralizing events spread over several centres (Schiarizza et al., 2009; Bouzari et al., 2016, 2017). Currently, the Woodjam property contains six mineralized zones (Megabuck, Deerhorn, Takom, Three Firs, Southeast, and Megaton). The batholith consists of two major units: the Late Triassic to Early Jurassic Boss Creek unit and the Early Jurassic, megacrystic Schoolhouse Lake unit. The Woodjam Creek unit in the northwestern part of the batholith is texturally distinct, but compositionally similar to the Schoolhouse Lake unit (Schiarizza et al., 2009). Along the northwestern boundary of the batholith, porphyry Cu-Mo-Au mineralization is hosted by the Woodjam Creek unit or small satellite porphyry dykes and adjacent volcanic rocks (Bouzari et al., 2016, 2017).

Hogem Batholith

The large, composite, Early Jurassic to Cretaceous Hogem Batholith occurs in the northern Quesnel terrane, along its western edge (Fig. 5). The north-central part of the batholith, as mapped by Ootes et al. (2019), is separated into four suites. The oldest of these is the Thane Creek suite, which includes diorite, quartz monzodiorite, granodiorite, and tonalite. These rocks are cut by the Duckling Creek suite, which is composed of K-feldspar–rich syenite to monzonite and hosts the Lorraine deposit (Bath et al., 2014; Devine et al., 2014). Elsewhere, the Jurassic to Cretaceous, granitic Mesilinka suite and Cretaceous, mafic-poor, equigranular Osilinka suite also cut the Thane Creek suite. Age determinations for the Thane Creek suite cluster at ca. 204 to 203 Ma and ca. 199 to 188 Ma, whereas the Duckling Creek suite is dated at ca. 181 to 176 Ma (Fig. 5; Appendix A).

DISCUSSION

The temporal changes in alkalinity of the Late Triassic to Middle Jurassic intrusions of the Quesnel terrane in British Columbia have been well established (Breitsprecher et al., 2010; Logan and Mihalynuk, 2014; Schiarizza, 2014). What is less apparent is what the associated spatial distribution means in relation to the underlying tectonic controls. Logan and Mihalynuk (2014) ascribed the spatial distribution to the eastward migration of arc magmatism as the system evolved over two calc-alkalic to alkalic cycles. The transition to alkalic magmatism within an arc is best explained by the ingress of hot primitive mantle from the downgoing slab into the mantle wedge, with resulting radical changes to the conditions of partial melting (Hole et al., 1991; van de Zedde and Wortel, 2001; Logan and Mihalynuk, 2014). There are several potential mechanisms by which such mantle ingress can be achieved, such as slab rollback, slab window development, slab breakoff, or slab tears (Thorkelson, 1996; Wortel and Spakman, 2000; Niu et al., 2003; Thorkelson and Breitsprecher, 2005). Logan and Mihalynuk (2014) presented the case for slab tears being the underlying mechanism given the speed of magmatic character changes and the perceived temporal continuity of the change along the whole of the Quesnel terrane.

The interpreted spatial distribution of magmatic events was initially identified in the southern Quesnel terrane (Breitsprecher et al., 2010), where the terrane is distinctly broader than it is in north-central British Columbia (Fig. 2). It is apparent, though, that even in the region within which the spatial distribution was defined, the pattern only really reflects the oldest phase of intrusive magmatism in each specific area (Fig. 6). For instance, the Takomkane Batholith and adjacent bodies includes components that correspond to the Copper Mountain, Wildhorse, and Iron Lake suites of Breitsprecher et al. (2010). Consequently, the only sense of an eastward migration of magmatic centres at this latitude (52.0–52.5°N) is dependent on the Norian Granite Mountain Batholith (Fig. 4, 6); however, Schiarizza (2014) determined that the Granite Mountain Batholith is fault bounded, and so whilst it undoubtedly is representative of the Cache Creek–Quesnel terrane boundary region, it is not evident if it has any spatial relationship with the rest of the Quesnel terrane at this latitude. Furthermore, in the northern portion of the Quesnel terrane, in the vicinity of the Hogem Batholith (Fig. 5), sense of a temporal-spatial relationship to the intrusive magmatism is even less evident. The Thane Creek and Duckling Creek phases of the Hogem Batholith do not readily correlate with the time windows demarcated by the temporal-spatial suites that were defined for the southern Quesnel terrane. In addition, the Hogem Batholith contains the Mesilinka and Osilinka phases, which extend Hogem magmatism into the Cretaceous (post-accretionary setting). It is notable that the undated Lounge Lizard Intrusive Complex, which is positioned along the eastern margin of the Quesnel terrane at the same latitude as the Hogem Batholith (Fig. 5), was described by Nelson et al. (1993) as being petrographically similar to the mafic component of the Hogem Batholith (western margin of the Quesnel terrane). Irrespective of whether the Lounge Lizard Intrusive Complex is correlative with the Hogem Batholith, there is Alaskan-type Polaris Ultramafic Complex (Nixon et al., 1997) at the same structural horizon that is coeval with the pre-Middle Jurassic portions of the Hogem Batholith (Cui et al., 2017); hence, the structural position of these units dictates that the magmatic front transects the full width of the terrane at these latitudes.

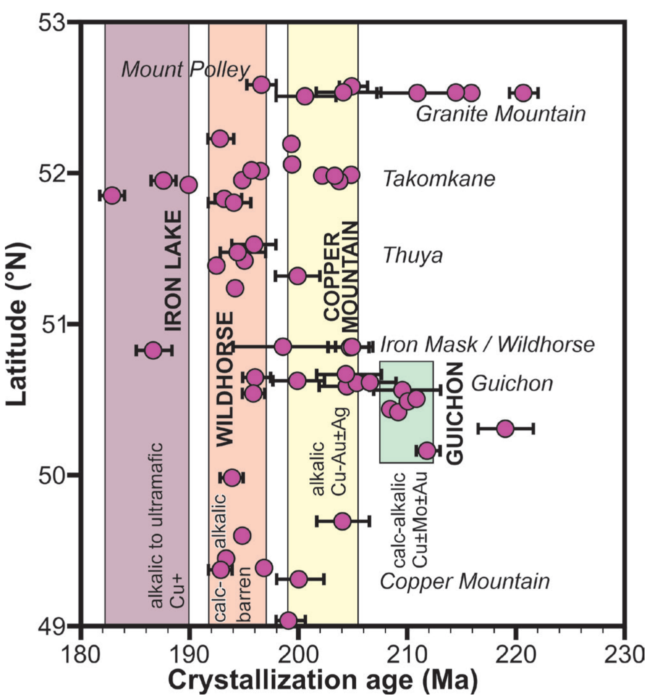

Figure 6. Time-space distribution of age determinations for Late Triassic to Early Jurassic intrusions in the southern to central Quesnel terrane. *Modified from* Breitsprecher et al. (2010) with additional data for the Granite Mountain (Oliver et al., 2009; R.G. Anderson, pers. comm., 2012; Mostaghimi, 2016), Iron Mask (Logan et al., 2007), and Takomkane (del Real et al., 2017) batholiths (*see also* Appendix A).

It is arguable that the northern Quesnel terrane is too narrow to display distinct temporal-spatial suites in the way that is apparent in southern British Columbia where the terrane is much broader (Fig. 2); however, even in this region where there is an across terrane temporal distribution defined, an eastward migration of arc magmatism is counter-intuitive within the overarching tectonic regime. Although occasional (and at least locally appreciable) erosive events are recorded through the Middle Triassic to Middle Jurassic due to local tectonic uplift (*see* Nelson et al., 1993; Höy and Dunne, 1997; Mihalynuk et al., 2014) or potentially surface erosion of a volcanic edifice (England and Molnar, 1990; A. Zagorevski, pers. comm., 2020), the overall paleoenvironment is marine (i.e. a submergent margin setting). For a continental arc to be dominantly submergent throughout its history, the upper plate would have to be in general extensional, or at least in a neutral setting rather than compressional, where the arc overrides the trench. The simplest way to model an extensional arc setting with migration of the magmatic loci would be via slab rollback or the stepping back of the subduction zone. In either case, the migration of arc magmatism would be toward the subducting plate, not away from the margin. Given an east-dipping subduction zone, eastward migration of magmatism would require a shallowing of the slab over time, which would likely cause an Andes-style, emergent upper plate.

Similarly, the enclosure model for the amalgamation of the Intermontane superterrane (Mihalynuk et al., 1994) describes the development of an orocline, which requires the limbs of the orocline to be rotational relative to the apex; consequently, the relative rate of subduction would increase along the limbs away from the oroclinal apex. In terms of the Quesnel terrane, this would suggest that the relative subduction rate is highest at the southern end of the terrane near the British Columbia–Washington State border. The most likely mechanism to explain such an arrangement would be differential slab rollback, but this is antithetical with eastward magmatic migration becoming more prevalent at the terrane's southern end. Theoretically, upper plate motion could be the driver, which would be consistent with eastward migration of magmatism, but the submergent setting and the observed changing width of the terrane are not consistent with such circumstances. Also, there is no obvious mechanism to explain such upper plate–driven motion.

An alternative explanation for the observed eastward progression of intrusive units in the southern Quesnel terrane is provided by the distribution of supracrustal units. In the Princeton - Merritt area, the Eastern, Central, and Western belts of the Nicola Group are distributed between multiple fault panels corresponding to different levels of the Nicola Group. The Western belt is dominated by the lower parts of the Nicola Group (Ladinian–Norian), whereas the Eastern belt is dominated by sequences that are Rhaetian and possibly younger. Evidently it is not possible for supracrustal sequences to be cut by intrusions that are older than they are. Hence, Guichon Creek age rocks, for instance, would be unlikely to be exposed in the Eastern belt as defined for this area. This simple organizational constraint also explains why relatively young magmatic products are present on the western side of the terrane. In the Quesnel terrane of south-central British Columbia, the Lower Jurassic volcanic and sedimentary rocks of the Rossland Group are limited to the eastern margin of the terrane, whereas the presumably equivalent sequences farther north (Chuchi Lake, Twin Creek, and Discovery Creek) do not exhibit such constraints; therefore, the observed distribution of both the Middle Triassic to Middle Jurassic supracrustal and intrusive rocks in the Princeton - Merritt area can be rationalized to the Quesnel terrane having an overall effective homoclinal structure that is at the very least fault-modified, if not primarily fault controlled, with no significant migration of magmatism required during this time period. This is not suggesting that a *sensu stricto* homocline is present, as that would likely require an infeasibly thick supracrustal sequence, but rather that the observed distribution in the southern Quesnel terrane can be achieved through various combinations of faulting and folding without the necessity of substantive eastward migration of magmatism (Fig. 7).

Although the above interpretation does not require the wholesale migration of magmatic centres, the type of magmatism does cycle between calc-alkalic and alkalic systems. Logan and Mihalynuk's (2014) preferred mechanism of slab tears to explain these changes in magmatism is fully compliant with the homoclinal distribution model. Logan and Mihalynuk (2014) further contend that the magmatic types "changed abruptly along the entire length of the arc". Given the oroclinal tectonic paradigm for Intermontane amalgamation that defines a relative rotational motion for the orocline limbs, it would require a remarkably convenient orientation of structures in the downgoing plate to produce margin-parallel impacts to the upper plate (cf. Zagorevski (2015) in regards to the related Cache Creek terrane entrapment). Furthermore, subsequent age determinations indicate that the exact timing of the calc-alkalic to alkalic cycles are actually somewhat transgressive along the length of the terrane (Fig. 2). Variations in the timing of calc-alkalic to alkalic transitions along a rotating arc segment are to be expected, and fit well with slab tears as the fundamental control on the observed chemical transition of magmatism. Low-angle convergence between breaks (e.g. transform faults) on the downgoing plate and the trench can form a slab window should the break open up as a tear and the orientation of slab subduction shift (Thorkelson, 1996; Thorkelson and Breitsprecher, 2005). A segmented break or series of parallel breaks in the downgoing plate could result in the opening of multiple slab windows along the margin that correspond to the temporal and spatial distribution of magmatism both across and along the Quesnel terrane.

CONCLUSION

The Late Triassic to Early Jurassic subduction-related intrusions into the Quesnel terrane, British Columbia, host numerous, major porphyry-style mineral deposits. Detailed mapping and analysis by numerous researchers have established the temporal evolution of magmatism through repeated cycles of calc-alkalic to alkalic plutonism, which have been linked to changes in the subduction dynamics. There have also been attempts to link these compositional changes to spatial patterns that define orogen-long bands of related plutonism. Given that the type and likely commodity of a porphyry deposit is genetically controlled by magma composition (i.e. Cu-Mo±Ag±Au for calc-alkalic systems; Cu-Au for alkalic systems) and there are somewhat subjective indications that the magnitude of deposit corresponds to the age of mineralization (such observations are subjective as it is not possible to consider resources that remain undiscovered, underdeveloped, or have been excised), a reliable distribution model for porphyry mineralization would define prospectivity. As discussed above, the apparent distribution of plutonism derived from the Quesnel terrane of

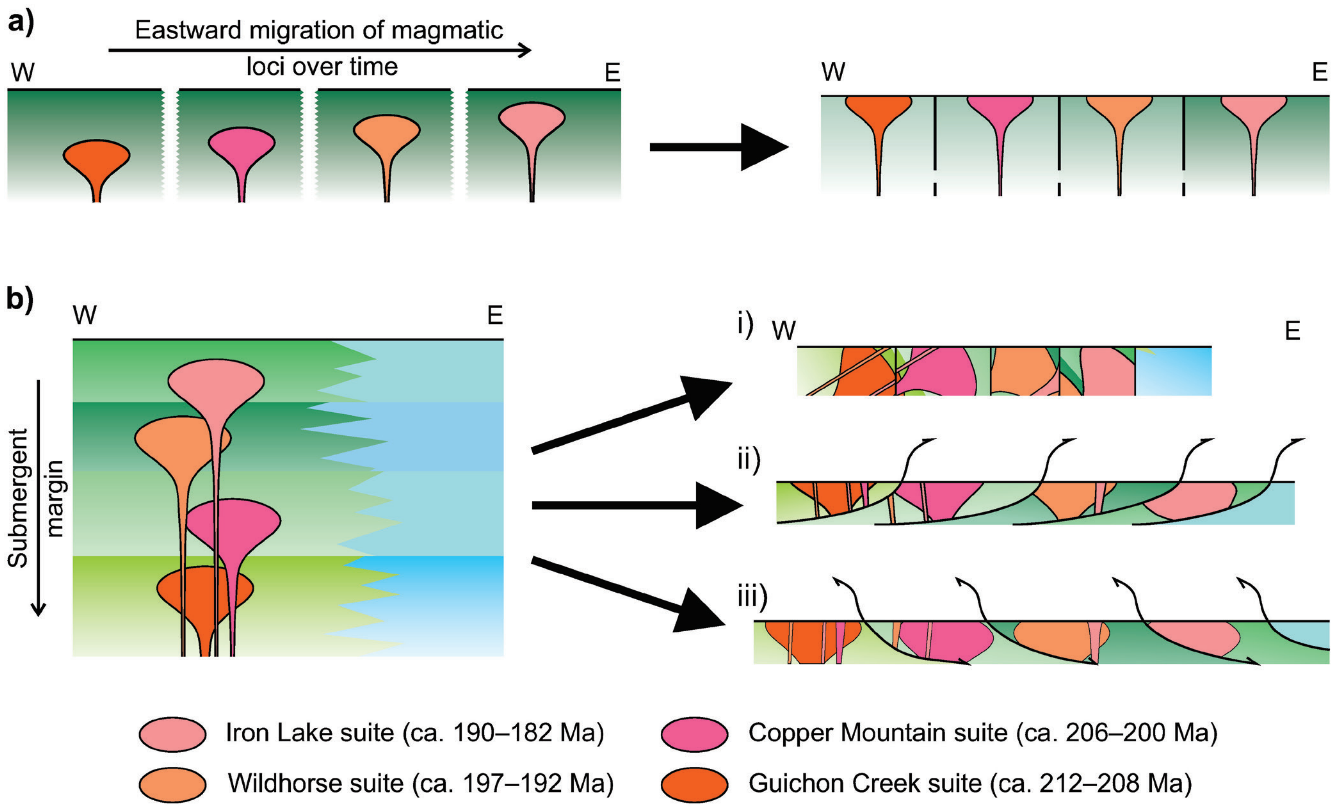

Figure 7. Schematic representation of end-member models to explain the observed distribution of porphyry mineralization within the southern Quesnel terrane. These models follow the division of Late Triassic to Early Jurassic intrusions given in Breitsprecher et al. (2010). These representations are dimensionally non-representative; specifically, there is no correlation between vertical and horizontal dimensions within or between figure panels: **a)** A representation of porphyry mineralization distribution primarily controlled by eastward migration of magmatic centres over time. The left panel represents an original distribution of intrusions that progressively migrated to the east as the Nicola Group evolved. There are indeterminate distances both across and along the arc between the different periods of magmatism. The right panel represents the final distribution with the various intrusions partially excised within a series of fault-bounded blocks. The green shading of the country rocks (e.g. Nicola Group basaltic volcanic rocks) is indicative of younging, but is not intended to have any specific stratigraphic significance. **b)** Representation of magmatic pulses in a progressively submerging basin. Apparent basin depth in the left panel is greatly exaggerated for clarity, with actual magmatism likely to have formed in a basin that attained a maximum depth in the range of 2 to 5 km, with the individual intrusive bodies spread over several tens of kilometres both across and along the eastern margin of the Quesnel terrane. Country rock shading does not have any specific stratigraphic significance, but is intended to indicate temporal evolution of volcanic dominated sequences toward the east of the terrane (e.g. Nicola Group basaltic volcanic rocks) and sedimentary dominated sequences toward the west of the terrane (e.g. Slocan Group). The right panels represent different combinations of structural processes that can produce a similar final surface distribution of units: i) folding followed by dominantly strike-slip faulting; ii) dominantly thrust faulting; and iii) dominantly extensional faulting.

south-central British Columbia, and the associated model for eastward migration of magmatism over time, is not readily applicable farther north.

An alternative explanation for the observed distribution of Late Triassic to Early Jurassic intrusions in south-central British Columbia is given by the southern Quesnel terrane having an overall, effective homoclinal structure. This alternate model does not equate with a *sensu stricto* homocline and it is beyond the scope of this paper to infer what combination of structural controls are present; however, it is clear that surface distribution of the southern Quesnel terrane is at the very least fault modified, if not primarily fault controlled. The broadly homoclinal distribution is supported by the dominantly Ladinian to Norian Western belt of the Nicola Group marking the western margin of the terrane, whereas the Late Jurassic Rossland and Ymir groups occur adjacent to the eastern margin. If this structural control of distribution is correct, then it raises the possibility that porphyry deposits comparable to those hosted by the Norian Guichon Creek and Granite Mountain batholiths (Highland Valley and Gibraltar deposits, respectively) could be repeated at depth within the different fault panels. Given that whole-scale migration of magmatic centres is not required by this model, it follows that it is likely that the location for such buried porphyry deposits would be in the vicinity of subsequent plutonism. That said, given the duration of magmatism, it is virtually inevitable that the downgoing plate consisted of several plates that controlled the temporal and spatial distribution of magmatic centres. As the deposition of porphyry mineralization is broadly constrained by the depth of intrusion, any younger intrusions within the more deeply excised (i.e. western) fault panels are unlikely to preserve significant, associated mineralization. Younger magmatism in such excised panels could induce thermal overprints and remobilization of ore resources, as is observed in the Guichon Creek, Granite Mountain, Iron Mask, Thuya, and Takomkane batholiths.

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APPENDIX A

Compilation of Mesozoic age determinations from the Quesnel terrane

Compiled summary data of Mesozoic radiogenic isotope age determinations from the Quesnel terrane between 49° and 56.5° north is available in file POR6_Rogers_TGI5syn_App_A_FINAL.xlsx. Information recorded includes sample number codes, location, interpreted age and 2σ error, epoch, stage, analytical method deployed, rock type, additional notes and original source. For age determinations that are included within British Columbia Geological Survey's MapPlace 2 digital geology (Cui et al., 2017) the BCGS age number is also provided. This Appendix has not been edited to Geological Survey of Canada specifications.