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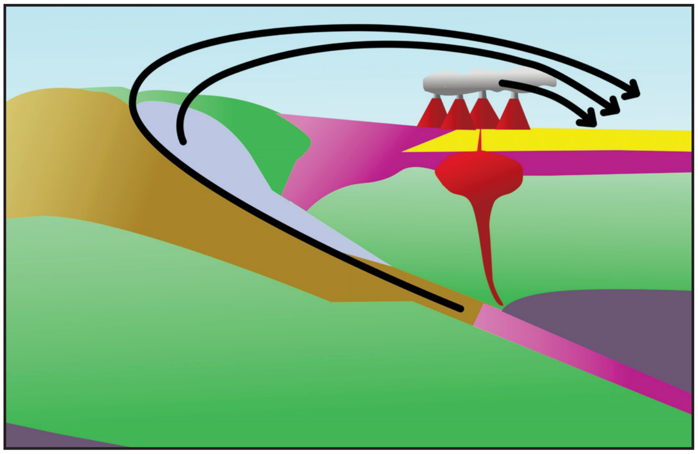

The Jurassic Laberge Group in the Whitehorse Trough of the Canadian Cordillera: Using Detrital Mineral Geochronology and Thermochronology to Investigate Tectonic Evolution

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SUMMARY

The Laberge Group is an Early to Middle Jurassic sequence of mostly siliciclastic sedimentary rocks that were deposited in a marginal marine environment in the northern Canadian Cordillera. It forms a long narrow belt with a total thickness of 3–4 km extending for more than 600 km across southern Yukon and northwestern British Columbia. These sedimentary rocks overlap the Yukon-Tanana, Stikinia and Cache Creek terranes that form the main components of the Intermontane superterrane. The Laberge Group contains a record of the erosion of some of these terranes, and also offers some constraints on the timing of their amalgamation and accretion to the Laurentian margin. The Laberge Group was deposited with local unconformity on the Late Triassic Stuhini Group (in British Columbia) and correlative Lewes River Group (in Yukon), both of which are volcanic-rich, and assigned to the Stikinia terrane. The Laberge Group is in turn overlain by Middle Jurassic to Cretaceous clastic rocks, including the Bowser Lake Group in B.C. and the Tantalus Formation in Yukon. Clast compositions and detrital zircon populations within the Laberge Group and between it and these bounding units indicate major shifts in depositional environment, basin extent and detrital sources from Late Triassic to Late Jurassic. During the Early Jurassic clast compositions in the Laberge Group shifted from sediment- and volcanic-dominated to plutonic-dominated, and detrital zircon populations are dominated by grains that yield ages that approach or overlap their inferred depositional ages. This pattern is consistent with progressive dissection and unroofing of (an) active arc(s) to eventually expose Triassic to Jurassic plutonic suites. Detrital rutile and muscovite data from the Laberge Group indicate rapid cooling and then exhumation of adjoining metamorphic rocks during the Early Jurassic, allowing these to contribute detritus on a more local scale. The most likely source for such metamorphic detritus is within the Yukon-Tanana terrane, and its presence in the Laberge Group may constrain the timing of amalgamation and accretion of the Yukon-Tanana and Stikinia terranes. Thermochronological data also provide new insights into the evolution of the Laberge Group basin. Results from the U–Th/(He) method on detrital apatite suggest that most areas experienced post-depositional heating to 60°C or more, whereas U–Th/(He) results from detrital zircon show that heating to more than 200°C occurred on a more local scale. In detail, Laberge Group cooling and exhumation was at least in part structurally controlled, with more strongly heated areas situated in the footwall of an important regional fault system. The thermochronological data are preliminary, but they suggest potential to eventually constrain the kinematics and timing of inversion across the Laberge Group basin and may also have implications for its energy prospectivity.

In summary, the Laberge Group is a complex package of sedimentary rocks developed in an active, evolving tectonic realm, and many questions remain about the details of its sources and evolution. Nevertheless, the available information demonstrates the potential of combined geochronological and thermochronological methods applied to detrital minerals to unravel links between regional tectonics, basin development and clastic sedimentation.

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RÉSUMÉ

Le groupe de Laberge est une séquence du Jurassique inférieur à moyen composée principalement de roches sédimentaires silicoclastiques qui se sont déposées dans un milieu margino-marin, dans le nord de la Cordillère canadienne. Il forme une longue ceinture étroite d'une épaisseur totale de 3 à 4 km s'étendant sur plus de 600 km à travers le sud du Yukon et le nord-ouest de la Colombie-Britannique. Ces roches sédimentaires chevauchent les terranes Yukon-Tanana, Stikinia et Cache Creek qui forment les principales composantes du superterrane Intermontagneux. Le groupe de Laberge contient un enregistrement de l'érosion de certains de ces terranes, et offre également certaines contraintes sur la datation de leur amalgamation et de leur accrétion à la marge laurentienne. Le groupe de Laberge a été déposé avec une discordance locale sur le groupe de Stuhini du Trias supérieur (en Colombie-Britannique) et le groupe corrélatif de Lewes River (au Yukon), tous deux riches en volcans et attribués au terrane de Stikinia. Le groupe de Laberge est à son tour recouvert de roches clastiques du Jurassique moyen à Crétacé, comprenant le groupe de Bowser Lake en Colombie-Britannique et la formation de Tantalus au Yukon. Les compositions de clastes et les populations de zircons détritiques au sein du groupe de Laberge et entre celui-ci, et ces unités limitrophes indiquent des changements majeurs dans l'environnement de dépôt, l'étendue du bassin et les sources détritiques du Trias supérieur jusqu'au Jurassique supérieur. Au cours du Jurassique inférieur, les compositions des clastes du groupe de Laberge sont passées d'une prédominance sédimentaire et volcanique à une prédominance plutonique, et les populations de zircons détritiques sont dominées par des grains qui donnent des âges qui se rapprochent ou chevauchent l'âge présumé de leur déposition. Ce modèle est cohérent avec la dissection progressive et le dévoilement d'un ou plusieurs arcs actifs pour éventuellement exposer les suites plutoniques du Trias au Jurassique. Les données sur le rutile détritique et la muscovite du groupe de Laberge indiquent un refroidissement rapide puis une exhumation des roches métamorphiques adjacentes au cours du Jurassique inférieur, permettant à celles-ci d'ajouter des débris à une échelle plus locale. La source la plus probable de ces débris métamorphiques se trouve dans le terrane Yukon-Tanana, et sa présence dans le groupe de Laberge peut apporter des contraintes sur la datation de l'amalgamation et de l'accrétion des terranes Yukon-Tanana et Stikinia. Les données thermo-chronologiques apportent également de nouveaux éclairages sur l'évolution du bassin du groupe de Laberge. Les résultats de la méthode U–Th/(He) sur l'apatite détritique suggèrent que la plupart des régions ont été soumises à des conditions de température post-dépôt de 60°C ou plus, tandis que les résultats U–Th/(He) sur zircon détritique montrent que des conditions de température de plus de 200° C se sont produites à une échelle plus locale. Dans le détail, le refroidissement et l'exhumation du groupe de Laberge étaient au moins en partie structurellement contrôlés, avec des régions plus fortement chauffées situées dans le mur d'un important système de failles régionales. Les données thermo-chronologiques sont préliminaires, mais elles suggèrent un potentiel pour éventuellement contraindre la cinématique et le moment de l'inversion à travers le bassin du groupe de Laberge et peuvent également avoir des implications sur sa capacité énergétique.

En résumé, le groupe de Laberge est un ensemble complexe de roches sédimentaires développées dans un domaine tectonique actif et en évolution, et de nombreuses questions demeurent quant aux détails de ses sources et de son évolution. Néanmoins, les informations disponibles démontrent le potentiel de la combinaison des méthodes géochronologiques et thermo-chronologiques appliquées aux minéraux détritiques pour démêler les liens entre la tectonique régionale, le développement du bassin et la sédimentation clastique.

Traduit par la Traductrice

INTRODUCTION

The Cordilleran Orogen of northwestern Canada developed through the successive accretion of discrete late Paleozoic and Mesozoic terranes against a long-lived active margin. Figure 1 shows the regional distribution of these terranes in British Columbia, Yukon and parts of Alaska, including the area of the research discussed in this paper. Five terranes, together comprising the Intermontane superterrane (i.e. Slide Mountain, Yukon-Tanana, Stikinia, Quesnellia and Cache Creek terranes) are of particular importance, as their accretion to the Laurentian margin has been considered to represent the initiation of the northern Canadian Cordillera orogen (Colpron et al. 2015; Monger and Gibson 2019). The exact geometry, timing and conditions of the accretion event(s) are not well established, and several outstanding questions are reviewed elsewhere (Zagorevski et al. 2017, 2021). Understanding the relative and absolute timing of these events is important in developing and improving the economic geology framework for the region (e.g. Logan and Mihalynuk 2014). The Late Triassic to Cretaceous sedimentary rocks in northern British Columbia (B.C.) and southern Yukon provide a record of changes in depositional environments and the evolution of those sedimentary basins through the time interval of progressive terrane accretion. This paper reviews the broader Late Triassic to Cretaceous evolution of this key segment of the orogen (Fig. 1) but focuses most of its attention on the Early–Middle Jurassic Laberge Group of the Whitehorse trough (Fig. 2; Wheeler 1961; Eisbacher 1974), and particularly recent and new data on sediment provenance, depositional constraints, and the timing and conditions of basin deformation. The principal tools that provide insight into the development of the Laberge Group are detrital geo- and thermochronology (U–Pb methods using zircon and rutile, and $^{40}Ar/^{39}Ar$ methods using muscovite and biotite) that constrain sediment source regions and low temperature thermochronological methods (U–Th/He on zircon and apatite) that illustrate aspects of basin evolution. The paper is an extension of a recent Geological Survey of Canada report (Kellett and Zagorevski 2021) and is intended to illustrate how diverse techniques can be applied together to understand the linked processes of tectonic accretion and basin development.

The Laberge Group is mostly found along the eastern flank of the Stikinia terrane, so Stikinia is the most likely source

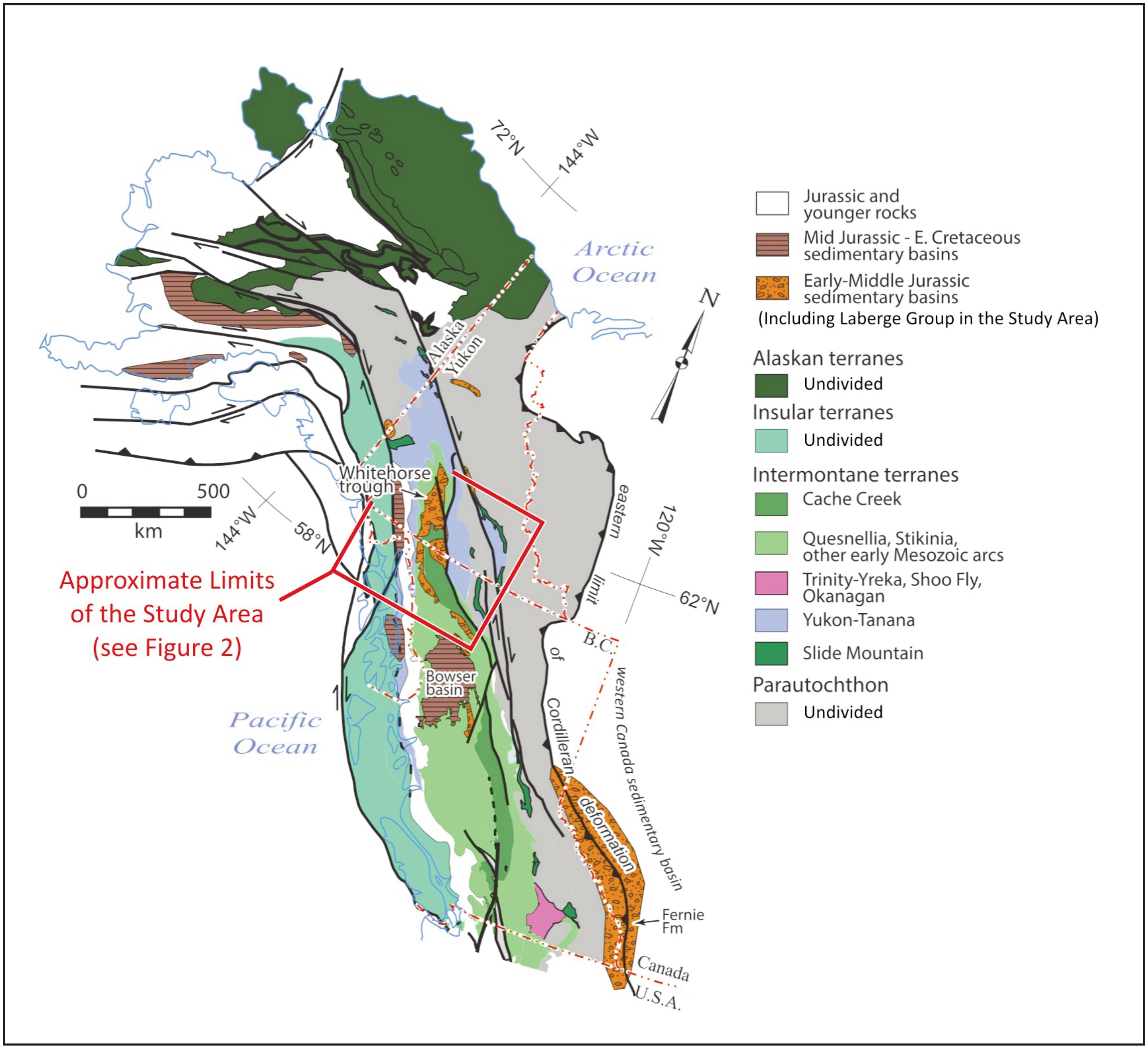

Figure 1. Terrane map of the Canadian Cordillera and adjacent regions of Alaska adapted from Colpron et al. (2015).

region for detritus entering the Laberge Group basin (e.g. Colpron et al. 2015; Fig. 2). Much of the research on Laberge Group sedimentary rocks has been focussed on provenance and identification of terrane-specific detritus that might constrain the timing of terrane amalgamation. Identification of detritus that could be derived from other now-adjacent terranes (e.g. the Yukon-Tanana or Cache Creek terranes; Figs. 1, 2) may provide a temporal constraint on their initial juxtaposition with Stikinia. However, the precise timing may be obscured if detritus is multicyclic. For example, sediment that was derived by erosion and recycling of an exhumed melange may significantly postdate the timing of accretion. In addition to timing of accretion, the nature of detritus in the Laberge Group sedimentary rocks can provide other critical constraints on the evolution of the orogen. The Laberge Group includes detritus of rock units that are either no longer exposed, or were removed completely by such erosion, providing 'snapshots' of the geological architecture of the Cordilleran Orogen throughout the Early Jurassic. Clast composition, such as clasts of high-pressure metamorphic rocks or mineral grains indicative of such conditions, can be diagnostic of specific tectonic settings, and provide insight into tectonic setting of the Intermontane terranes at a particular time. Overall, the range of source materials deposited into the Laberge Group basin pro-

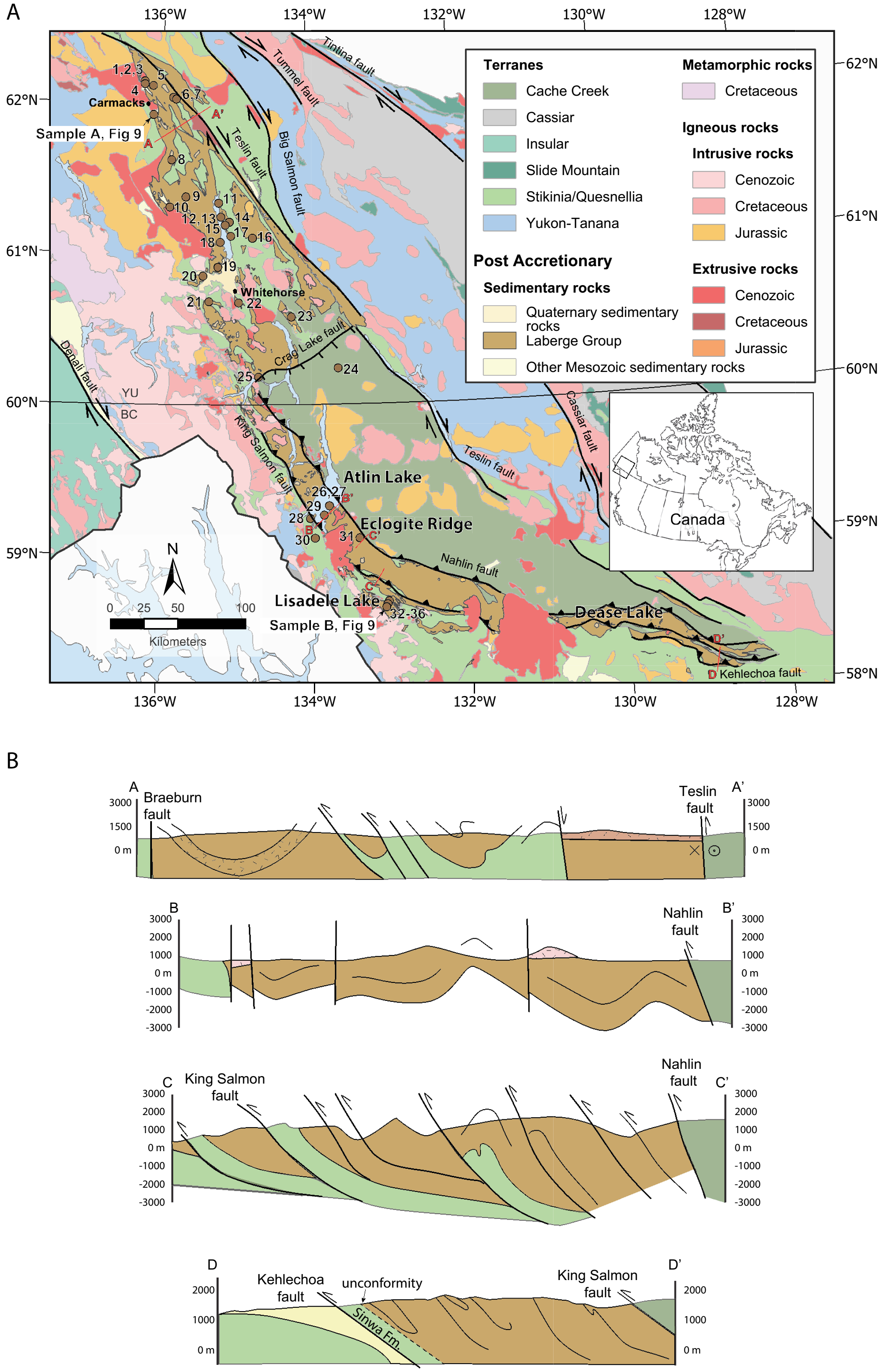

Figure 2. A. Terrane map of the study area highlighting post-accretionary units in the northern Cordillera, particularly the Early–Middle Jurassic Laberge Group. Map modified from Cui et al. (2017) and Colpron et al. (2016a). Numbers indicate detrital zircon U–Pb samples listed in Table 1 and reviewed in this study. Letters indicate detrital muscovite $^{40}Ar/^{39}Ar$ samples described in this study. B. Cross-sections through Laberge Group. Section lines are shown on the map. A–A' is redrawn from White et al. (2012). B–B' and C–C' are redrawn from English et al. (2005), and D–D' is redrawn from van Straaten and Bichlmaier (2018b).

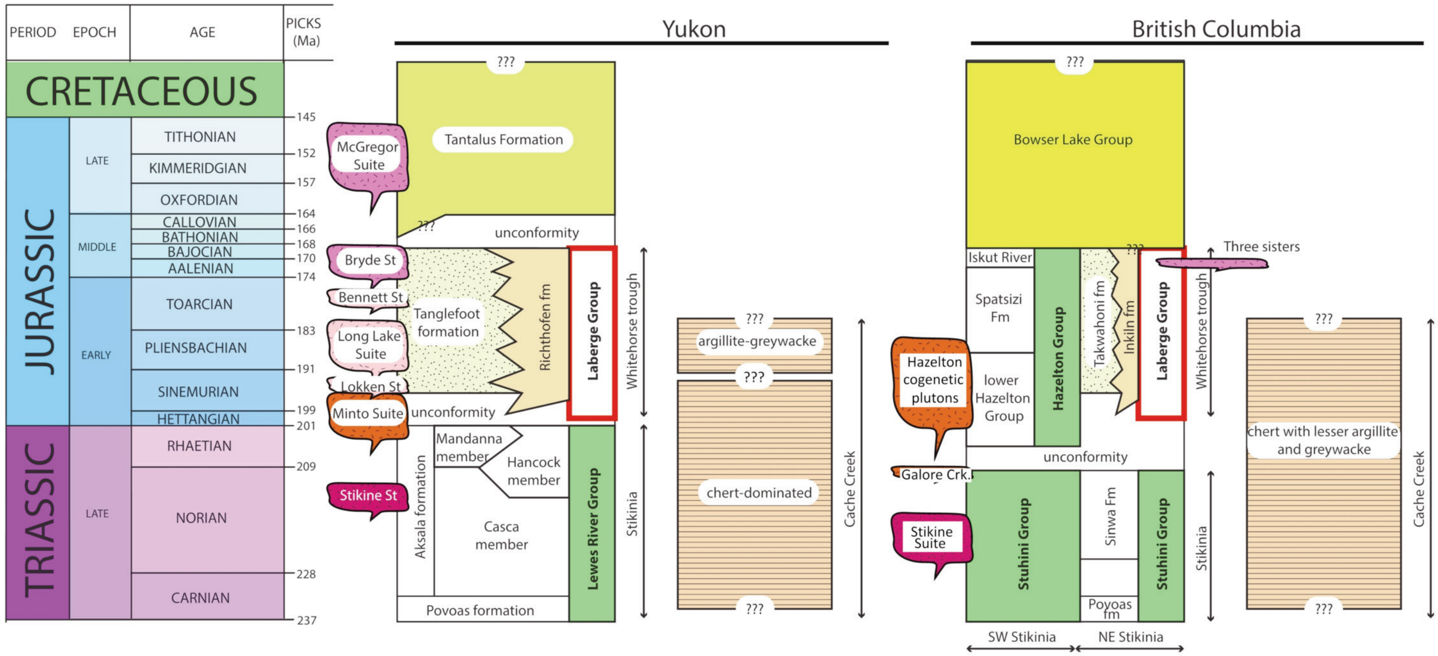

Figure 3. Comparative Upper Triassic to Lower Cretaceous lithological sections for Yukon (modified from Hutchison 2017; Sack et al. 2020 and references therein) and British Columbia (modified from Souther 1972; Shirmohammad et al. 2011; van Straaten and Bichlmaier 2017; Nelson et al. 2018; Mihalynuk et al. 2018 and references therein). Geologic Time Scale from Walker et al. (2018). Note that some units indicated here are not identified individually in Figure 2, and that some minor subdivisions of units referenced in the text cannot be represented in this summary diagram.

vides a record of vigorous erosion and deep incision of a young and evolving orogen.

TERMINOLOGY AND DATA SOURCES

The *Whitehorse trough* is a pre-plate tectonic term that was originally introduced to describe a linear belt of volcanic and sedimentary rocks in southern Yukon and northwestern B.C., including throughout the Whitehorse area (Fig. 3). Initially, the term was intended to include part or all of the Triassic Lewes River and Stuhini groups (located in the Yukon and B.C., respectively) and the Jurassic Laberge Group (in both areas), while more recent studies have also included the overlying Jurassic–Cretaceous Tantalus Formation in Yukon. The regional stratigraphic and geological relationships are summarized in the time–space diagram of Figure 3 (after Wheeler 1961; Hart 1997; Lowey 2008; Templeman-Kluit 2009), although not all components indicated on the figure are specifically discussed in this paper. A more restrictive definition of the Whitehorse Trough (Hutchison 2017) includes only the Laberge Group.

The Laberge Group extends from Carmacks in southern Yukon to Dease Lake in B.C. (Fig. 2). Regional mapping has resulted in two sets of formal nomenclature for geological units that are at least in part equivalent (Fig. 3). In this paper, the B.C. nomenclature is used for B.C. field areas, and Yukon nomenclature is used for Yukon field areas, with the probable equivalence identified where appropriate. This is done to aid the reader, but it should be noted that this may introduce some inconsistencies as the formal definitions of lithologically similar units are not necessarily identical.

The transition from the Lewes River and Stuhini groups into the Laberge Group was interpreted in both B.C. and the Yukon to represent a Hettangian (or younger) unconformity, above which the sedimentary environment changed markedly, and sedimentation rates increased (e.g. Johannson and McNicoll 1997; Shirmohammad et al. 2011; Colpron et al. 2015; Hutchison 2017; van Drecht and Beranek 2018). The boundary between the Laberge Group and the overlying Late Jurassic to Early Cretaceous Tantalus Formation in southern Yukon is a locally angular unconformity that also marks a significant change in sedimentary environment, and change in the extent of the sedimentary basin (Fig. 3; Colpron et al. 2015). The varied definitions of Whitehorse trough make this term ambiguous. In this contribution, rock units are mostly referred to using specific lithological or stratigraphic terminology, and, following Hutchison (2017), the term Whitehorse trough is used synonymously with the Laberge Group.

The Geological Survey of Canada's Geomapping for Energy and Minerals Program (GEM) included acquiring a range of new geochronological and thermochronological data from sedimentary rocks in the Cordilleran Orogen, under the GEM2 (2013–2020) Cache Creek and Yukon Tectonic Evolution activities. Recent work by the British Columbia Geological Survey and the Yukon Geological Survey has also generated significant new geochronological datasets for sedimentary rocks across the region shown in Figure 2. These new data add greatly to existing and new sedimentological (e.g. Hutchison 2017; van Drecht and Beranek 2018), biostratigraphic (e.g. Johannson et al. 1997; Golding 2018), and structural (e.g. English et al. 2002; White et al. 2006) information. Collectively, these multidisciplinary datasets allow improved understanding of the sedimentary evolution and later structural inversion of the Laberge Group. The following sections provide a brief regional overview of recent work.

GEOLOGICAL OVERVIEW

Tectonic Setting

The Canadian Cordillera is a long-lived and presently active accretionary orogen on the western margin of North America (Coney et al. 1980; Nelson et al. 2013). The oldest component of the orogen is a late Neoproterozoic to early Paleozoic passive margin sequence that developed on the Ancestral North American (or Laurentian) margin. The passive margin sedimentation was terminated by Devonian magmatism that has been interpreted to mark the initiation of east-directed (present coordinates) subduction beneath Laurentia (Mortensen 1992). The Devonian arc that formed on the Laurentian margin rifted away, becoming the Yukon-Tanana terrane and opening the intervening Slide Mountain ocean. During the Late Paleozoic, the Yukon-Tanana terrane and related island arc terranes (Stikinia and Quesnellia) developed outboard of Laurentia (Nelson et al. 2013; van Staal et al. 2018; Parsons et al. 2018). The Laurentian margin that was facing the Slide Mountain ocean resumed passive margin sedimentation (Monger 1977). The Yukon-Tanana, Stikinia and Quesnellia terranes (representing arc-type settings) and the adjacent Atlin, Cache Creek and Slide Mountain terranes were accreted to the Laurentian margin sometime between the late Paleozoic and the Middle Jurassic. This represents the first major accretionary event on the western Laurentian margin (Monger et al. 1982; Colpron et al. 2015; Monger and Gibson 2019). The Intermontane sedimentary record spanning this period of terrane amalgamation and superterrane accretion to the margin is relatively complete (Fig. 3), and provides a chronicle of the orogen's evolution through this critical time period.

Triassic Sedimentation

The Late Triassic Stikinia and Quesnellia terranes are characterized by arc-related volcanic and plutonic rocks. The Triassic sedimentary components of Stikinia are included in the Stuhini Group in B.C., and equivalent Lewes River Group in the Yukon, and in Quesnellia terrane's Shonektaw Formation (not separated in Fig. 3). By the Latest Triassic, magmatism had started to wane, and siliciclastic rocks became more abundant. These include the undivided Stuhini Group in B.C., the Mandanna Member of the Lewes River Group in Yukon, and the Nazcha Formation in Quesnellia, B.C. (not separated in Fig. 3). Then, limestone was deposited, forming the Sinwa Formation in B.C., and the Hancock Member of the Lewes River Group in Yukon (Templeman-Kluit 2009). The deposition of Late Norian to Rhaetian limestone is generally interpreted to mark the end of the Stuhini–Lewes River–Nicola arc (English and Johnston 2005 Long 2005; Shirmohammad et al. 2011; Logan and Mihalynuk 2014). As discussed previously, these rocks form the underlying strata upon which Laberge Group sediments were deposited. Late Triassic sedimentary rocks also occur in the adjacent Cache Creek terrane, where they include bedded radiolarian chert, siltstone and sandstone of the Kedahda Formation and its equivalents (Monger et al. 1991; Golding et al. 2016). The differences between Late Triassic sedimentary rocks in the Stikinia and Cache Creek terranes were previously interpreted to reflect different tectonic settings, i.e. arc-proximal for Stikinia versus subducting plate for Cache Creek (e.g. Mihalynuk et al. 2004; Colpron et al. 2015). Recent provenance studies of the Kedahda Formation in the Cache Creek terrane suggest that it was likely derived from Late Triassic Stikinia and/or Quesnellia terranes and overlaps all older Cache Creek terrane components (Monger et al. 1991; Zagorevski et al. 2016; 2018; 2021). Thus it is possible that Late Triassic siliciclastic rocks from the Stikinia terrane (Stuhini Group, Sinwa Formation, Aksala formation), the Cache Creek terrane (Kedahda Formation), and the Quesnellia terrane (Shonektaw Formation) represent a single overlapping sedimentary basin with internal facies variations (Zagorevski et al. 2018).

Early–Middle Jurassic Sedimentation – Laberge Group

Stikinia's Triassic rocks are overlain by the Early to Middle Jurassic siliciclastic rocks of the Laberge Group (Mihalynuk et al. 1995; Dickie and Hein 1995; Johannson et al. 1997). An angular unconformity locally defines this transition (Bordet et al. 2019) and it is associated with a marked change in the sedimentary environment, as discussed in the introduction. Southwest of the Laberge Group, volcanic and sedimentary rocks of the Hazelton Group were unconformably deposited on the Stuhini Group, representing a similar transition (Fig. 3; Marsden and Thorkelson 1992; Brown et al. 1996; van Straaten and Nelson 2016; Hutchison 2017; Nelson et al. 2018). The Hazelton Group is at least partially equivalent to the Laberge Group (Fig. 3).

The Laberge Group comprises 3–4 km of siliciclastic sedimentary rocks (Dickie and Hein 1995; Johannson et al. 1997; Shirmohammad 2006) that can be traced for ~ 600 km along strike, from near Carmacks, Yukon to ~ 100 km east of Dease Lake, B.C. (Figs. 2, 3). It is structurally complex, because it is located within a regional fold and thrust belt, which disrupted and repeated the original stratigraphy through translation and imbrication (Fig. 2B). Major structures that affect the Laberge Group include the King Salmon, Nahlin and Kehlechoa faults (e.g. Mihalynuk et al. 1995; Gabrielse 1998; English et al. 2002; Mihalynuk et al. 2017; van Straaten and Gibson 2017; van Straaten and Bichlmaier 2018a, b; Fig. 2B). It is also dissected by younger major dextral strike-slip faults including the Teslin and Big Salmon faults (Fig. 2A, B; Gabrielse et al. 2006; Colpron 2011). Consequently, it is difficult to reconstruct the complete stratigraphy of the Laberge Group in many areas, but it is locally well-preserved, notably at Lisadele Lake (Mihalynuk et al. 1995; 2004; Shirmohammad et al. 2007; 2011). The good preservation of diagnostic fossils also allows precise biostratigraphic control in other regions, which assists in reconstructing the wider stratigraphic sequence (e.g. Johannson et al. 1997).

The Laberge Group includes two coeval units; a more distal, turbiditic unit, and a more proximal, coarse clastic unit, collectively representing a tidal- and fluvial-influenced coastal depositional environment (Colpron and Friedman 2008; Shirmohammad et al. 2011; White et al. 2012; Hutchison 2017). It also includes intercalated Pliensbachian volcaniclastic horizons and rare porphyritic dacite to andesite (Nordenskiöld facies). The distal unit, referred to as the Richthofen formation in Yukon and the Inklin formation in B.C., is a graded siltstone to very fine-grained sandstone with minor conglomerate, volcaniclastic and limestone layers (Lowey 2008). These strata are interpreted to have formed as mass flows, submarine fans and turbidites (Lowey 2008; Hutchison 2017). The more proximal member, referred to as the Tanglefoot formation in Yukon, includes coal-bearing sandstone, mudstone, conglomerate and volcaniclastic rocks, with minor limestone, interpreted to represent shallow marine, deltaic, and fluvial settings (Lowey 2008; Hutchison 2017). The Tanglefoot formation was considered to be a potential source rock for petroleum accumulations (Lowey and Long 2006). The Takwahoni formation in B.C., which is broadly equivalent to the Tanglefoot formation, comprises conglomerate, tuff and laminated greywacke and shale (Gabrielse 1998). As discussed above, recent investigations of the Laberge Group suggest that the Richthofen and Tanglefoot formations in the Yukon and the Inklin and Takwahoni formations in B.C. respectively represent distal and proximal facies within a common depositional system. Consequently, distinguishing between the units can be challenging (Hutchison 2017; Mihalynuk et al. 2017). Recent Yukon-based investigations of the Laberge Group concluded that it was deposited only on the Stikinia terrane and is everywhere in tectonic contact with rocks of the Cache Creek terrane (e.g. Bickerton et al. 2013). However, recent mapping in the Sinwa Creek area of B.C. indicates that the Inklin formation was also deposited on late Permian to Middle Triassic rocks of the Kutcho arc (not separated on Fig. 3), which is assigned to the Cache Creek terrane (Mihalynuk et al. 2017). Similar relationships are described in the Kutcho area, where the Sinwa Formation and southernmost Laberge Group stratigraphically overlie the Kutcho arc assemblage (Gabrielse 1998; Schiarizza 2011).

Early–Middle Jurassic Sedimentation External to Laberge Group

Southwest of the mapped extent of the Laberge Group, Pliensbachian to Aalenian sandstone, siltstone and shale of the Spatsizi Formation forms part of the Hazelton Group in northern B.C, which is interpreted as part of the Stikinia terrane (Fig. 3; Gagnon et al. 2012; Nelson et al. 2018). The Spatsizi Formation is thought to have been deposited during thermal subsidence that marked the decline of the older Hazelton arc (Gagnon et al. 2012). East of the Laberge Group, a sequence of Early Jurassic chert to argillite–greywacke was deposited above chert-dominated Triassic sedimentary rocks in the northern Cache Creek terrane (Fig. 3; Cordey et al. 1991; Gordey and Stevens 1994; Colpron et al. 2015).

The Hettangian to Tithonian Fernie Formation of southeastern British Columbia, which was deposited at the western edge of the Western Canada sedimentary basin, is also age-equivalent to the Laberge Group. The Fernie Formation records Early–Middle Jurassic passive margin sedimentation followed by Late Jurassic initiation of the Western Interior foreland basin (Pană et al. 2019). Paleomagnetic reconstructions place the Laberge Group at about the latitude of southern Alberta during the Early Jurassic (Kent and Irving 2010 and references therein), suggesting that the Laberge Group and Fernie Formation depocentres were closer to each other than their current positions would imply. Other small, isolated Early Jurassic basins in Yukon are reviewed in Colpron et al. (2015) and are not discussed here.

Middle Jurassic to Early Cretaceous Sedimentation

Sedimentary rocks that postdate the Laberge Group in southern Yukon are represented by conglomerate of the Bathonian(?) to Upper Cretaceous Tantalus Formation (Bostock 1936; Colpron et al. 2015; van Drecht and Beranek 2018). The Tantalus Formation unconformably overlies the Laberge Group, and represents a major shift in depositional setting, from shallow marine to fluvial. The transition is marked by a shift from the abundant volcanic and igneous lithic clasts in the Laberge Group to chert, quartz and silicified mudstone clasts in the Tantalus Formation (Long 2005). The Tantalus Formation is interpreted to have been deposited in restricted (confined) mountainous river valleys and is notable for its coal deposits near Tantalus Butte, which were mined historically (Long 2015; Colpron et al. 2015).

In north-central B.C., the Bowser Lake Group forms the main component of the extensive Late Jurassic to Mid Cretaceous Bowser basin (Tipper and Richards 1976; Evenchick and Thorkelson 2005; Fig. 1). In its type area, the Bowser Lake Group was deposited on the Spatsizi Formation of the Jurassic Hazelton Group (Fig. 3). Unlike the Tantalus Formation, the Bowser Lake Group was deposited in a marine setting, progressing to non-marine in the uppermost strata (Evenchick and Thorkelson 2005). The wider Bowser basin is interpreted to be the west-facing foreland basin of a doubly vergent Jurassic orogenic system, with the Western Canada sedimentary basin forming the other flank (Fig. 1; Evenchick et al. 2007). Bajocian to Lower Cretaceous siliciclastic strata that sit unconformably on Laberge Group strata in northern B.C., southwest of the King Salmon fault and structurally lower Kehlechoa fault (Figs. 2, 3), have been correlated with the Bowser Lake Group. These include rocks at Lisadele Lake (Shirmohammad et al. 2011) and south of Dease Lake (van Straaten and Gibson 2017; van Straaten and Bichlmaier 2018a). Correlative strata have not been reported from the hanging wall of the King Salmon fault (Fig. 2). This may be because they were removed by erosion in this area, or because the fault juxtaposes distinct sub-basins.

Both the Tantalus Formation and the Bowser Lake Group differ markedly from the underlying strata of the Laberge Group. They contain far fewer volcanic and plutonic clasts, and their clast populations are dominated by chert and silicified mudstone. In both cases, these chert-dominated clast populations have been interpreted as derived from the Cache

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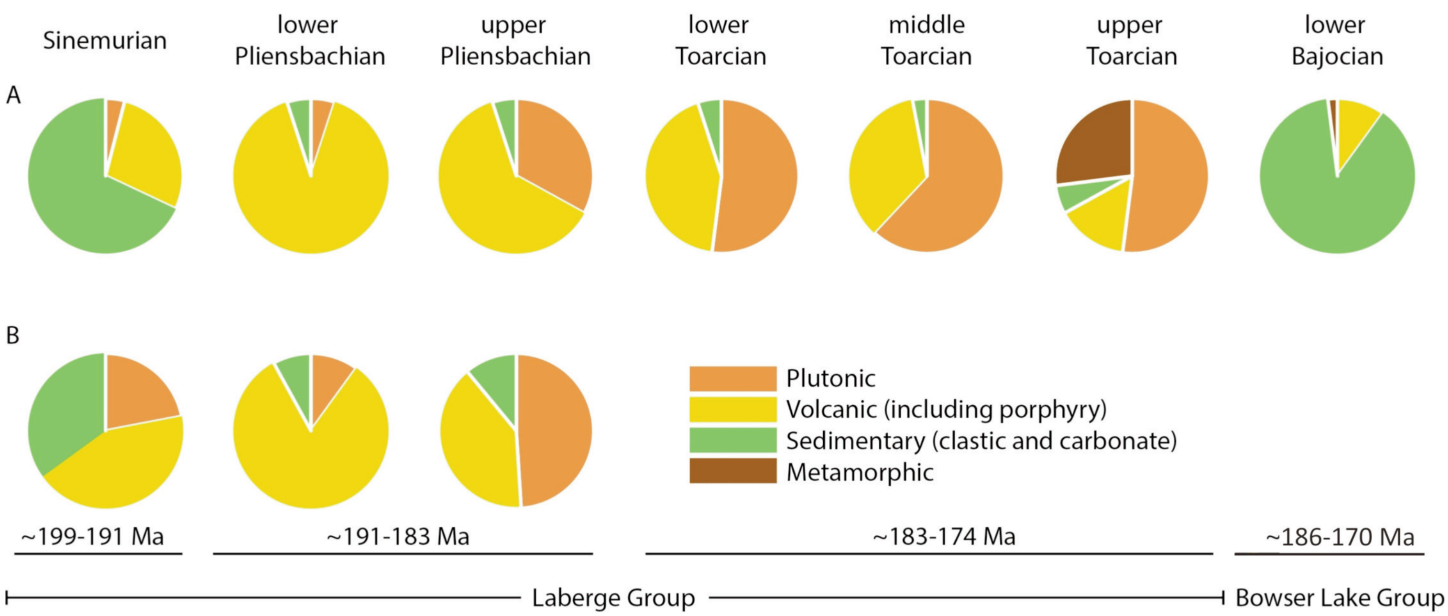


Figure 4. Clast composition distribution for Laberge Group and lower Bajocian Bowser Lake Group conglomerates. A) Lisadele Lake area (Shirmohammad 2006); and B) Atlin Lake area (Johannson et al. 1997).

Creek terrane, based on their Early Permian to Triassic ages. This shift in provenance was interpreted to record the juxtaposition of Stikinia and Cache Creek terranes (Cordey et al. 1991; Cordey 1992; Mihalynuk et al. 2004; Evenchick and Thorkelson 2005; Colpron et al. 2015). However, chert is also common in the Paleozoic–Triassic Stikinia terrane, including the Stikine assemblage (Logan et al. 2000; Mihalynuk et al. 2012), the Tsabayhe Group (Read 1984) and the Sinwa Formation (Mihalynuk et al. 2017) as well as in the Slide Mountain terrane (e.g. Harms and Murchey 1992). The presence of chert detritus in the Tantalus Formation and Bowser Lake Group thus may not be diagnostic of a Cache Creek source (see also Long 2015).

LABERGE GROUP – DETRITUS TYPES AND AGES

Laberge Group Clast Populations

Clast types and proportions in conglomerate beds of the Laberge Group in both southern Yukon and northern B.C. show clear trends related to stratigraphy (Dickie and Hein 1995; Hart et al. 1995; Johannson et al. 1997; Shirmohammad et al. 2011). These are summarized for the strata of northern B.C. in Figure 4 (Johannson, 1994; Shirmohammad et al. 2011). At the base of the Laberge Group, Sinemurian strata at both Lisadele Lake and Atlin Lake (B.C.) contain mostly volcanic and sedimentary clasts, with the latter thought to be largely derived from the underlying Stuhini Group. In overlying lower Pliensbachian strata, volcanic and subvolcanic clasts dominate whereas sedimentary and plutonic clasts are rare. From upper Pliensbachian into middle Toarcian strata there is an increase in the proportion of plutonic clasts to > 60%, largely at the expense of the volcanic clasts.

A regional compilation from the Laberge Group in southern Yukon (Dickie and Hein 1995) illustrates a similar pattern. There is a dominance of sedimentary and volcanic clasts in the basal strata, presumably derived from the older Lewes River Group, and then a shift to > 60% plutonic clasts (largely granite) in Pliensbachian and younger strata. The shifting proportions of volcanic, plutonic and sedimentary clasts through the Laberge Group stratigraphy is interpreted as a shift in the tectonic setting of the source regions. The earlier Sinemurian strata are thought to record flank uplift of the Triassic arc, while the later strata record arc and dissected arc sources through the late Pliensbachian and early Toarcian. The Middle Jurassic arrival of chert-dominated sedimentary clasts in post-Laberge Group strata is interpreted to signal a return to flank uplift (Fig. 4; Dickie and Hein 1995; Johannson et al. 1997; Shirmohammad et al. 2011).

Metamorphic rocks provided discrete, short-lived sources of detritus for the Laberge Group, but two well-described occurrences in B.C. are important. A diverse range of metamorphic clasts and minerals were identified in upper Pliensbachian to lower Toarcian strata at Eclogite Ridge (Fig. 2), including eclogite, granulite, amphibolite, mica schist and garnet peridotite (Canil et al. 2006; Kellett et al. 2018). Upper Pliensbachian strata containing abundant garnet near Janus Point (within Atlin Lake; Fig. 2) are thought to represent the same stratigraphic horizon (Canil et al. 2006; Kellett et al. 2018). Higher in the Laberge Group, metamorphic clasts form a major component of upper Toarcian conglomerate at Lisadele Lake (Fig. 4), where they are mostly quartzofeldspathic schist and gneiss (Shirmohammad 2006). The Lisadele Lake section sits in the footwall of the King Salmon fault, and Toarcian conglomerate in the equivalent setting at the foot of the Llewellyn glacier (Atlin Lake) also contains gneiss clasts (Mihalynuk et al. 2006; Kellett and Iraheta-Muniz 2019). Metamorphic clasts are less commonly reported from the Laberge Group in the Yukon, but they do form a minor component (< 5%) in probable Middle Jurassic strata west of Whitehorse.

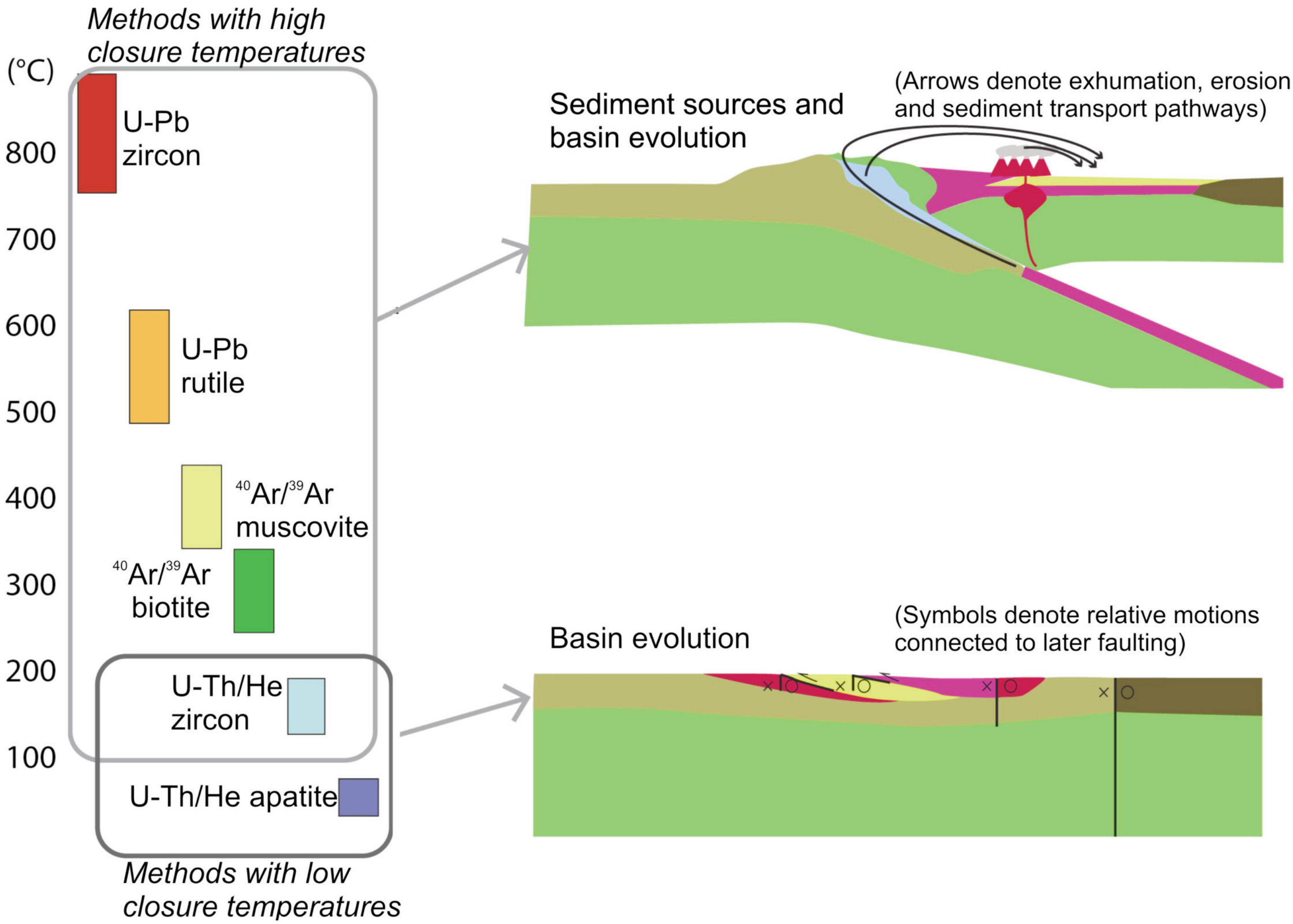


Figure 5. Approximate closure temperatures for geo- and thermochronometers mentioned in this review, based on Harrison et al. (1985); Cherniak (2000); Cherniak and Watson (2001); Farley and Stockli (2002); Reiners (2005); Harrison et al. (2009).

The clast rock types include quartzite, quartz–mica schist, chlorite schist, orthogneiss and marble (Hart et al. 1995). Possible eclogite clasts were reported from exposures in the northernmost Laberge Group (Colpron et al. 2015). Metamorphic clasts were also recognized in the argillite–greywacke units of the Cache Creek Terrane (Mulligan 1963; see Fig. 3). In all these cases, the source of the metamorphic clasts is uncertain (e.g. Hart et al. 1995), but new geochronological data from detrital minerals (discussed below) now provides better constraints.

Geochronology and Thermochronology of Detrital Minerals

Techniques and Their Applications

Geochronological and thermochronological studies of detrital minerals, either as free grains or in relationship to other minerals within rock clasts, provide valuable information for the study of sedimentary basins and their complex links to evolving tectonic processes. Geochronology uses the measurement of radioactive isotopes to yield the 'age' of a particular mineral, but this age is not always the time at which the dated mineral formed. Some mineral decay systems, (e.g. production of ^{40}Ar via decay of ^{40}K in muscovite or biotite) are open systems at geologically high temperatures, such that the daughter products of radioactive decay are not retained (i.e. the radiometric 'clock' doesn't start) until the material reaches a temperature range at which thermal diffusion of daughter elements becomes energetically unfavourable. In such cases, the radiometric age provides data on when the mineral cooled below its 'closure' temperature, rather than when it first formed. These temperature-sensitive mineral decay systems are called *thermochronometers* and they can illustrate the influence of tectonic events, e.g. by providing estimates of exhumation rates. In this section of the paper, geochronological and thermochronological data from the Laberge Group are reviewed and discussed, with emphasis on recent studies. The main methods include the U–Pb geochronometer applied to detrital zircon and rutile grains, and the ^{40}Ar/^{39}Ar thermochronometer, applied to detrital muscovite and biotite. Preliminary information from the (U–Th)/He system applied to zircon and apatite is also reviewed. As indicated in Figure 5, these systems vary widely in their trapping (or 'closure') temperatures. For example, in the case of zircon, the closure temperature ranges from < 200°C for the (U–Th)/He system to > 750°C for the U–Pb system. Systems with higher closure temperatures that have remained closed since the exhumation and erosion of source regions are useful in investigating the sources of sedimentary detritus. Systems that have low closure temperatures may undergo resetting (open system behaviour, a reset of the radiometric clock) following the deposition of the host rocks, so these are more useful in understanding later processes such as sediment burial and basin inversion. In an active setting such as the Jurassic basins of the northern Canadian Cordillera, the depositional and structural histories of sedimentary basins are closely linked, so both approaches are valuable.

U–Pb on Detrital Zircon

U–Pb data from detrital zircon grains in the Laberge Group are available for the entire length of the basin, and some data are also available from older (Stuhini and Lewes River groups) and younger strata (Tantalus Formation and Bowser Lake Group). The compiled information is listed in Table 1 and illustrated in Figures 6 and 7 (information from Shirmohammad et al. 2011; Colpron et al. 2015; Kellett et al. 2018; Kellett and Iraheta-Muniz 2019).

The ages derived from detrital zircon grains in a sample do not automatically provide information on the depositional age of a sample, but since all grains formed in precursor source rocks, they provide a maximum possible age of sedimentation. There are different methods to estimate the maximum depositional age (MDA) of a stratigraphic layer based on its spectrum of U–Pb detrital zircon ages. A robust and widely used approach is to calculate the weighted mean age of all grains within 1σ error of the youngest dated grain, and this is applied in cases where it is anticipated that some zircon grains formed shortly before deposition (Dickinson and Gehrels 2009; Coutts et al. 2019). The abundance of volcanic and plutonic clasts in the Laberge Group strata attests to nearby active magmatic systems that would provide a continual source of contemporary zircon. The weighted mean age method outlined above is applied, following previous U–Pb studies of detrital zircon in these rocks (e.g. Colpron et al. 2015). Whereas MDAs may not be true depositional ages, evidence suggests that they are a useful measure in studies of the Laberge Group. Direct comparison of U–Pb data from detrital zircon at Lisadele Lake with local biostratigraphic constraints demonstrated that the MDAs for Laberge Group samples approach their true depositional ages, as expected for sedimentation close to an active

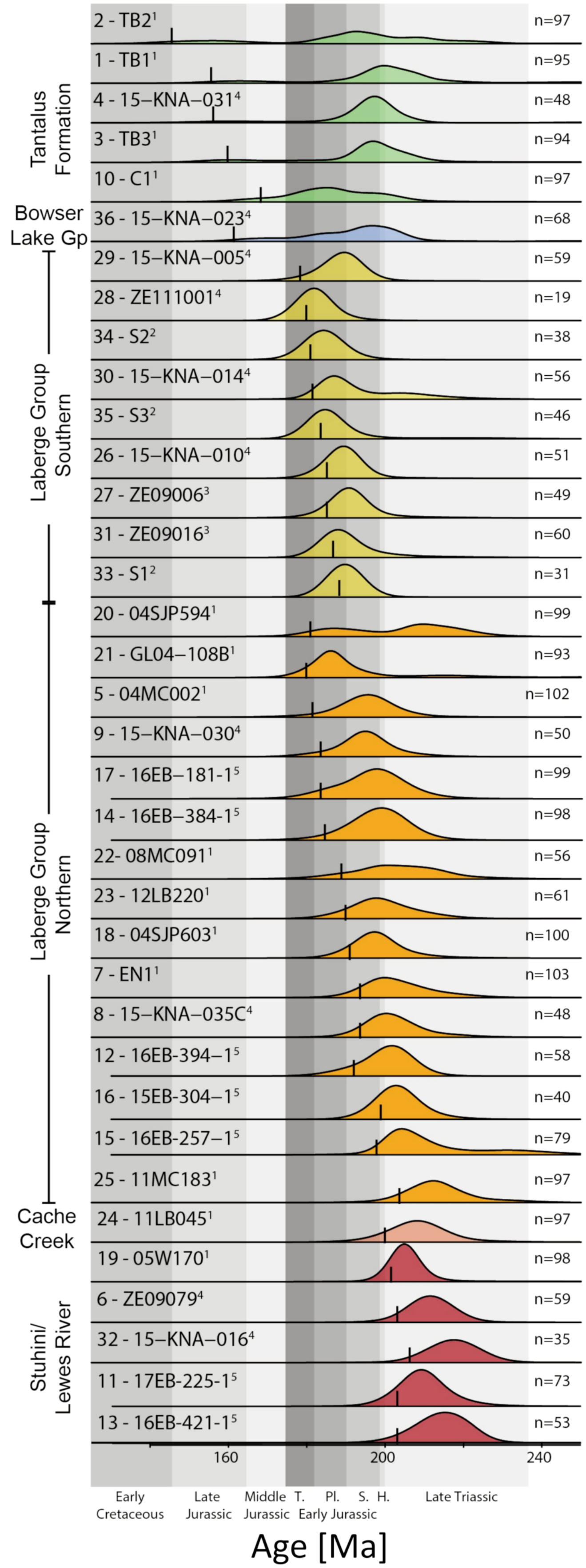


Figure 6. (*opposite*) Kernel density estimates (KDE) for all detrital zircon U–Pb data ($^{206}Pb/^{238}U$ ages), grouped by formation, with northern (Yukon) Laberge Group samples separated from southern (B.C.) Laberge Group samples, and sorted within each group by maximum depositional age. For clarity, only age determinations of < 250 Ma are shown. Tick marks indicate maximum depositional ages as listed in Table 1. Samples are numbered, and those numbers refer to sample locations on Figure 1. Data sources are indicated with superscripts: 1, Colpron et al. (2015); 2, Shirmohammad et al. (2011); 3, Kellett et al. (2018); 4, Kellett and Iraheta-Muniz (2019); 5, Bordet et al. (2019). KDE plots were constructed using IsoplotR (Vermeesch 2018). H = Hettangian; S = Sinemurian; Pl = Pliensbachian; T = Toarcian.

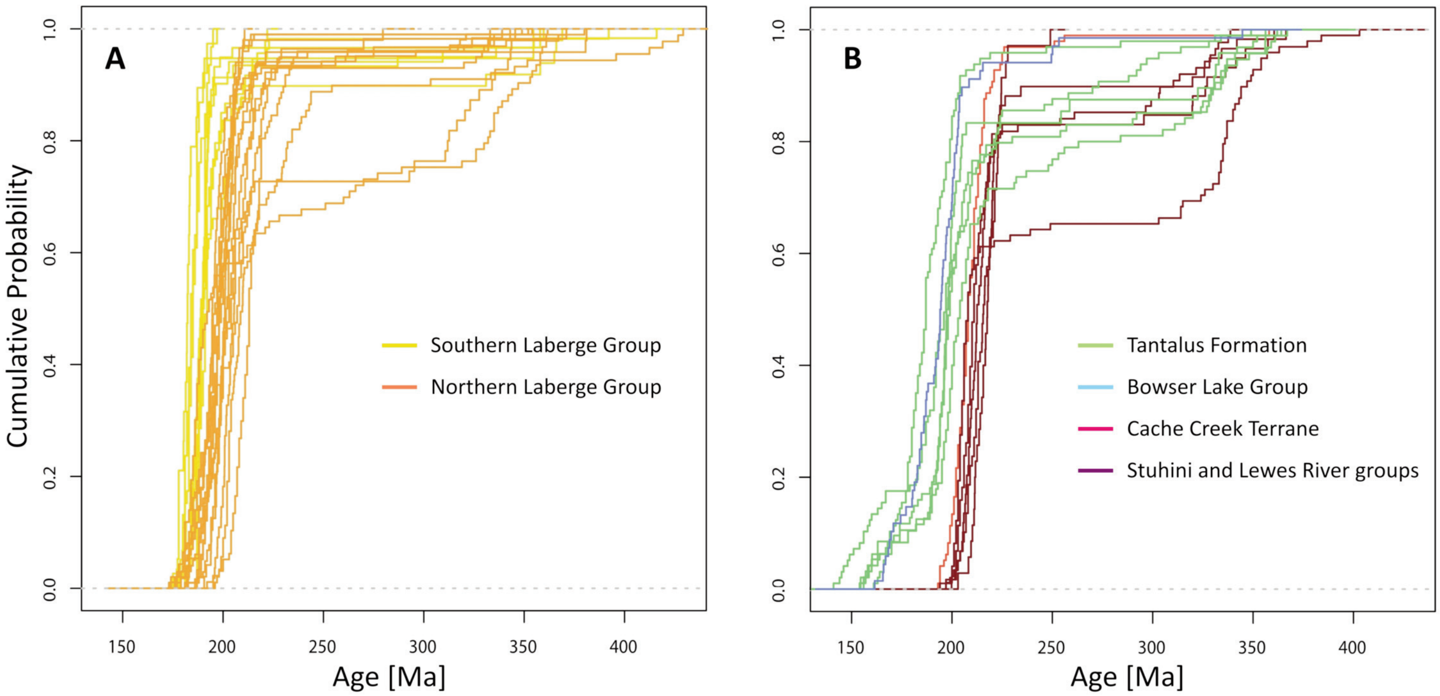


Figure 7. Cumulative age distribution (CAD) plots showing data from Figure 6 coloured by formation. Laberge Group age distributions are shown in A, and younger and older stratigraphic units are shown in B. CAD plots were constructed using IsoplotR (Vermeesch 2018).

arc (Table 1; Shirmohammad et al. 2011). MDAs determined in this way are also very close to the youngest age peaks in all Laberge Group samples and are generally within ± 2% of precise U–Pb ages derived using chemical abrasion thermal ionization mass spectrometry (CA–TIMS) ages for the youngest zircon grains (Table 1; Colpron et al. 2015; Bordet et al. 2019). These two criteria are appropriate methods to assess the relevance of MDA estimates based on detrital zircon ages. Collectively, the U–Pb isotopic data from the Laberge Group and their correspondence with biostratigraphic constraints indicate that the reported maximum depositional ages (MDA) represent a reliable and useful parameter.

The U–Pb data from detrital zircon in the Laberge Group and associated rock units that predate and postdate the Laberge Group reveal interesting spatial and temporal patterns that suggest variations in source terranes and depositional ages. To illustrate those trends, northern Laberge Group results (Yukon) are separated from southern Laberge Group (B.C.) in Figure 6, which shows the maximum depositional age and the age distributions for all dated samples. The MDAs for the northern Laberge Group range from ca. 204–181 Ma compared to frequency maxima between 212–186 Ma, whereas the MDAs for the southern Laberge Group range from ca. 188–178 Ma, compared to frequency maxima between 191 and 182 Ma.

This pattern of maximum depositional ages may suggest that deposition of the Laberge Group progressed southward from Yukon to B.C over a period of some 30 million years. However, the situation may be more complex than it appears from Figure 6. First, the MDA is not necessarily equivalent to a true depositional age, although the evidence presented above suggests broad equivalence. Second, several of the samples from Yukon were selected specifically to represent basal strata of the Laberge Group (Colpron et al. 2015; Bordet et al. 2019), whereas none of the B.C. samples specifically represent this part of the succession. The oldest MDA for the southern Laberge Group, sample S1 from Lisadele Lake, was collected ~ 250 m stratigraphically above the base of the Laberge Group (Shirmohammad et al. 2011). This sampling bias may explain the apparent transgression and should be tested by further research in B.C. aimed specifically at basal Laberge Group strata.

All southern Laberge Group samples are dominated by Pliensbachian zircon (191–183 Ma), but only two of the southernmost samples from Yukon captured significant zircon of this age (04SJP594 and GL04-108B, localities 20 and 21 in Fig. 2), with the remaining 9 samples being dominated by Norian to Sinemurian zircon (228–191 Ma), even though a few have MDAs young enough that they could feasibly have captured Pliensbachian zircon (04MC002, 15-KNA-030, localities 5 and 9 in Fig. 2). The Nordenskiöld tuff units, which are interbedded with the Laberge Group in Yukon are of Pliensbachian age (Templeman-Kluit 2009), so some zircon of this age range could be expected. The lack of Pliensbachian zircon suggests either some sampling bias, or that source catchments for the Laberge Group were locally restricted, perhaps due to the topography of the underlying Lewes River Group (van Drecht and Beranek 2018). In terms of potential igneous zircon sources, it appears that the youngest zircon populations from the northern Laberge Group zircon samples (from Rhaetian through Pliensbachian strata) are similar in age to igneous rocks of the Minto and Texas Creek plutonic suites (Fig. 3). A

Table 1. Summary of detrital zircon U–Pb data for Laberge Group and spatially associated sedimentary rocks of the Cache Creek, Stuhini Group, Bowser Lake Group, Tantalus and Aksala formations.

Map Locality	Sample Number	Latitude dd.dddd	Longitude ddd.dddd	Stratigraphic Unit	Youngest age peak (Ma)	Maximum depositional age* (Ma)	Youngest Zircon (CA-TIMS; Ma) or stratigraphic age	Reference
1	TB1	62.1422	-136.2662	Tantalus Fm.	162	156	159.20 ± 0.08	Colpron et al. (2014)
2	TB2	62.1422	-136.2662	Tantalus Fm.	155	146	148.51 ± 0.06	Colpron et al. (2014)
3	TB3	62.1230	-136.2639	Tantalus Fm.	160	160		Colpron et al. (2014)
4	15-KNA-031	62.1233	-136.2652	Tantalus Fm.	197	157		Kellett and Iraheta-Muniz (2019)
5	04MC002	62.1117	-136.1491	Laberge Gp. (N)	196	182		Colpron et al. (2014)
6	ZE09079	62.0240	-135.8219	Aksala fm.	212	203		Kellett and Iraheta-Muniz (2019)
7	EN1	62.0238	-135.8226	Laberge Gp. (N)	200	194		Colpron et al. (2014)
8	15-KNA-035C	61.6212	-135.8777	Laberge Gp. (N)	200	194		Kellett and Iraheta-Muniz (2019)
9	15-KNA-030	61.3765	-135.6744	Laberge Gp. (N)	195	184		Kellett and Iraheta-Muniz (2019)
10	C1	61.3424	-135.9727	Tantalus Fm.	185	168		Colpron et al. (2014)
11	17EB-225-1	61.3364	-135.2227	Aksala fm.	210	208	211.33 ± 0.01	Bordet et al. (2019)
12	16EB-394-1	61.2503	-135.1888	Laberge Gp. (N)	201	199	199.78 ± 0.06	Bordet et al. (2019)
13	16EB-421-1	61.2439	-135.1910	Aksala fm.	215	214	214.75 ± 0.07	Bordet et al. (2019)
14	16EB-384-1	61.2106	-135.0755	Laberge Gp. (N)	199	190	186.38 ± 0.07	Bordet et al. (2019)
15	16EB-257-1	61.1909	-135.1328	Laberge Gp. (N)	205	202	203.46 ± 0.14	Bordet et al. (2019)
16	15EB-304-1	61.1042	-134.7580	Laberge Gp. (N)	203	202	202.4 ± 1.5	Bordet et al. (2019)
17	16EB-181-1	61.0994	-135.0755	Laberge Gp. (N)	197	189	186.22 ± 0.09	Bordet et al. (2019)
18	04SJP603	61.0761	-135.1965	Laberge Gp. (N)	197	191		Colpron et al. (2014)
19	05W170	60.8476	-135.3738	Lewes River Gp.	205	202		Colpron et al. (2014)
20	04SJP594	60.8527	-135.4326	Laberge Gp. (N)	187	181		Colpron et al. (2014)
21	GL04-108B	60.6997	-135.3737	Laberge Gp. (N)	186	180		Colpron et al. (2014)
22	08MC091	60.6653	-134.9095	Laberge Gp. (N)	201	189		Colpron et al. (2014)
23	12LB220	60.5083	-134.1222	Laberge Gp. (N)	198	190		Colpron et al. (2014)
24	11LB045	60.2585	-133.6483	Cache Creek	208	200		Colpron et al. (2014)
25	11MC183	60.1838	-134.6850	Laberge Gp. (N)	212	212		Colpron et al. (2014)
26	15-KNA-010	59.3272	-133.7708	Laberge Gp. (S)	189	185		Kellett and Iraheta-Muniz (2019)
27	ZE09006	59.3271	-133.7721	Laberge Gp. (S)	191	185		Kellett et al. (2018a)
28	ZE111001	59.2793	-134.0748	Laberge Gp. (S)	182	180		Kellett and Iraheta-Muniz (2019)
29	15-KNA-005	59.2653	-133.8401	Laberge Gp. (S)	188	178		Kellett and Iraheta-Muniz (2019)
30	15-KNA-014	59.1136	-133.9623	Laberge Gp. (S)	187	183		Kellett and Iraheta-Muniz (2019)
31	ZE09016	59.1102	-133.3873	Laberge Gp. (S)	188	187		Kellett et al. (2018a)
32	15-KNA-016	58.6887	-133.0308	Stuhini Gp.	212	206		Kellett and Iraheta-Muniz (2019)
33	S1	58.6825	-133.0384	Laberge Gp. (S)	190	188	Pliensbachian	Shirmohammad et al. (2011)
34	S2	58.6757	-133.0429	Laberge Gp. (S)	184	181	Lower Toarcian	Shirmohammad et al. (2011)
35	S3	58.6695	-133.0489	Laberge Gp. (S)	184	184	Upper Toarcian	Shirmohammad et al. (2011)
36	15-KNA-023	58.6491	-133.0671	Bowser Lake Gp.	170	162		Kellett and Iraheta-Muniz (2019)

*Maximum depositional age determined as the weighted mean age of grains within 1σ of youngest grain (see explanation in text of the paper). Both youngest age peaks and calculated maximum depositional age are shown rounded to nearest m.y.: two-sigma errors for calculated MDAs are typically 1%. Where CA-TIMS ages for youngest zircon grains are available, they are listed for comparison with the calculated MDA, with their 2σ errors. Where precise biostratigraphic constraints are available, they are also listed for comparison. Biostratigraphic age (Shirmohammad et al. 2011). See sample locations on the map in Figure 2. For methods and laboratories, see original references.

comparison of MDA against youngest zircon age peak, show the interval between crystallization of those zircon grains and their deposition is 5–15 million years (Fig. 8). In contrast, the youngest zircon populations from the southern Laberge Group samples (Pleinsbachian strata) are similar in age to igneous rocks of the Texas Creek and Long Lake plutonic suites (Fig. 3) and were deposited within 10 million years of crystallization (Fig. 8). Note that this inference depends on the assumption that the MDA estimates approximate true depositional ages.

Based on the available data, there is little to no gap in MDA between the Stuhini and Lewes River Group rocks and the Laberge Group sedimentary rocks, at least for the northern part of the study area. The MDAs for samples 05W170 and ZE09079 (Lewes River Group and Mandanna member, respectively, localities 19 and 6 in Fig. 2) overlap with those calculated for Laberge Group sample 11MC183 (locality 25 in Fig. 2). The data suggest a gap of ~ 10 m.y. between the latest Laberge Group deposition and deposition of Bowser Lake Group and Tantalus Formation. Other work has suggested that deposition of the Bowser Lake Group began in the Bajocian (Evenchick et al. 2010; Shirmohammad et al. 2011), so there is little to no time gap between the Laberge Group and these rocks at the regional scale.

Only one sample from sedimentary rocks of the Cache Creek Terrane provides U–Pb data from detrital zircon grains.

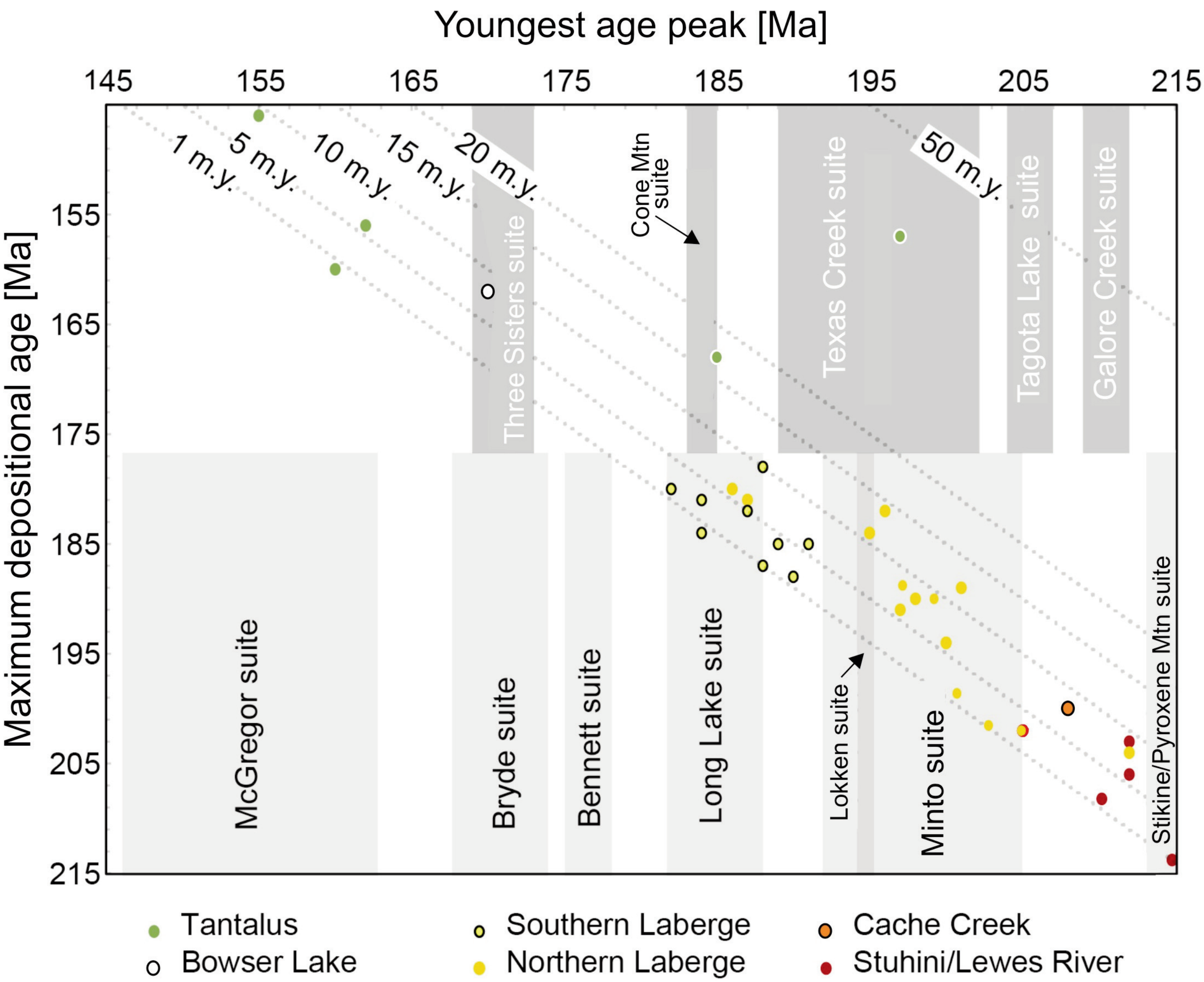


Figure 8. Plot of maximum depositional age vs. youngest age peak for detrital zircon data illustrated in Figures 6 and 7. Dashed lines show lag times in m.y. Light shaded boxes indicate age ranges of plutonic suites of southern Yukon from Figure 3: Stikine/Pyroxene Mountain suite (217–214 Ma), Minto suite (205–194 Ma), Lokken suite (195–192 Ma), Long Lake suite (188–182 Ma), Bennett suite (178–175 Ma), Bryde suite (174–168 Ma) and McGregor suite (ca. 163–146 Ma) (Colpron et al. 2016b; Sack et al. 2020). Dark shaded boxes indicate age ranges of plutonic suites for northern B.C. from Figure 3: Stikine suite (229–216 Ma), Galore Creek suite (212–209 Ma), Tatogga Lake suite (207–204 Ma), Texas Creek suite (202–189 Ma), Cone Mountain suite (185–183 Ma) and Three Sisters suite (173–169 Ma) (van Straaten et al. BCGS Open House presentation 2018).

Sample 11LB045 (locality 24 in Fig. 2) is closest in MDA to Stuhini sample 05W170 (locality 19), and has a younger MDA than the 'oldest' Laberge Group sample (11MC183; locality 25). Its detrital zircon population is similar to both of these samples (Figs. 6, 7).

Cumulative probability plots (Fig. 7) show that the Laberge Group samples contain fewer Paleozoic grains compared to samples from the older units of the Stuhini and Lewes River groups, and younger strata of the Tantalus Formation. However, there are older grains present in some Laberge Group samples. The most likely explanation for the contrast is that the detritus arriving to form the Laberge Group was dominated by erosion products from the nearby Stikine arc, consistent with the pattern shown by clast compositions (Fig. 4). Other zircon grains derived from older sources would simply have been swamped by material derived from the young adjacent arc terranes (e.g. Colpron et al. 2015).

Detrital zircon has also been isolated from igneous clasts in conglomerate of the Laberge Group in southern Yukon, and in the Lisadele Lake region. U–Pb dating of multigrain zircon fractions from clasts in the Yukon samples by TIMS yielded ages from 215 to 208 Ma (Hart et al. 1995), suggesting derivation from members of the Late Triassic Stikine plutonic suite, such as the Willison Bay pluton near Atlin (Mihalynuk et al. 2006) and the Tally Ho leucogabbro in southernmost Yukon (Hart 1996). TIMS dating of zircon in clasts from Lisadele

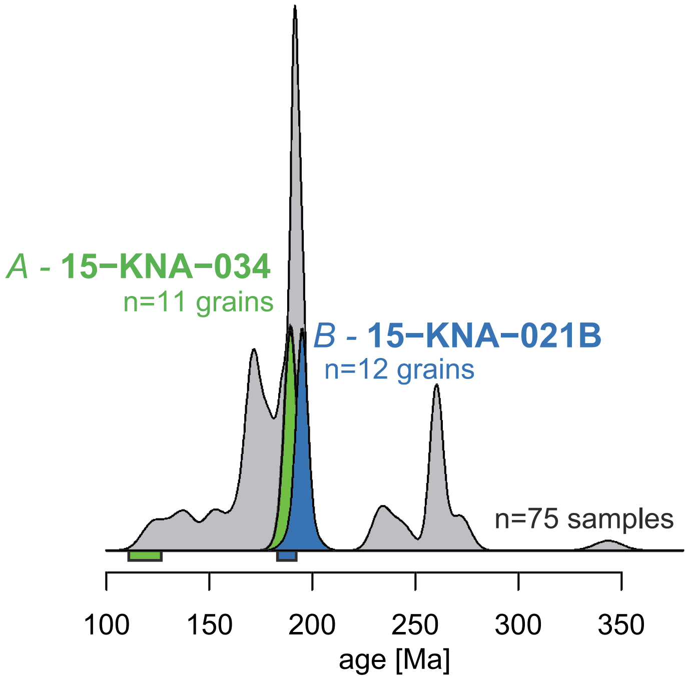


Figure 9. Kernel density estimate (KDE) plot for single crystal step heating detrital muscovite ages from samples 15-KNA-034 (Tantalus Formation) and 15-KNA-021B (a clast in Toarcian strata of Laberge Group). Sample locations are identified in Figure 2 as A and B, respectively, and their geographic coordinates are listed in the text. Note that data are overlain on a KDE that compiles all published muscovite $^{40}Ar/^{39}Ar$ metamorphic cooling ages from southern Yukon (Yukon Age Database 2006; Joyce et al. 2015). Bars beneath KDE plot show maximum depositional ages coloured by sample, as discussed in text.

Lake samples yielded crystallization ages of 186.6 ± 0.5 Ma and 221 ± 1 Ma (Shirmohammad et al. 2011). The older age coincides with the age of the Stikine plutonic suite, but the younger age is not represented in igneous rocks of northern B.C. However, an age of ca. 187 Ma overlaps the age range of the Hazelton Group (Cutts et al. 2015) and the Long Lake plutonic suite of southern Yukon (Colpron et al. 2016b; Sack et al. 2020).

U–Pb on Detrital Rutile

Pliensbachian Laberge Group strata at and south of Atlin Lake, including at Eclogite Ridge, contain minerals associated with high-grade metamorphism and discrete metamorphic rock clasts (English et al. 2002). These strata are the likely source of micro-diamonds captured in nearby stream sediment surveys (Canil et al. 2005). Metamorphic clasts within this horizon include eclogite, granulite, amphibolite and mica schist. These rock types are accompanied by porphyry, volcanic and granitic clasts that are more typical in the Laberge Group. The geochemistry of detrital garnet, spinel and pyroxene indicates that sources include ultra-high pressure (> 2.8 GPa) garnet peridotite (MacKenzie et al. 2005; Canil et al. 2006). Recent detailed studies of pristine eclogite clasts suggested peak temperature and pressure conditions of ≥ 800°C and ≥ 2.2 GPa, with U–Pb dating of rutile indicating that samples cooled through about 610°C during the Early Jurassic (182 ± 15 Ma; Kellett et al. 2018). In order for these clasts be deposited into the Laberge Group by the latest Pliensbachian, the source rocks must have been exhumed from depths of about 80 km depth at a mean vertical rate of at least 4 km/m.y. during the Early Jurassic (Kellett et al. 2018). This rapid rate of exhumation is typical for rocks exhumed at active subduction zones (e.g. Baldwin et al. 2004), and the eclogite clasts are interpreted to have been carried in a subduction channel between the Yukon-Tanana and Stikinia terranes (Kellett et al. 2018).

$^{40}Ar/^{39}Ar$ on Detrital Mica

Detrital muscovite is rare in the Late Triassic to Early Cretaceous sedimentary rocks of the northern Canadian Cordillera, likely because the Triassic to Early Jurassic magmatic rocks that contributed most detritus are generally sub-greenschist facies. However, muscovite is abundant in potential metamorphic source rocks such as the Snowcap assemblage of Yukon-Tanana terrane which may have contributed detritus to the Laberge Group (e.g. Piercey and Colpron 2009). Thus, although detrital muscovite is rare in Laberge Group samples, it is an important data source that provides information about exclusively metamorphic sources that are difficult to identify using detrital zircon. The nominal closure temperature for Ar in muscovite is ~ 400°C (Fig. 5). Muscovite from a strongly foliated and lineated quartz–feldspar schist clast in an Upper Toarcian horizon of the Laberge Group at Lisadele Lake, B.C. (Sample B in Fig. 2; latitude 58.6714N, longitude 133.0471W) was dated by Kellett and Iraheta-Muniz (2019). The depositional age for this location is constrained by biostratigraphy (Shirmohammad et al. 2011). Matrix detrital muscovite from a horizon of the Tantalus Formation along the Klondike Highway in the southern Yukon (Sample A in Fig. 2; latitude 61.75N; longitude 136.00W) was also dated by Kellett and Iraheta-Muniz (2019). This location has a Cretaceous (Aptian) mean depositional age (van Drecht, L., pers. comm. 2017).

Step heating results of individual muscovite crystals from the two sampled horizons indicate homogeneous $^{40}Ar/^{39}Ar$ age populations for these samples (Fig. 9). The clast from Lisadele Lake (locality B in Fig. 2, sample 15-KNA-021B) yielded a muscovite cooling age of ca. 195 Ma, and detrital grains from the Tantalus Formation (locality A in Fig. 2, sample 15-KNA-034) yielded an age peak of ca. 190 Ma. Both these results match $^{40}Ar/^{39}Ar$ age populations that are documented in metamorphic rocks from the Yukon-Tanana terrane in southern Yukon (Fig. 9). The age overlap between these detrital muscovite populations and bedrock metamorphic muscovite ages in southern Yukon suggests that Yukon-Tanana terrane metamorphic rocks are a likely source for horizons including metamorphic detritus in the Laberge Group and the Tantalus Formation. The data also indicate that the metamorphic source rock for the muscovite-bearing clasts in the Laberge Group must have been exhumed rapidly. Using a nominal closure temperature for metamorphic or igneous muscovite of 400°C, a 25°C/km geothermal gradient, and a depositional age of ca. 180 Ma, a source rock containing muscovite with 195 Ma cooling age would need to be exhumed at a mean rate of about 1 km/m.y. during the Early Jurassic.

Detrital biotite grains from two metamorphic clasts within Upper Toarcian Laberge Group strata at Lisadele Lake, B.C.

Table 2. Summary of preliminary zircon and apatite U–Th/He data for Laberge Group and spatially associated sedimentary rocks of the Lewes River Group, Bowser Lake Group and Tantalus Formation.

Map Locality*	Sample	Stratigraphic Unit	Latitude dd.dddd	Longitude ddd.dddd	ZHe* (Ma)	Number of grains	Age Dispersion	AHe* (Ma)	Number of grains	Age Dispersion
2	TB2	Tantalus Fm.	62.1422	-136.2662				56.2	3	
4	15KNA031	Tantalus Fm.	62.1233	-136.2652	203–170	5				
5	04MC002	Laberge Gp.	62.1117	-136.1491				47.4	5	
	15KNA032	Laberge Gp.	62.0347	-135.8619	156.7	7		43	5	Y
6	ZE09079	Lewes River Gp.	62.024	-135.8219	223–185	7	Y	39.3	2	Y
7	EN1	Laberge Gp.	62.0238	-135.8226				64.8	5	
	15KNA034	Tantalus Fm.	61.75	-136.00	176–152	4		40.4	5	
8	15KNA035C	Laberge Gp.	61.6212	-135.8777	150.1	5	Y	50.2	6	
9	15KNA030	Laberge Gp.	61.3765	-135.6744	111.3	6		51.2	4	Y
	15KNA029	Laberge Gp.	61.077	-135.1981	82.3	4				
	15KNA028	Laberge Gp.	60.9783	-135.1835	72.4	8		26.5	7	Y
	15KNA027	Laberge Gp.	60.9116	-135.2304	148.5	5	Y	41.9	5	
	15KNA025	Laberge Gp.	60.2676	-134.7457				43.1	5	
25	11MC183	Laberge Gp.	60.1838	-134.685				72.3	5	
26	15KNA010	Laberge Gp.	59.3272	-133.7708	198–173	4	Y	43.7	5	
27	ZE09006	Laberge Gp.	59.3271	-133.7721	205–180	7	Y			
28	ZE111001	Laberge Gp.	59.2793	-134.0748	61.5	7				
29	15KNA005	Laberge Gp.	59.2653	-133.8401	117.2	6		32.5	6	
	15KNA012	Laberge Gp.	59.2435	-134.0198	109.7	4		41.5	4	
30	15KNA014	Laberge Gp.	59.1136	-133.9623	103.4	5				
31	ZE09016	Laberge Gp.	59.1102	-133.3873	207–165	8				
32	15KNA016	Stuhini Gp.	58.6887	-133.0308				37.4	4	
35	S3	Laberge Gp.	58.6695	-133.0489	97.8	6	Y			
36	15KNA023	Bowser Lake Gp	58.6491	-133.0671	89	3	Y			

*Locality numbers in Figure 2 where indicated; otherwise, sample locations in Figure 10.

were dated with ^{40}Ar/^{39}Ar (Shirmohammad 2006) and yielded hump-shaped spectra generally indicative of partial Ar loss, in this case likely after deposition, and potentially a minor excess ^{40}Ar contribution (i.e. ^{40}Ar not produced by decay within the biotite) (Shirmohammad 2006). The final heating steps in these samples yielded poorly defined ca. 220 Ma and ca. 195 Ma ages which were interpreted by Kellett and Zagorevski (2021) to broadly represent maximum cooling ages.

In summary, cooling ages of metamorphic detritus in the Laberge Group indicate (a) source region(s) that experienced Early Jurassic Barrovian to high-pressure metamorphism that was quickly followed by rapid exhumation, erosion and deposition. The evidence for widespread Early Jurassic metamorphism in the Yukon-Tanana terrane (Currie and Parrish 1993; Dusel-Bacon et al. 2002; Berman et al. 2007; Morneau 2017) and other evidence for rapid exhumation and cooling (Johnston and Erdmer 1995; Johnston et al. 1996; Joyce et al. 2015) suggest it is the most likely source for the metamorphic detritus (e.g. Canil et al. 2006; Kellett et al. 2018).

(U–Th)/He on Detrital Zircon

Radiogenic He is a by-product of alpha decay of U, Th and Sm, and the decay chain from ^{238}U to ^{206}Pb, for example, produces 8 ^{4}He atoms. The nominal closure temperature for trapping and accumulating He atoms in zircon is ~ 180°C (Reiners 2005), but can vary significantly depending on cooling rate, grain size and radiogenic content (Whipp et al. in press). The U–Pb age of zircon generally (but not always) provides the timing of zircon crystallization, but the (U–Th)/He age of a zircon grain (ZHe) records the time when the crystal last cooled through ~ 180°C. Depending on thermal conditions in the sedimentary basin, ZHe ages of detrital zircon grains may provide either a record of source exhumation ages (i.e. they give ages *older* than depositional age) or a record of the basin's thermal history (i.e. ages *younger* than depositional age). The resetting of the U–Th/(He) ages in the second scenario could be related to sedimentary and structural burial, contact metamorphism, local hydrothermal fluid circulation or influences from nearby tectonic events.

Preliminary results from ZHe and (U–Th)/He dating of apatite (AHe) from Laberge Group and associated rocks are presented in Table 2 and Figure 10. ZHe dating was performed on zircon from 14 Laberge Group samples. These data are augmented by three matrix samples from the Tantalus Formation and one matrix sample from the Bowser Lake Group, representing younger Cretaceous strata. Two matrix samples from the Triassic Lewes River and Stuhini groups represent units older than the Laberge Group and were collected close to basal Laberge strata (Kellett et al. 2017). Five of these samples were double-dated, that is, U–Pb and He dates were obtained from the same individual zircon crystals (Table 2; Fig. 11). Double-dating of detrital zircon is a powerful approach for studying sediment provenance (Reiners et al. 2005).

The ZHe ages of detrital zircon from the northernmost Laberge Group and from the area between the King Salmon and Nahlin faults, are slightly older than or within error of

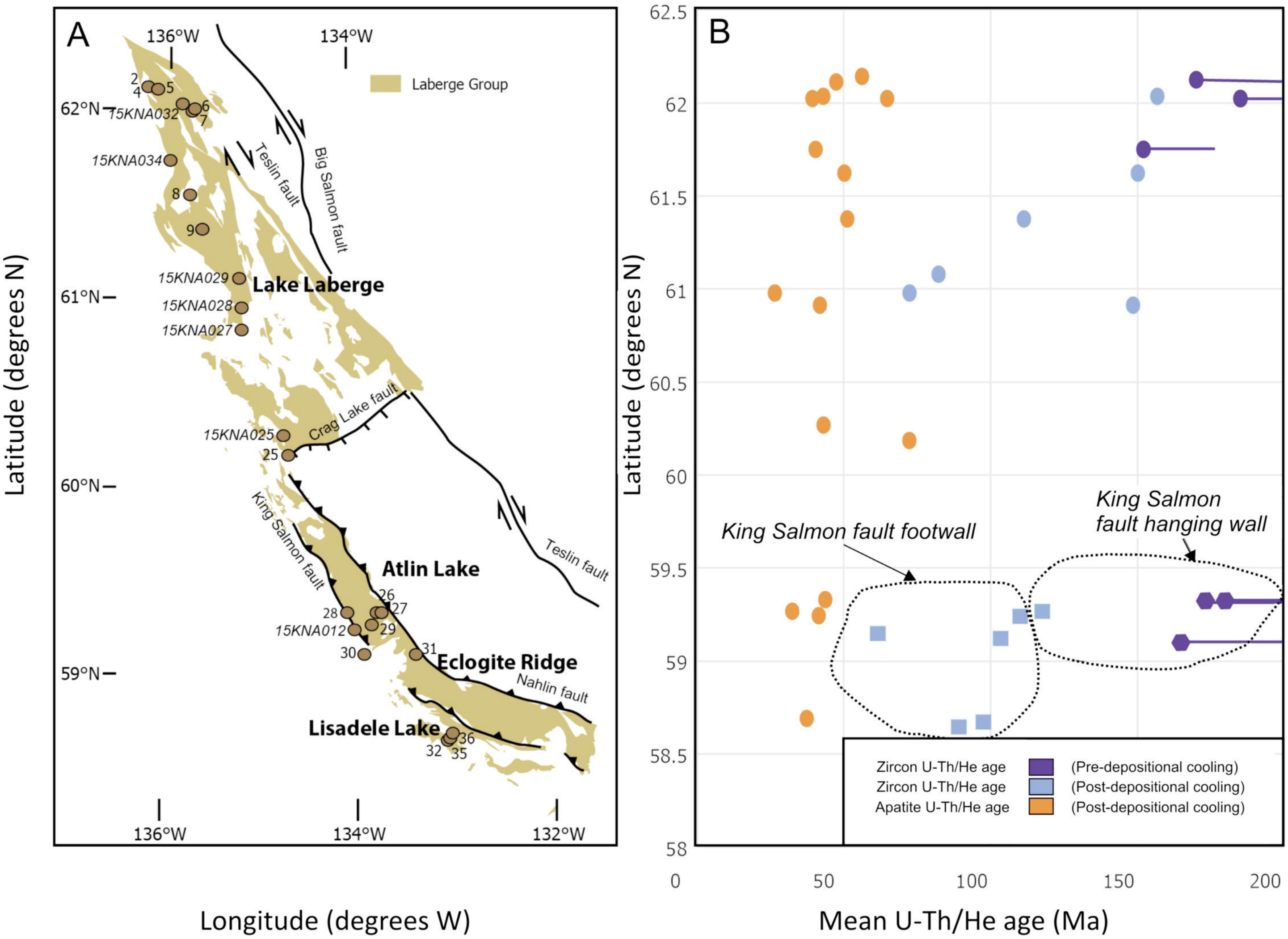


Figure 10. A. Laberge Group map footprint extracted from Figure 2 showing locations of U-Th/He samples. Short locality numbers correspond to samples shown in Figure 2 and listed in Table 1, and longer sample numbers represent additional analyses listed in Table 2. These additional samples do not have corresponding detrital zircon data. Map modified from Cui et al. (2017) and Colpron et al. (2016a). B. Mean U–Th/He ages for zircon and apatite from Table 2 plotted against sample latitude, as a proxy for along-strike position in the basin. Hexagonal ZHe data points are from the hanging wall of the King Salmon thrust, while square ZHe data points are from the footwall. Horizontal blue bars indicate range of detrital ZHe ages.

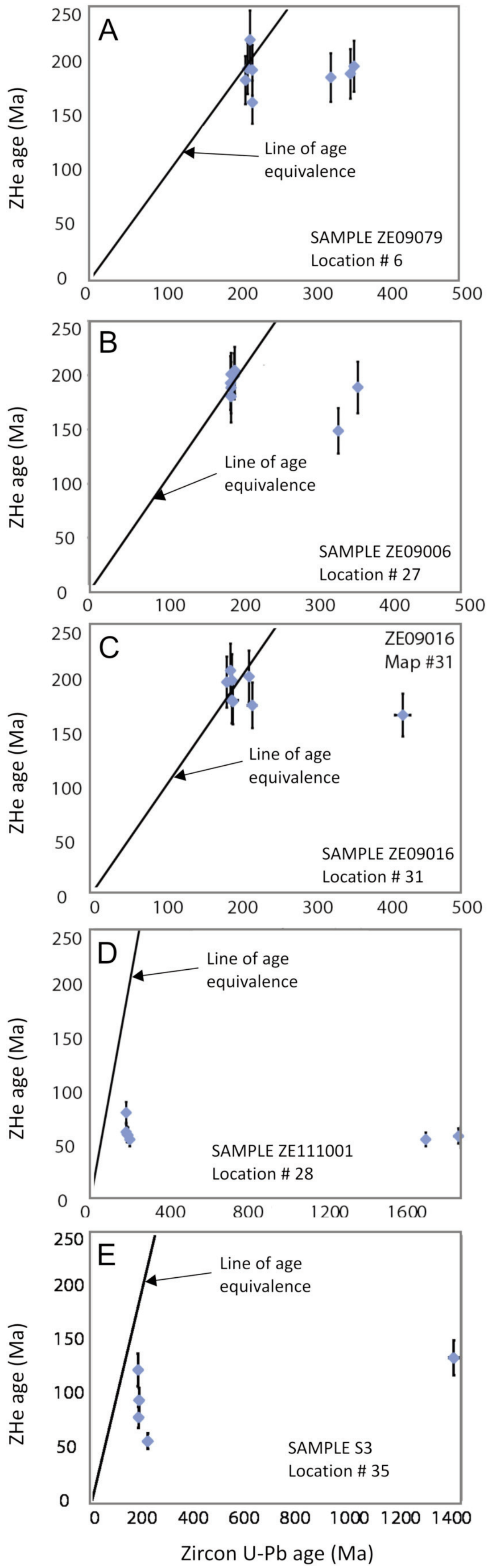
their depositional ages indicating that they preserve information about the exhumation and cooling history of their source rocks (Fig. 10). The similarity between U–Pb ages and ZHe ages, as demonstrated clearly in double-dated samples ZE09006, ZE09016 and ZE09079 (Fig. 11; localities 27, 31 and 6 in Fig. 2), indicates that those rocks did not experience post-depositional temperatures higher than ~ 180°C. In contrast, there are two regions where ZHe dates have been reset by post-depositional heating (i.e. ZHe ages are significantly younger than depositional ages; Figs. 10, 11). Samples collected northwest and southwest of Lake Laberge yielded post-depositional ZHe dates between ~ 150 and 80 Ma. Finally, all samples collected from the footwall of the King Salmon thrust yielded post-depositional ZHe dates of 110 Ma or younger (Figs. 10, 11). These include samples collected from units older than the Laberge Group (e.g. 15KNA016; locality 32), and younger sedimentary rocks of the Bowser Lake Group (15KNA023; locality 36).

(U–Th)/He on Detrital Apatite

Compared to He in zircon, He in apatite has a significantly lower nominal trapping temperature, ~60°C (Farley and Stockli 2002). Thus, apatite grains are more likely to be reset during burial or heating events than zircon grains, i.e. AHe ages are expected to be young than depositional ages, and younger than ZHe ages from the same samples. All AHe dates obtained to date from Mesozoic sedimentary rocks range from late Cretaceous to Oligocene, significantly postdating deposition of their host strata (Fig. 10). These results indicate that final cooling and exhumation of the post-accretionary basins following basin inversion mostly occurred during the Paleogene.

DISCUSSION

The Jurassic sedimentary strata of the Laberge Group in northern British Columbia and southern Yukon provide an impressive record of basin development linked to progressive tectonic evolution and coeval arc magmatism. The earliest



Laberge Group strata were deposited unconformably on late Triassic volcanic-dominated sequences of the Lewes River Group in Yukon and in the Stuhini Group in B.C., both of which belong to the arc-related Stikinia terrane. During Sinemurian to Toarcian times (199 Ma to 174 Ma) the Stikinia terrane was uplifted and incised through erosion of its supracrustal rocks, which locally reached its plutonic roots. This process is revealed by changes in clast proportions in the Laberge Group sequence, which received detritus from the still active but eroding arc terranes. At the same time, older rocks of the adjacent Yukon-Tanana terrane were metamorphosed under Barrovian and (locally) high-pressure conditions, and were then rapidly exhumed and eroded. This metamorphic detritus, representing all crustal levels and including possible subduction-zone eclogite, was also deposited in the Laberge Group, but such contributions were minor compared to those from volcanic and plutonic rocks. Nevertheless, its presence as a minor component suggests that the Stikinia and Yukon-Tanana terranes were amalgamated (or re-amalgamated) during the Early Jurassic, with the Yukon-Tanana terrane representing the lower plate. The relationship between the Stikinia and Cache Creek terranes during the Early Jurassic remains enigmatic, yet the potential for correlation between Late Triassic and Early Jurassic clastic and volcanoclastic units within them suggests that more detailed studies could clarify this problem.

By the Bajocian (Middle Jurassic, 170 to 168 Ma) deposition of the Laberge Group was nearly complete, some of these strata were eroded, and successor Late Jurassic and Cretaceous sequences of the Tantalus Formation and the Bowser Lake Group developed. The abundance of chert clasts in these strata and the paucity of volcanic or plutonic detritus indicate an important shift in sediment sources. The shift from a marine depositional setting in the Laberge Group to a restricted fluvial depositional setting in the Tantalus Formation, and the widespread contribution of chert debris could suggest the closure and inversion of a marine basin.

The Laberge Group, the Bowser Lake Group and correlative rocks were eventually inverted and shortened into a west-facing fold and thrust belt that includes the King Salmon fault (Tipper 1978; English et al. 2002; see Fig. 2). The locally angular unconformity between the Laberge Group and the overlying younger units suggests that more than one phase of folding and thrusting occurred during the Jurassic, before and after the younger sequences were deposited. Any westward overthrusting of the Cache Creek terrane onto the Stikinia terrane (and the Laberge Group) must have been limited, as U–Th/(He) data indicate that Laberge Group rocks lying in the footwall of the Nahlin fault were not buried sufficiently to

Figure 11. (*opposite*) Double dating of detrital zircon crystals. U–Pb ages are from Kellett and Iraheta-Muniz (2019) (A, D), Kellett et al. (2018) (B, C) and Shirmohammad et al. (2011) (E), while ZHe ages for the same crystals are preliminary data. Sample numbers and locality numbers correspond to those listed in Table 2 and shown in Figures 2 and 10. Points that plot on the line of age equivalence have identical U-Pb and ZHe ages within error. Error bars are at the 1σ level for both U–Pb and ZHe data.

reach ~ 180°C (~ 7 km for a geothermal gradient of 25°C/km). However, Laberge Group rocks in southernmost Yukon and west of the King Salmon fault in northern B.C. were heated to more than 180°C during Late Jurassic to Early Cretaceous, before eventually cooling, likely by being exhumed into the shallow crust. Movements on post-accretionary structures such as the King Salmon, Nahlin and Teslin faults may have contributed to regional differences in exhumation and cooling rates throughout the Cretaceous, and to a lesser extent during the Paleogene.

CONCLUSIONS

Information from multiple isotopic systems, including U–Pb studies of detrital zircon and rutile, $^{40}Ar/^{39}Ar$ studies of detrital muscovite and biotite, and U–Th/(He) investigations of zircon and apatite, provide valuable information about the geological history of the Laberge Group and associated rocks, and these data also provide directions for future studies. U–Pb data from detrital zircon show that the Laberge Group was sourced largely from Mesozoic volcanic and plutonic rocks, which in most cases were only slightly older than the documented and inferred depositional ages of the sedimentary rocks. Older Triassic sedimentary rocks in the region, and a few younger Late Jurassic to Cretaceous sedimentary rocks contain higher proportions of older (Paleozoic) zircon grains than typical Laberge Group samples, suggesting that they had more diverse source terranes. The contribution of nearly contemporary or slightly older volcanic and plutonic rocks to the Laberge Group basin seems to have generally swamped other sediment sources, which is consistent with sources in the arc-related rocks of the Stikinia Terrane, with very few older contributions. Maximum depositional ages (MDA) calculated from the detrital zircon data hint at regional age variations within the Laberge Group, with older strata in the north and deposition progressing southward, but these patterns may be influenced by sampling bias. Nevertheless, the close correspondence between calculated MDA for Laberge Group samples and the peak age ranges for detrital zircon implies that it provides a useful measure of depositional age, and the calculated MDA are at least locally consistent with biostratigraphic evidence.

Preliminary data for U–Th/(He) studies of selected Laberge Group samples, combined with constraints on depositional ages from detrital zircon U–Pb data, allow the definition of at least five broad domains within the basin that have contrasting thermal histories. Some parts of the Laberge Group basin retain ZHe ages that correspond to or are slightly older than calculated maximum depositional ages, whereas others seem to have experienced post-depositional heating above about ~ 180°C. There is also a contrast between the ZHe and AHe ages, with the latter being completely reset, indicating post-depositional heating to 60°C or more occurred almost everywhere. The regions that show greater heating to ~ 180°C are at least in part structurally controlled, as some are associated with the location of an important regional structure known as the King Salmon fault.

Further analyses are required to explore whether the other thermal history domains are also structurally controlled, and to what degree these data can be used to constrain the timing and kinematics of slip on the intervening structures. The regional extent of contrasting thermal history domains within the Laberge Group may be significant for evaluation of the basin's petroleum potential. The domains where ZHe data indicate heating above ~ 180°C are likely to be overmature for oil and gas, but the data on the timing of heating may assist in the identification of possible traps for migrating oil and gas in areas where ZHe and AHe data indicate lesser degrees of post-burial heating.

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REFERENCES

Baldwin, S.L., Monteleone, B.B., Webb, L.E., Fitzgerald, P.G., Grove, M., and Hill, E.J., 2004, Pliocene eclogite exhumation at plate tectonic rates in eastern Papua New Guinea: Nature, v. 431, p. 263–267, https://doi.org/10.1038/nature02846.

Berman, R.G., Ryan, J.J., Gordey, S.P., and Villeneuve, M., 2007, Permian to Cretaceous polymetamorphic evolution of the Stewart River region, Yukon Tanana terrane, Yukon, Canada: P–T evolution linked with in situ SHRIMP monazite geochronology: Journal of Metamorphic Geology, v. 25, p. 803–827, https://doi.org/10.1111/jmg.12042.

Bickerton, L., Colpron, M., and Gibson, D., 2013, Cache Creek terrane, Stikinia, and overlap assemblages of eastern Whitehorse (NTS 105D) and western Teslin (NTS 105C) map areas, *in* MacFarlane, K.E., Nordling, M.G., and Sack, P.J., *eds*., Yukon Exploration and Geology 2012: Yukon Geological Survey, p. 1–17.

Bickerton, L., Colpron, M., Gibson, D., Thorkelson, D.J., and Crowley, J.J., 2019, The northern termination of the Cache Creek terrane in Yukon: Middle Triassic arc activity and Jurassic-Cretaceous structural imbrication: Canadian Journal of Earth Sciences, v. 57, p. 227–248, https://doi.org/10.1139/cjes-2018-0262.

Bordet, E., Crowley, J.L., and Piercey, S.J., 2019, Geology of the eastern Lake Laberge area (105E), south-central Yukon: Yukon Geological Survey, Open File 2019-1, 120 p.

Bostock, H.S., 1936, Carmacks district, Yukon: Geological Survey of Canada, Memoir 189, 67 p., 2 sheets, https://doi.org/10.4095/100821.

Brown, D.A., Gunning, M.H., and Greig, C.J., 1996, The Stikine project: geology of western Telegraph Creek map area, northwestern British Columbia (NTS104G/5, 6, 11W 12 and 13): British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin 95, 174 p., 1 sheet.

Canil, D., Mihalynuk, M., MacKenzie, J.M., Johnston, S.T., and Grant, B., 2005, Diamond in the Atlin-Nakina region, British Columbia: insights from heavy minerals in stream sediments: Canadian Journal of Earth Sciences, v. 42, p. 2161–2171, https://doi.org/10.1139/e05-069.

Canil, D., Mihalynuk, M., and Charnell, C., 2006, Sedimentary record for exhumation of ultrahigh pressure (UHP) rocks in the northern Cordillera, British Columbia, Canada: Geological Society of America Bulletin, v. 118, p. 1171–1184, https://doi.org/10.1130/B25921.1.

Cherniak, D.J., 2000, Pb diffusion in rutile: Contributions to Mineralogy and Petrology, v. 139, p. 198–207, http://doi.org/10.1007/PL00007671.

Cherniak, D.J., and Watson, E.B., 2001, Pb diffusion in zircon: Chemical Geology, v. 172, p. 5–24, https://doi.org/10.1016/S0009-2541(00)00233-3.

Colpron, M., 2011, Geological compilation of Whitehorse trough – Whitehorse (105D), Lake Laberge (105E), and part of Carmacks (115I), Glenlyon (105L), Aishihik Lake (115H), Quiet Lake (105F) and Teslin (105C) (1:250,000 scale): Yukon Geological Survey, Geoscience Map 2011-1 3 maps, legend and appendices.

Colpron, M., and Friedman, R.M., 2008, U–Pb zircon ages for the Nordenskiold formation (Laberge Group) and Cretaceous intrusive rocks, Whitehorse trough, Yukon, *in* Emond, D.S., Blackburn, L.R., Hill, R.P., and Weston, L.H., *eds*., Yukon Exploration and Geology 2007: Yukon Geological Survey, p. 139–151.

Colpron, M., Crowley, J.L., Gehrels, G., Long, D.G.F., Murphy, D.C., Beranek, L., and Bickerton, L., 2015, Birth of the northern Cordilleran orogen, as recorded by detrital zircons in Jurassic synorogenic strata and regional exhumation in

Yukon: Lithosphere, v. 7, p. 541–562, https://doi.org/10.1130/L451.1.
Colpron, M., Israel, S., Murphy, D., Pigage, L., and Moynihan, D., 2016a, Yukon Bedrock Geology Map: Yukon Geological Survey, Open File 2016-1, 1:1,000,000 scale map and legend.
Colpron, M., Israel, S., and Friend, M., 2016b, Yukon Plutonic Suites: Yukon Geological Survey, Open File 2016-37, 1:750,000 scale map and legend.
Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329–333, https://doi.org/10.1038/288329a0.
Cordey, F., 1992, Radiolarian ages from chert pebbles of the Tantalus Formation, Carmacks area, Yukon Territory, in Current Research, Part E: Geological Survey of Canada, Paper 92-1E, p. 53–59, https://doi.org/10.4095/133554.
Cordey, F., Gordey, S.P., and Orchard, M.J., 1991, New biostratigraphic data for the northern Cache Creek terrane, Teslin map area, southern Yukon, in Current Research, Part E: Geological Survey of Canada Paper 91-1E, p. 67–76, https://doi.org/10.4095/132629.
Coutts, D.S., Matthews, W.A., and Hubbard, S.M., 2019, Assessment of widely used methods to derive depositional ages from detrital zircon populations: Geoscience Frontiers, v. 10, p. 1421–1435, https://doi.org/10.1016/j.gsf.2018.11.002.
Cui, Y., Miller, D., Schiarizza, P., and Diakow, L.J., 2017, British Columbia digital geology: British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9 p.
Currie, L., and Parrish, R.R., 1993, Jurassic accretion of Nisling terrane along the western margin of Stikinia, Coast Mountains, northwestern British Columbia: Geology, v. 21, p. 235–238, https://doi.org/10.1130/0091-7613(1994)022<0089:JAONTA>2.3.CO;2.
Cutts, J.A., McNicoll, V.J., Zagorevski, A., Anderson, R.G., and Martin, K., 2015, U–Pb geochronology of the Hazelton Group in the McTagg anticlinorium, Iskut River area, northwestern British Columbia, in Geological Fieldwork 2014: British Columbia Geological Survey Paper 2015-1, p. 87–101.
Dickie, J.R., and Hein, F.J., 1995, Conglomeratic fan deltas and submarine fans of the Jurassic Laberge Group, Whitehorse Trough, Yukon Territory, Canada: fore-arc sedimentation and unroofing of a volcanic island arc complex: Sedimentary Geology, v. 98, p. 263–292, https://doi.org/10.1016/0037-0738(95)00036-8.
Dickinson, W.R., and Gehrels, G.E., 2009, Use of U–Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic database: Earth and Planetary Science Letters, v. 288, p. 115–125, https://doi.org/10.1016/j.epsl.2009.09.013.
Dusel-Bacon, C., Lanphere, M.A., Sharp, W.D., Layer, P.W., and Hansen, V.L., 2002, Mesozoic thermal history and timing of structural events for the Yukon-Tanana Upland, east-central Alaska: $^{40}Ar/^{39}Ar$ data from metamorphic and plutonic rocks: Canadian Journal of Earth Sciences, v. 39, p. 1013–1051, https://doi.org/10.1139/e02-018.
Eisbacher, G., 1974, Evolution of successor basins in the Canadian Cordillera, *in* Dott, R.H. and Shaver, R. H., *eds*., Modern and ancient geosynclinals sedimentation: Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists, Special Publication 19, p. 274–291, https://doi.org/10.2110/pec.74.19.0274.
English, J.M., and Johnston, S.T., 2005, Collisional orogenesis in the northern Canadian Cordillera; implications for Cordilleran crustal structure, ophiolite emplacement, continental growth, and the terrane hypothesis: Earth and Planetary Science Letters, v. 232, p. 333–344, https://doi.org/10.1016/j.epsl.2005.01.025.
English, J.M., Mihalynuk, M.G., Johnston, S.T., Orchard, M.J., Fowler, M., and Leonard, L.J., 2002, Atlin TGI, Part VI: Early to Middle Jurassic sedimentation, deformation and a preliminary assessment of hydrocarbon potential, central Whitehorse Trough and northern Cache Creek terrane: Geological Fieldwork, 2003-1, British Columbia Geological Survey, Geological Fieldwork 2002, Paper 2003-1, p. 187–201.
English, J.M., Johannson, G.G., Johnston, S.T., Mihalynuk, M.G., Fowler, M., and Wight, K.L., 2005, Structure, stratigraphy and petroleum resource potential of the Central Whitehorse Trough, Northern Canadian Cordillera: Bulletin of Canadian Petroleum Geology, v. 53, p. 130–153, https://doi.org/10.2113/53.2.130.
Evenchick, C.A., and Thorkelson, D.J., 2005, Geology of the Spatsizi River map area, north-central British Columbia: Geological Survey of Canada, Bulletin no. 577, 2005, 276 p., 1 CD-ROM, https://doi.org/10.4095/215877.
Evenchick, C.A., McMechan, M.E., McNicoll, V.J., and Carr, S.D., 2007, A synthesis of the Jurassic–Cretaceous tectonic evolution of the central and southeastern Canadian Cordillera: Exploring links across the orogen: Geological Society of America Special Papers, v. 433, p. 117–145, https://doi.org/10.1130/2007.2433(06).
Evenchick, C.A., Poulton, T., and McNicoll, V., 2010, Nature and significance of the diachronous contact between the Hazelton and Bowser Lake groups (Jurassic), north-central British Columbia: Bulletin of Canadian Petroleum Geology, v. 58, p. 235–267, https://doi.org/10.2113/gscpgbull.58.3.235.
Farley, K.A., and Stockli, D.F., 2002, (U–Th)/He dating of phosphates: apatite, monazite, and xenotime: Reviews in Mineralogy and Geochemistry, v. 48, p. 559–577, https://doi.org/10.2138/rmg.2002.48.15.
Frebold, H., and Tipper, H.W., 1970, Status of the Jurassic in the Canadian Cordillera of British Columbia, Alberta, and southern Yukon: Canadian Journal of Earth Sciences, v. 7, p. 1–21, https://doi.org/10.1139/e70-001.
Gabrielse, H., 1998, Geology of Cry Lake and Dease Lake map areas, north-central British Columbia: Geological Survey of Canada Bulletin 504, 147 p., https://doi.org/10.4095/210074.
Gabrielse, H., Haggart, J.W., Murphy, D.C., Mortensen, J.K., Enkin, R.J., and Monger, J.W.H., 2006, Cretaceous and Cenozoic dextral orogen-parallel displacements, magmatism, and paleogeography, north-central Canadian Cordillera: Geological Association of Canada Special Paper 46, p. 255–276.
Gagnon, J.-F., Barresi, T., Waldron, J.W.F., Nelson, J.L., Poulton, T.P., and Cordey, F., 2012, Stratigraphy of the upper Hazelton Group and the Jurassic evolution of the Stikine terrane, British Columbia: Canadian Journal of Earth Sciences, v. 49, p. 1027–1052, https://doi.org/10.1139/e2012-042.
Golding, M.L., 2018, Heterogeneity of conodont faunas in the Cache Creek Terrane, Canada; significance for tectonic reconstructions of the North American Cordillera: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 506, p. 208–216, https://doi.org/10.1016/j.palaeo.2018.06.038.
Golding, M.L., Orchard, M.J., and Zagorevski, A., 2016, Microfossils from the Cache Creek Complex in northern British Columbia and southern Yukon: Geological Survey of Canada, Open File 8033, 25 p., https://doi.org/10.4095/298696.
Gordey, S.P., and Stevens, R.A., 1994, Tectonic framework of the Teslin region, southern Yukon Territory, in Current Research 1994-A: Geological Survey of Canada, p. 11–18, https://doi.org/10.4095/193617.
Harms, T.A., and Murchey, B.L., 1992, Setting and occurrence of late Paleozoic radiolarians in the Sylvester Allochthon, part of a proto-Pacific ocean floor terrane in the Canadian Cordillera: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 96, p. 127–139.
Harrison, T.M., Célérier, J., Aikman, A.B., Hermann, J., and Heizler, M.T., 2009, Diffusion of ^{40}Ar in muscovite: Geochimica et Cosmochimica Acta, v. 73, p. 1039–1051, https://doi.org/10.1016/j.gca.2008.09.038.
Harrison, T.M., Duncan, I., and McDougall, I., 1985, Diffusion of ^{40}Ar in biotite: temperature, pressure and compositional effects: Geochimica et Cosmochimica Acta, v. 49, p. 2461–2468, https://doi.org/10.1016/0016-7037(85)90246-7.
Hart, C.J.R., 1996, Magmatic and tectonic evolution of the Intermontane superterrane and Coast Plutonic complex in southern Yukon Territory: Unpublished MSc thesis, University of British Columbia, Vancouver, 198 p., https://doi.org/10.14288/1.0052733.
Hart, C.J.R., 1997, A transect across northern Stikinia: Geology of the northern Whitehorse map area, southern Yukon Territory (105D/13-16): Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, Bulletin 8, 112 p.
Hart, C.J.R., Dickie, J.R., Ghosh, D.K., and Armstrong, R.L., 1995, Provenance constraints for Whitehorse Trough conglomerate: U–Pb zircon dates and initial Sr ratios of granitic clasts in Jurassic Laberge Group, Yukon Territory, *in* Miller, D.M., and Busby, C., *eds*., Jurassic Magmatism and Tectonics of the North American Cordillera: Geological Society of America Special Papers, v. 299, p. 47–63, https://doi.org/10.1130/SPE299-p47.
Hutchison, M.P., 2017, Whitehorse trough: Past, present and future petroleum research – with a focus on reservoir characterization of the northern Laberge Group: Yukon Geological Survey, Open File 2017-2, 48 p., plus appendices and plates.
Johannson, J.J., 1994, Provenance constraints on Early Jurassic evolution of the northern Stikinian arc: Laberge Group, Whitehorse Trough, northwestern British Columbia: Unpublished MSc thesis, University of British Columbia, Vancouver, 299 p., https://doi.org/10.14288/1.0052494.
Johannson, G.G., and McNicoll, V.J., 1997, New U–Pb data from the Laberge Group, northwest British Columbia: implications for Stikinian arc evolution and Lower Jurassic time scale calibrations, in Radiogenic Age and Isotopic Studies, Report 10: Geological Survey of Canada, Current Research, 1997-F, p. 121–129, https://doi.org/10.4095/209098.
Johannson, G.G., Smith, P.L., and Gordey, S.P., 1997, Early Jurassic evolution of the northern Stikinian arc: evidence from the Laberge Group, northwestern British Columbia: Canadian Journal of Earth Sciences, v. 34, p. 1030–1057, https://doi.org/10.1139/e17-085.
Johnston, S.T., and Erdmer, P., 1995, Hot-side-up aureole in southwest Yukon and

limits on terrane assembly of the northern Canadian Cordillera: Geology, v. 23, p. 419–422, https://doi.org/10.1130/0091-7613(1995)023<0419:HSUAIS>2.3.CO;2.

Johnston, S.T., Mortensen, J.K., and Erdmer, P., 1996, Igneous and metaigneous age constraints for the Aishihik metamorphic suite, southwest Yukon: Canadian Journal of Earth Sciences, v. 33, p. 1543–1555, https://doi.org/10.1139/e96-117.

Joyce, N.L., Ryan, J.J., Colpron, M., Hart, C.J.R., and Murphy, D.C., 2015, A compilation of $^{40}Ar/^{39}Ar$ age determinations for igneous and metamorphic rocks, and mineral occurrences from central and southeast Yukon: Geological Survey of Canada, Open File 7924, 1 zip file, https://doi.org/10.4095/297446.

Kellett, D.A., and Iraheta-Muniz, P., 2019, Detrital U–Pb zircon and $^{40}Ar/^{39}Ar$ muscovite geochronology of the Whitehorse Trough, and surrounding rocks, Yukon and British Columbia: Geological Survey of Canada, Open File 8565, 33 p., https://doi.org/10.4095/314694.

Kellett, D.A., and Zagorevski, A., 2021, Overlap assemblages: Laberge Group of the Whitehorse Trough, northern Canadian Cordillera, *in* Ryan, J.J., and Zagorevski, A., *eds.*, Northern Cordillera geology: a synthesis of research from the Geo-mapping for Energy and Minerals program, British Columbia and Yukon: Geological Survey of Canada Bulletin 610, p. 123–144, https://doi.org/10.4095/326064.

Kellett, D.A., Ryan, J.J., Colpron, M., Zagorevski, A., Joyce, N., and Zwingmann, H., 2017, Report of activities, 2017, for Yukon tectonic evolution – late Mesozoic to Tertiary: GEM2 Cordillera Project: Geological Survey of Canada, Open File 8306, 14 p., https://doi.org/10.4095/305956.

Kellett, D.A., Weller, O.M., Zagorevski, A., and Regis, D., 2018, A petrochronological approach for the detrital record: Tracking mm-sized eclogite clasts in the northern Canadian Cordillera: Earth and Planetary Science Letters, v. 494, p. 23–31, https://doi.org/10.1016/j.epsl.2018.04.036.

Kent, D.V., and Irving, E., 2010, Influence of inclination error in sedimentary rocks on the Triassic and Jurassic apparent pole wander path for North America and implications for Cordilleran tectonics: Journal of Geophysical Research, v. 115, B10103, 25 p., https://doi.org/10.1029/2009JB007205.

Logan, J.M., and Mihalynuk, M.G., 2014, Tectonic controls on early Mesozoic paired alkaline porphyry deposit belts (Cu-Au±Ag-Pt-Pd-Mo) within the Canadian Cordillera: Economic Geology, v. 109, p. 827–858, https://doi.org/10.2113/econgeo.109.4.827.

Logan, J.M., Drobe, J.R., and McClelland, W.C., 2000, Geology of the Forrest Kerr-Mess Creek area, northwestern British Columbia (NTS 104B/10,15 & 104G/2 & 7W): British Columbia Ministry of Energy and Mines, Energy and Minerals Division, Geological Survey Branch, Bulletin 104, 164 p., 1 sheet.

Long, D.G.F., 2005, Sedimentology and hydrocarbon potential of fluvial strata in the Tantalus and Aksala formations, northern Whitehorse Trough, Yukon, *in* Emond, D.S., Lewis, L.L., and Bradshaw, G.D., *eds.*, Yukon Exploration and Geology 2004, Whitehorse, Yukon, Canada: Yukon Geological Survey, p. 167–176.

Long, D.G.F., 2015, Provenance and depositional framework of braided and meandering gravel-bed river deposits and associated coal deposits in active intermontane piggyback basins: The Upper Jurassic to Lower Cretaceous Tantalus Formation, Yukon: Yukon Geological Survey, Open File Report 2015-23, 80 p. plus appendices.

Lowey, G.W., 2008, Summary of the stratigraphy, sedimentology and hydrocarbon potential of the Laberge Group (Lower-Middle Jurassic), Whitehorse trough, Yukon, *in* Emond, D.S., Blackburn, L.R., Hill, R.P., and Weston, L.H., *eds.*, Yukon Exploration and Geology 2007: Yukon Geological Survey, p. 179–197.

Lowey, G.W., and Long, D., 2006, Summary of Rock-Eval data for the Whitehorse Trough, Yukon: Implications concerning the hydrocarbon potential of a frontier basin, *in* Emond, D.S., Blackburn, L.R., Hill, R.P., and Weston, L.H., *eds.*, Yukon Exploration and Geology 2007: Yukon Geological Survey, p. 207–230.

MacKenzie, J.M., Canil, D., Johnston, S.T., English, J., Mihalynuk, M.G., and Grant, B., 2005, First evidence for ultrahigh-pressure garnet peridotite in the North American Cordillera: Geology, v. 33, p. 105–108, https://doi.org/10.1130/G20958.1.

Marsden, H., and Thorkelson, D.J., 1992, Geology of the Hazelton volcanic belt in British Columbia: Implications for the Early to Middle Jurassic evolution of Stikinia: Tectonics, v. 11, p. 1266–1287, https://doi.org/10.1029/92TC00276.

Mihalynuk, M.G., Meldrum, D., Sears, S., and Johannson, G., 1995, Geology and mineralization of the Stuhini Creek area (104K/11), in Geological Fieldwork 1994: British Columbia Geological Survey Branch, Paper 1995-1, p. 321–342.

Mihalynuk, M.G., Erdmer, P., Ghent, E.D., Cordey, F., Archibald, D.A., Friedman, R.M., and Johannson, G.G., 2004, Coherent French Range blueschist: Subduction to exhumation in < 2.5 my?: Geological Society of America Bulletin, v. 116, p. 910–922, https://doi.org/10.1130/B25393.1.

Mihalynuk, M.G., Gabites, J.E., Orchard, M.J., and Tozer, E.T., 2006, Age of the Willison Bay pluton and overlying sediments: implications for the Carnian stage boundary, in Geological Fieldwork 1996: British Columbia Geological Survey Branch, Paper 1997-1, p. 171–180.

Mihalynuk, M.G., Zagorevski, A., and Cordey, F., 2012, Geology of the Hoodoo Mountain area (NTS 104B/14W), Geological Fieldwork 2011: British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Paper 2012-1, p. 45–68.

Mihalynuk, M.G., Zagorevski, A., English, J.M., Orchard, M.J., Bidgood, A.K., Joyce, N., and Friedman, R.M., 2017, Geology of the Sinwa Creek area, northwest BC (104K/14), in Geological Fieldwork 2016: British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2017-1, p. 153–178.

Mihalynuk, M.G., Zagorevski, A., Milidragovic, D., Tsekhmistrenko, M., Friedman, R.M., Joyce, N., Camacho, A., and Golding, M., 2018, Geologic and geochronologic update of the Turtle Lake area, NTS 104M/15, northwest British Columbia, in Geological Fieldwork 2017: British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Paper 2018-1, p. 83–128.

Monger, J.W.H., 1977, Upper Paleozoic rocks of the western Canadian Cordillera and their bearing on Cordilleran evolution: Canadian Journal of Earth Sciences, v. 14, p. 1832–1859, https://doi.org/10.1139/e77-156.

Monger, J.W.H., and Gibson, H.D., 2019, Mesozoic-Cenozoic deformation in the Canadian Cordillera: the record of a "Continental Bulldozer"?: Tectonophysics, v. 757, p. 153–169, https://doi.org/10.1016/j.tecto.2018.12.023.

Monger, J.W.H., Price, R.A., and Tempelman-Kluit, D.J., 1982, Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera: Geology, v. 10, p. 70–75, https://doi.org/10.1130/0091-7613(1982)10<70:TAATOO>2.0.CO;2.

Monger, J.W.H., Wheeler, J.O., Tipper, H.W., Gabrielse, H.., Harms, T., Struik, L.C., Campbell, R.B., Dodds, C.J., Gehrels, G.E., and O'Brien, J., 1991, Upper Devonian to Middle Jurassic Assemblages, *in* Gabrielse, H., and Yorath, C.J., *eds.*, Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, Geology of Canada Series no. 4, p. 281–328, https://doi.org/10.4095/134091.

Morneau, Y.E., 2017, Tectono-metamorphic evolution of the Snowcap assemblage, Yukon-Tanana terrane, west-central Yukon: Unpublished MSc thesis, Carleton University, Ottawa, 198 p., https://doi.org/10.22215/etd/2017-12073.

Mortensen, J.K., 1992, Pre-mid-Mesozoic tectonic evolution of the Yukon-Tanana Terrane, Yukon and Alaska: Tectonics, v. 11, p. 836–853, https://doi.org/10.1029/91TC01169.

Mulligan, R., 1963, Geology of the Teslin Map-Area, Yukon Territory (105C): Geological Survey of Canada Memoir 326, 96 p. (1 sheet), https://doi.org/10.4095/100551.

Nelson, J.L., Colpron, M., and Israel, S., 2013, The Cordillera of British Columbia, Yukon, and Alaska: Tectonics and metallogeny: Tectonics, Metallogeny, and Discovery: The North American Cordillera and Similar Accretionary Settings: Society of Economic Geologists Special Publication 17, p. 53–109, https://doi.org/10.5382/SP.17.03.

Nelson, J., Waldron, J., van Straaten, B., Zagorevski, A., and Rees, C., 2018, Revised stratigraphy of the Hazelton Group in the Iskut River region, northwestern British Columbia, in Geological Fieldwork 2017: British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Paper 2018-1, p. 15–38.

Pană, D.I., Poulton, T.P., and DuFrane, S.A., 2019, U–Pb detrital zircon dating supports Early Jurassic initiation of the Cordilleran foreland basin in southwestern Canada: Geological Society of America Bulletin, v. 131, p. 318–334, https://doi.org/10.1130/B31862.1.

Parsons, A.J., Zagorevski, A., Ryan, J.J., McClelland, W.C., van Staal, C.R., Coleman, M.J., and Golding, M.L., 2018, Petrogenesis of the Dunite Peak ophiolite, south-central Yukon, and the distinction between upper-plate and lower-plate settings: A new hypothesis for the late Paleozoic−early Mesozoic tectonic evolution of the Northern Cordillera: Geological Society of America Bulletin, v. 131, p. 274–298, https://doi.org/10.1130/B31964.1.

Piercey, S., and Colpron, M., 2009, Composition and provenance of the Snowcap assemblage, basement to the Yukon-Tanana terrane, northern Cordillera: Implications for Cordilleran crustal growth: Geosphere, v. 5, p. 439–464, https://doi.org/10.1130/GES00505.1.

Read, P.B., 1984, Geology, Klastline River East, Ealue Lake West, Cake Hill West and Stikine Canyon East, British Columbia: Geological Survey of Canada, Open File 1080, 1 sheet, https://doi.org/10.4095/12983.

Reiners, P.W., 2005, Zircon (U–Th)/He Thermochronometry: Reviews in Mineralogy and Geochemistry, v. 58, p. 151–179.

Reiners, P.W., Campbell, I.H., Nicolescu, S., Allen, C.M., Hourigan, J.K., Garver, J.I., Mattinson, J.M., and Cowan, D.S., 2005, (U–Th)/(He–Pb) double dating of detrital zircons: American Journal of Science, v. 305, p. 259–311, https://doi.org/10.2475/ajs.305.4.259.

Sack, P.J., Colpron, M., Crowley, J.L., Ryan, J.J., Allan, M.M., Beranek, L.P., and Joyce, N.L., 2020, Atlas of Late Triassic to Jurassic plutons in the Intermontane terranes of Yukon: Yukon Geological Survey, Open File 2020-1, 365 p.

Schiarizza, P., 2011, Geology of the Kutcho Assemblage between Kehlechoa and Tucho Rivers, northern British Columbia (NTS 104I/01, 02): Geological Fieldwork, Ministry of Energy, Mines and Petroleum Resources, Paper 2012-1, p. 99–118.

Shirmohammad, F., 2006, Triassic-Jurassic stratigraphy and paleontology of the Takwahoni and Sinwa formations at Lisadele Lake, Tulsequah map-area, northwestern British Columbia: Unpublished MSc thesis, University of British Columbia, Vancouver, 188 p., https://doi.org/10.14288/1.0052577.

Shirmohammad, F., Smith, P.L., Anderson, R.G., Loxton, J., and McNicoll, V.J., 2007, Preliminary report on the Triassic and Jurassic stratigraphy and paleontology of the Sinwa and Takwahoni formations near Lisadele Lake, Tulsequah map area, northwestern British Columbia: Geological Survey of Canada, Current Research 2007-A9, 11 p., https://doi.org/10.4095/224091.

Shirmohammad, F., Smith, P.L., Anderson, R.G., and McNicoll, V.J., 2011, The Jurassic succession at Lisadele Lake (Tulsequah map area, British Columbia, Canada) and its bearing on the tectonic evolution of the Stikine terrane: Volumina Jurassica, 2011, v. IX, p. 43–60.

Souther, J.G., 1972, Telegraph Creek map-area, 104G, British Columbia: Geological Survey of Canada Paper 71-44, 38 p., 1:250,000 map, https://doi.org/10.4095/105501.

Tempelman-Kluit, D.J., 2009, Geology of Carmacks and Laberge map areas, central Yukon: Incomplete draft manuscript on stratigraphy, structure and its early interpretation (ca. 1986): Geological Survey of Canada, Open File 5982, 399 p., https://doi.org/10.4095/247335.

Tipper, H.W., 1978, Jurassic biostratigraphy, Cry Lake map-area, British Columbia: Geological Survey of Canada, Current Research, Part A, Paper 78-lA, p. 25–27, https://doi.org/10.4095/103101.

Tipper, H.W., and Richards, T.A., 1976, Jurassic stratigraphy and history of north-central British Columbia: Geological Survey of Canada, Bulletin 270, 82 p., 1 sheet, https://doi.org/10.4095/103065.

van Drecht, L.H., and Beranek, L.P., 2018, New investigations of basal Laberge Group stratigraphy, Whitehorse trough, central Yukon, *in* MacFarlane K.E., *ed.*, Yukon Exploration and Geology 2017: Yukon Geological Survey, p. 151–163.

van Staal, C.R., Zagorevski, A., McClelland, W.C., Escayola, M.P., Ryan, J.J., Parsons, A.J., and Proenza, J., 2018, Age and setting of Permian Slide Mountain terrane ophiolitic ultramafic-mafic complexes in the Yukon: Implications for late Paleozoic-early Mesozoic tectonic models in the northern Canadian Cordillera: Tectonophysics, v. 744, p. 458–483, https://doi.org/10.1016/j.tecto.2018.07.008.

van Straaten, B.I., and Bichlmaier, S., 2018a, Late Early to Middle Jurassic Hazelton Group volcanism and its tectonic setting, McBride River area, northwest British Columbia, in Geological Fieldwork 2017: British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Paper 2018-1, p. 39–66.

van Straaten, B.I., and Bichlmaier, S.J., 2018b, Preliminary bedrock geology of the McBride River area: British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2018-3, 1:50,000 scale.

van Straaten, B.I., and Gibson, R., 2017, Late Early to Middle Jurassic Hazelton Group volcanism and mineral occurrences in the McBride-Tanzilla area, northwest British Columbia, in Geological Fieldwork 2016: British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2017-1, p. 83–115.

van Straaten, B.I., and Nelson, J., 2016, Syncollisional late Early to early Late Jurassic volcanism, plutonism, and porphyry-style alteration on the northeastern margin of Stikinia, in Geological Fieldwork 2015: British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2016-1, p. 113–143.

Vermeesch, P., 2018, IsoplotR: a free and open toolbox for geochronology: Geoscience Frontiers, v. 9, p. 1479–1493, https://doi.org/10.1016/j.gsf.2018.04.001.

Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2018, Geologic Time Scale v. 5.0: Geological Society of America, https://doi.org/10.1130/2018.CTS005R3C.

Wheeler, J.O., 1961, Whitehorse Map-Area, Yukon Territory, 105D: Geological Survey of Canada Memoir 312, 156 p., https://doi.org/10.4095/100539.

Whipp, D., Kellett, D.A., and Coutand, I., (in press), Short communication: Modelling competing effects of cooling rate, grain size and radiation damage in low temperature thermochronometers: Geochronology, https://doi.org/10.5194/gchron-2021-29.

White, D., Colpron, M., Buffet, G., and Roberts, B., 2006, Structural constraints for oil and gas assessment in the Whitehorse Trough: New results from seismic profiling, *in* Emond, D.S., Bradshaw, G.D., Lewis, L.L., and Weston, L.H., *eds.*, Yukon Exploration and Geology 2005: Yukon Geological Survey, p. 315–323.

White, D., Colpron, M., and Buffett, G., 2012, Seismic and geological constraints on the structure and hydrocarbon potential of the northern Whitehorse trough, Yukon, Canada: Bulletin of Canadian Petroleum Geology, v. 60, p. 239–255, https://doi.org/10.2113/gscpgbull.60.4.239.

Yukon Age Database, 2006: Yukon Geological Survey, https://data.geology.gov.yk.ca/Compilation/1. Accessed October, 2018.

Zagorevski, A., Mihalynuk, M.G., McGoldrick, S., Bédard, J.H., Golding, M., Joyce, N.L., Lawley, C., Canil, D., Corriveau, A.S., Bogatu, A., and Tremblay, A., 2016, Geological framework of ancient oceanic crust in northwestern British Columbia and southwestern Yukon, GEM 2 Cordillera: Geological Survey of Canada Open File 8140, 15 p.

Zagorevski, A., Bédard, J.H., Bogatu, A., Coleman, M., Golding, M., and Joyce, N., 2017, Stikinia bedrock report of activities, British Columbia and Yukon: GEM 2 Cordillera: Geological Survey of Canada, Open File 8329, 13 p., https://doi.org/10.4095/306144.

Zagorevski, A., Soucy La Roche, R., Golding, M., Joyce, N., Regis, D., and Coleman, M., 2018, Stikinia bedrock, British Columbia and Yukon: GEM-2 Cordillera Project, report of activities 2018: Geological Survey of Canada, Open File 8485, 12 p., https://doi.org/10.4095/311325.

Zagorevski, A., Bédard, J.H., Bogatu, A., Canil, D., Coleman, M., Golding, M., Joyce, N., Lawley, C., McGoldrick, S., Mihalynuk, M., Parsons, A., Schiarizza, P., and van Staal, C.R., 2021, Overview of Cordilleran oceanic terranes and their significance for the tectonic evolution of the northern Cordillera, *in* Ryan, J.J., and Zagorevski, A., *eds.*, Northern Cordillera geology: a synthesis of research from the Geo-mapping for Energy and Minerals program, British Columbia and Yukon: Geological Survey of Canada, Bulletin 610, p. 21–65, https://doi.org/10.4095/326053.

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