Overlap assemblages: Laberge Group of the Whitehorse trough, northern Canadian Cordillera

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Abstract: The Laberge Group was deposited during the Early to Middle Jurassic in a marginal marine environment, in the northern Canadian Cordillera. It occurs as a narrow, elongated siliciclastic unit along more than 600 km of strike length, overlapping the Intermontane terranes of southern Yukon and north-western British Columbia. The Laberge Group was deposited on the Late Triassic Stuhini and Lewes River groups, a volcano-plutonic complex of the Stikine terrane (Stikinia), and, locally, the Kutcho Arc. It is overlain by Middle Jurassic to Cretaceous clastic units. The variations in clast composition and detrital zircon populations among these units indicate major changes in depositional environment, basin extent, and sources during the latest Triassic to Middle Jurassic. Detrital zircon populations are dominated by near contemporary Stuhini–Lewes River arc grains, consistent with dissection of an active arc. Detrital rutile and muscovite data show rapid cooling and exhumation of metamorphic rocks during the Early Jurassic. Thermochronological data indicate that basin thermal evolution was domainal, with at least five regional temperature-time histories.

Résumé : Le Groupe de Laberge s'est déposé dans un milieu margino-marin au Jurassique précoce et moyen, dans le nord de la Cordillère canadienne. Il chevauche les terranes intermontagneux du sud du Yukon et du nord-ouest de la Colombie-Britannique et se présente sous la forme d'une unité silicoclastique étroite et allongée s'étirant dans une direction longitudinale sur plus de 600 km. Le Groupe de Laberge s'est déposé sur le complexe volcanoplutonique du Trias terminal formé des groupes de Stuhini et de Lewes River dans le terrane de Stikine (Stikinie) et, localement, sur l'arc de Kutcho. Il est recouvert d'unités de roches détritiques du Jurassique moyen au Crétacé. Les variations dans la composition des clastes et dans les populations de zircons détritiques au sein de ces unités indiquent que d'importants changements se sont produits du Trias terminal au Jurassique moyen en ce qui a trait au milieu sédimentaire, à l'étendue du bassin et aux sources de sédiments. Les populations de zircons détritiques sont dominées par des grains provenant de l'arc coexistant de Stuhini-Lewes River, ce qui est compatible avec la dissection d'un arc actif. Les données sur le rutile et la muscovite détritiques révèlent un refroidissement et une exhumation rapides de roches métamorphiques au Jurassique précoce. Les données thermochronologiques indiquent que l'évolution thermique du bassin s'est déroulée suivant des domaines distincts et qu'au moins cinq histoires température-temps régionales peuvent être distinguées.

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INTRODUCTION

The accretion of the Intermontane terranes (Cache Creek, Slide Mountain, Yukon–Tanana, Stikinia and Quesnellia) to the Laurentian margin has been described as initiating the northern Canadian Cordillera orogen (Colpron et al., 2015; Monger and Gibson, 2019). Outstanding questions remain about the geometry, timing, and conditions of accretion (Zagorevski et al., 2017, this volume), which are important information for constructing ore-deposit models for the region (e.g. Logan and Mihalynuk, 2014). The Late Triassic to Cretaceous sedimentary record of the northern Canadian Cordillera, including northern British Columbia and southern Yukon, captures aspects of accretion events and the developing orogen, including changes in depositional environment and basin extent, shifts in sediment types and provenance, and syn- to postdepositional basin shortening and deformation. In this paper, the Late Triassic to Cretaceous sedimentary history of this segment of the orogen is reviewed, focussing on the Early to Middle Jurassic Laberge Group, a major component of the Whitehorse trough (Fig. 1; Wheeler, 1961; Eisbacher, 1974). The paper also includes a presentation and discussion of recent and new data on sediment provenance, depositional constraints, and timing and conditions of basin deformation.

The term 'Whitehorse trough' was originally introduced to describe a linear belt of volcanic and sedimentary rocks in southern Yukon and northwestern British Columbia that included part or all of the Triassic Stuhini and Lewes River groups and the Jurassic Laberge Group, with more recent work sometimes including the overlying Jura-Cretaceous Tantalus Formation in Yukon (Fig. 2; Wheeler, 1961; Hart, 1997; Lowey, 2008; Tempelman-Kluit, 2009). However, the contact between the Sinwa and Aksala formations (Stuhini and Lewes River groups) and the Laberge Group has been evaluated in both British Columbia and Yukon to represent a Hettangian (or younger) unconformity, following which sedimentation type and environment changed markedly, sedimentation rates increased, and basin extent also changed (e.g. Johannson and McNicoll, 1997; Shirmohammad et al., 2011; Colpron et al., 2015; Hutchison, 2017; van Drecht and Beranek, 2018, see Frebold and Tipper (1970) for a different opinion). The overlying Late Jurassic to Early Cretaceous Tantalus Formation in southern Yukon is also separated from the Laberge Group by a (locally angular) unconformity, above which there is a significant change in sedimentation type, as well as in basin environment and extent (Fig. 2; Colpron et al., 2015). Consequently, the definition of the Whitehorse trough has varied in the literature, including just the Laberge Group at its most restrictive (Hutchison, 2017). To avoid ambiguity in nomenclature with previous studies, the term 'Whitehorse trough' is generally avoided in this study in favour of lithological terminology, or the definition including just the Laberge Group (Hutchison, 2017) is followed (e.g. Fig. 1, 2).

Observations and discussion focusing around new, primarily geochronological and thermochronological data obtained under the Geological Survey of Canada's Geomapping for Energy and Minerals Cordillera Cache Creek and Yukon Tectonic Evolution activities are included in this paper, as well as recent work by the British Columbia Geological Survey and the Yukon Geological Survey. However, there is a wealth of 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) data that also contributes to understanding the sedimentation and basin-inversion record during this dynamic period of the Canadian Cordillera's tectonic history. Although each of these data sources merits a dedicated analysis, only some relevant aspects of them are touched upon below.

The Laberge Group extends from approximately Carmacks, in southern Yukon, to Dease Lake, in British Columbia. Regional survey mapping has resulted in two sets of formal nomenclature for most of the studied units (Fig. 2). Where possible, British Columbia nomenclature is used for field areas in British Columbia and Yukon nomenclature, for Yukon field areas, with the probable equivalent terminology identified where appropriate. This is done to aid the reader, but it is important to note that this may introduce inadvertent inconsistencies as the formal definitions of similar units are not necessarily equivalent.

GEOLOGICAL OVERVIEW

The Canadian Cordillera is a long-lived and presently active accretionary orogen that has developed along the western margin of North America (Coney et al., 1980; Nelson et al., 2013). Following development of a late Neoproterozoic to early Paleozoic passive-margin sequence on the ancestral North American (or Laurentian) margin, Devonian eastward subduction of ocean crust beneath Laurentia formed a magmatic arc at the continental margin (Mortensen, 1992). The arc subsequently rifted from the margin, becoming the Yukon–Tanana terrane, separated from Laurentia by the Slide Mountain Ocean. During the Late Paleozoic, Yukon–Tanana and related island arcs (Stikinia/Quesnellia) developed in isolation from the Laurentian margin (Nelson et al., 2013; Parsons et al., 2018; van Staal et al., 2018), whereas the Laurentian margin accumulated sediment (Monger, 1977). Subsequent amalgamation and accretion of Yukon–Tanana, Stikinia and Quesnellia arcs, and intervening Cache Creek and Slide Mountain oceanic rocks to the North American margin, sometime between the late Paleozoic and Middle Jurassic, represents the first major accretionary event along the western North American margin of the northern Canadian Cordillera (Monger et al., 1982; Colpron et al., 2015; Monger and Gibson, 2019). The sedimentary record spanning this period of amalgamation and accretion is relatively complete (Fig. 2), and provides a chronicle of the orogen's evolution through this critical time period.

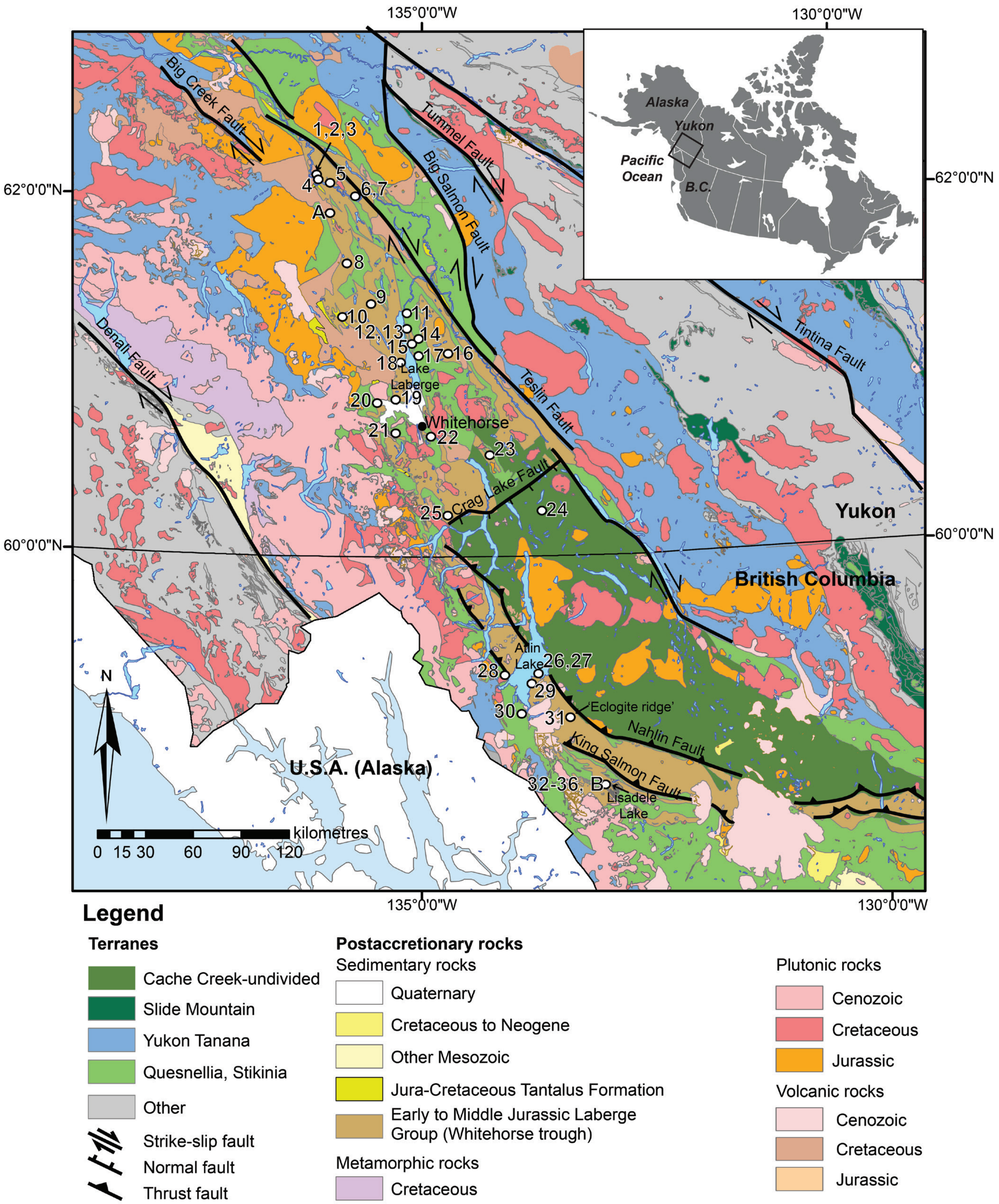

Figure 1. Geological map highlighting postaccretionary units in the northern Cordillera, particularly the Early to Middle Jurassic Laberge Group (*modified from* Cui et al., 2017 and Colpron et al., 2016b). Numbers 1 to 36 identify detrital zircon sample locations, and A and B, that of detrital muscovite samples.

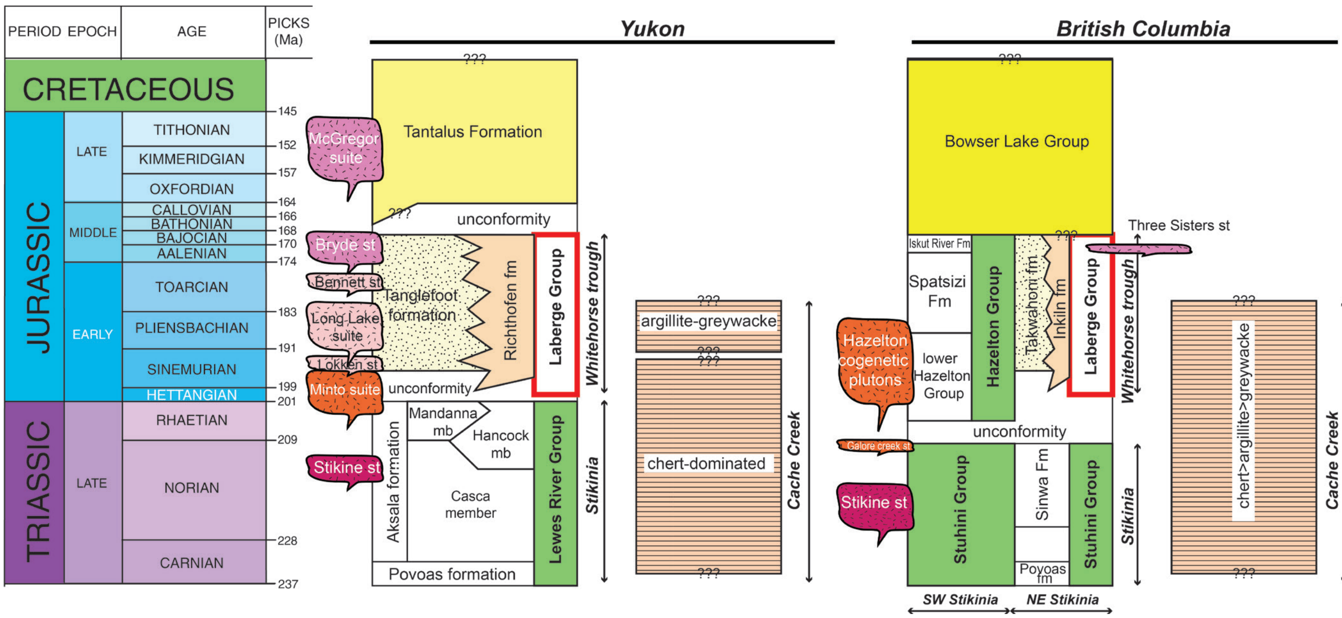

Figure 2. Comparative Upper Triassic to Lower Cretaceous stratigraphic sections showing Yukon stratigraphy (modified from Hutchison, 2017) and British Columbia stratigraphy (*modified from* Souther (1972), Shirmohammad et al. (2011), Mihalynuk et al. (2018), Nelson et al. (2018), van Straaten and Bichlmaier (2018)). Geological time scale *after* Walker et al. (2018). Abbreviations: fm, formation; mb, member; st, suite.

Triassic sedimentation

Late Triassic Stikinia and Quesnellia are characterized by the development of voluminous volcano-plutonic complexes: Stuhini Group (British Columbia) and Lewes River Group (Yukon) in Stikinia, and Shonektaw formation in Quesnellia. By the latest Triassic, magmatism started to wane, and siliciclastic (undivided Stuhini Group in British Columbia, Mandanna member in Yukon, Nazcha formation in Quesnellia, British Columbia) and limestone (Sinwa formation in British Columbia, Hancock member in Yukon) sedimentation ensued (Tempelman-Kluit, 2009). Deposition of the Late Norian to Rhaetian limestone is generally interpreted as the end of the Stuhini–Lewes River–Nicola arc (English and Johnston, 2005; Long, 2005; Shirmohammad et al., 2011; Logan and Mihalynuk, 2014). Late Triassic sediments are also present in the adjacent Cache Creek terrane, where they are characterized by bedded radiolarian chert, siltstone and sandstone of the Kedahda formation, and equivalents (Monger et al., 1991; Golding et al., 2016). Previous workers have interpreted the difference in Late Triassic sedimentation in Stikinia and Cache Creek terranes as the result of different tectonic settings: arc-proximal versus subducting plate (e.g. Mihalynuk et al., 2004; Colpron et al., 2015). Recent provenance studies of the Cache Creek terrane siliciclastic rocks (i.e. Kedahda formation) indicate that they are likely derived from Late Triassic Stikinia/Quesnellia rock units and overlap all Cache Creek terrane components (Zagorevski et al., 2016, 2018, this volume). Thus, it is possible that Late Triassic siliciclastic rocks from Stikinia (Stuhini Group, Sinwa formation, Aksala formation), Cache Creek terrane (Kedahda formation), and Quesnellia (Shonektaw formation) represent a common overlap sedimentary basin with facies variations (Zagorevski et al., 2018).

Early to Middle Jurassic sedimentation of the Laberge Group

Both the Lewes River Group of Yukon and Stuhini Group of northwesternmost British Columbia are overlain by Early to Middle Jurassic siliciclastic rocks of the Laberge Group (Dickie and Hein, 1995; Mihalynuk et al., 1995; Johannson et al., 1997), locally lying above an angular unconformity (Bordet et al., 2019). To the immediate southwest, the Hazelton Group volcanic and sedimentary rocks were unconformably deposited on Triassic Stikinia (Fig. 2; Marsden and Thorkelson, 1992; Brown et al., 1996; van Straaten and Nelson, 2016; Hutchison, 2017; Nelson et al., 2018). The Laberge Group is a package of clastic sedimentary rock 3 to 4 km thick (Dickie and Hein, 1995; Johannson et al., 1997; Shirmohammad, 2006) that extends for approximately 600 km along the strike length of the northern Canadian Cordillera (Fig. 1). It has been imbricated and translated by both compressional structures involving a regional fold and thrust belt that includes 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, 2018), and generally dextral strike-slip displacement, for example along the Teslin and Big Salmon faults (Fig. 1; Gabrielse et al., 2006; Colpron, 2011). However, there are a few locations in which a relatively complete stratigraphy of the Laberge Group is preserved, most notably at Lisadele Lake (Fig. 1; Mihalynuk et al., 1995, 2004; Shirmohammad et al., 2007, 2011), and the generally good preservation of diagnostic fossils has allowed for precise biostratigraphic control in other regions (e.g. Johannson et al., 1997).

The Laberge Group is informally described as comprising two coeval, units: a more distal, turbiditic member and a more proximal, coarse clastic member, as well as local, intercalated volcaniclastic horizons and rare porphyritic dacite to andesite (Nordenskiöld facies) of Pliensbachian age, together representing an overall tidal- and fluvial-influenced coastal depositional environment (Colpron and Friedman, 2008; Shirmohammad et al., 2011; White et al., 2012; Hutchison, 2017). The distal member, referred to as the Richthofen formation in Yukon and the Inklin formation in British Columbia, 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 Tanglefoot formation (Yukon) is a sequence of coal-bearing sandstone, mudstone, conglomerate, and volcaniclastic rock, with minor limestone, interpreted as shallow marine, deltaic, and fluvial beds (Lowey, 2008; Hutchison, 2017). Tanglefoot formation is considered to have good potential as a petroleum source rock (Lowey and Long, 2006). The Takwahoni formation, thought to be the British Columbia equivalent of the Tanglefoot formation, comprises conglomerate, tuff, and laminated greywacke and shale (Gabrielse, 1998). Recent investigations of the Laberge Group suggest that the Richthofen/Inklin and Tanglefoot/Takwahoni formations represent different facies within a common depositional system and, therefore, their distinction in the field may be challenging (Hutchison, 2017; Mihalynuk et al., 2017). Conclusions reached following some Yukon-based investigations of the tectonic context of the Laberge Group are that it was deposited exclusively on Stikine terrane and is everywhere in tectonic contact with Cache Creek terrane rocks (e.g. Bickerton et al., 2013). However, recent mapping in the Sinwa Creek area of British Columbia indicates that the Inklin formation was also deposited directly on the late Permian to Middle Triassic Kutcho Arc, assigned to the Cache Creek terrane (Mihalynuk et al., 2017). Similar relationships are described in the Kutcho area, where Sinwa formation and southernmost Laberge Group stratigraphically overlie the Kutcho assemblage (Gabrielse, 1998; Schiarizza, 2012).

Early to Middle Jurassic sedimentation external to the 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 of Stikinia in northern British Columbia (Fig. 2; 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 Hazelton Arc (Gagnon et al., 2012). Broadly to the east of the present day Laberge Group, a major sequence of Early Jurassic chert to argillite-greywacke succeeded the chert-dominated Triassic sediments that cap older Cache Creek terrane units in northern British Columbia and southern Yukon (Fig. 2; Cordey et al., 1991; Gordey and Stevens, 1994; Colpron et al., 2015). Far to the southeast, the Hettangian to Tithonian Fernie Formation, which was deposited at the western edge of the Western Canada Sedimentary Basin, records the arrival of westerly-derived sediments from the uplifting Canadian Cordillera, and the initiation of the Western Interior foreland basin (Pană et al., 2018). Paleomagnetic reconstructions place the Laberge Group at about the latitude of southern Alberta during the Early Jurassic (Kent and Irving, 2010), restoring these two depocentres more proximally than their current positions, although still geographically separated. Faro Peak and Macauley Ridge formations in Yukon were likely deposited in isolated Early Jurassic basins (*see* Colpron et al. (2015) for an overview of their characteristics).

Middle Jurassic to Early Cretaceous sedimentation

Post-Laberge Group sedimentation in southern Yukon is represented by the Bathonian(?) to Upper Cretaceous conglomeratic Tantalus Formation (Bostock, 1936; Colpron et al., 2015; van Drecht and Beranek, 2018; L.H. van Drecht, pers. comm., 2017). The Tantalus Formation unconformably overlies the Laberge Group and represents a major shift in depositional setting, from shallow marine to confined fluvial, as well as a shift in clast type, from the abundant volcanic and igneous lithic clasts that are typical of the Laberge Group to dominant chert, quartz, and silicified mudstone (Long, 2005). Sedimentation is interpreted to have occurred in restricted mountainous river valleys (Long, 2015). The Tantalus Formation is notable for its coal deposits, which were historically mined near Tantalus Butte, and for the abundance of chert clasts, which are by comparison rare in the underlying Laberge Group (Colpron et al., 2015; Long, 2015).

The Bowser Lake Group is the main component of the extensive Late Jurassic to mid-Cretaceous Bowser Basin of north-central British Columbia (Tipper and Richards, 1976; Evenchick and Thorkelson, 2005). At its type section, Bowser Lake Group was deposited on Jurassic Spatsizi Formation of Stikinia (Fig. 2). In contrast to the Tantalus Formation, the Bowser Lake Group was deposited in a marine depositional setting, progressing to nonmarine uppermost strata (Evenchick and Thorkelson, 2005). The Bowser Basin, which it fills, is interpreted as the west-facing foreland basin of a Jurassic doubly-vergent orogenic system, with the Western Canada Sedimentary Basin forming the other flank (Evenchick et al., 2007). Bajocian to Lower Cretaceous siliciclastic strata that are unconformable on Laberge Group strata in northern British Columbia, southwest of the King

Salmon and structurally lower Kehlechoa faults (Fig. 1, 2), have been correlated, based on their maximum depositional ages, clast composition, and sedimentology, with the Bowser Lake Group, including at Lisadele Lake (Shirmohammad et al., 2011) and south of Dease Lake (van Straaten and Gibson, 2017; van Straaten and Bichlmaier, 2018). Thus far, similar-aged strata have not been reported from the hanging wall of the King Salmon fault, either because the sediments have been removed by erosion, or because the fault has juxtaposed distinct subbasins.

Despite the differences in depositional environment and present-day extent, both the Tantalus Formation and the Bowser Lake Group exhibit a marked contrast in clast type to underlying strata: a significant decrease in volcanic and plutonic clasts, and abundant chert clasts, which dominate the overall clast populations. In both cases, chert clasts have generally been interpreted as being derived from the Cache Creek terrane, based on Early Permian to Triassic ages, potentially signalling the juxtaposition of Stikinia and Cache Creek (Cordey et al., 1991; Cordey, 1992; Mihalynuk et al., 2004; Evenchick and Thorkelson, 2005; Colpron et al., 2015). However, chert is also relatively common in Paleozoic–Triassic Stikinia, with examples including the Stikine assemblage (Logan et al., 2000; Mihalynuk et al., 2012), the "Tsabayhe group" (Read, 1984) and the Sinwa formation (*see* Long, 2015; Mihalynuk et al., 2017).

DETRITAL MINERAL GEOCHRONOLOGY AND THERMOCHRONOLOGY

A major target of recent research has been to determine the provenance of the Laberge Group sediments, most particularly as the arrival of terrane-specific sediment sources could indicate terrane amalgamation. Since the Laberge Group is predominantly situated on the eastern flank of Stikinia, most of the detritus comprising the Laberge Group could be expected to derive from Stikinia (e.g. Colpron et al., 2015). Clear evidence of a first arrival of, for example, Yukon–Tanana or Cache Creek terrane-derived sediment may signal their juxtaposition with Stikinia, though the precise nature of the proximity may remain obscured (overlap basin? recycled through an eroded melange?). Additionally, detrital materials that are diagnostic of specific tectonic settings (e.g. (ultra)high-pressure minerals or clasts) can shed light on the overall tectonic setting of the Intermontane terranes at a given time. Finally, a range of source materials deposited into the basin may represent deep incision or erosion of a young orogen. There may be detritus of particular rock suites captured in the basin that were not preserved or are not exposed at present. Thus, the Laberge Group stratigraphic section provides an opportunity to study snapshots of the orogen's surface rocks throughout the Early Jurassic.

Geochronological and thermochronological ages of detrital minerals, either as free grains or detrital clasts, are highly useful for the study of syntectonic basins. Geochronology utilizes the measurement of radioactive isotopes to yield the 'age' of a given mineral. Some geochronometers, or 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: the daughter products of decay are not retained until the rock/mineral cools through a temperature range at which thermal diffusion of that daughter product becomes energetically unfavourable. The resulting radiometric age is the time at which the mineral cooled through that 'closure' temperature window, rather than the time at which the mineral formed. These temperature-sensitive mineral-decay systems are called thermochronometers. New and recent geo- and thermochronometric data from Laberge Group detritus are discussed below, including the geochronometer zircon U-Pb, and the thermochronometers rutile U-Pb, muscovite and biotite ^{40}Ar/^{39}Ar, and zircon and apatite (U-Th)/He. The range of high- to low-trapping, or 'closure', temperatures that these different chronometers represent, shown in Figure 3, can be effectively applied to investigate both basin sources (higher temperature chronometers that have remained closed systems since their exhumation and erosion) and basin evolution (lower temperature chronometers that have thermally 'reset' since deposition in the basin).

Firstly, the range and distribution of different clast types preserved in conglomeratic units in the Laberge Group are discussed, to reveal the general progression in source-rock type through the Early Jurassic. The review of new and existing age data for minerals preserved in clasts (known rock type) and liberated grains (unknown rock type) follows.

Conglomerate clasts

Detailed investigations of clast type and proportion in Laberge Group conglomeratic units across both southern Yukon and northern British Columbia have identified clear trends through the Early Jurassic (Dickie and Hein, 1995; Hart et al., 1995; Johannson et al., 1997; Shirmohammad et al., 2011). Clast trends for northern British Columbia Laberge Group strata are summarized in Figure 4 (Johannson et al., 1997; Shirmohammad et al., 2011). At the base of the Laberge Group, clast compositions in Sinemurian strata at both Lisadele Lake and Atlin Lake (British Columbia) are dominated by sedimentary and volcanic clasts, with sedimentary clasts thought to have largely derived from the underlying Stuhini Group by partial erosion of the arc margin. In lower Pliensbachian strata, volcanic and hypabyssal clasts dominate, whereas sedimentary clasts are rare. Through the upper Pliensbachian and into lower Toarcian strata, the plutonic clast proportion steadily increases to over 60% at the expense of the volcanic clasts. A regional compilation of clast trends in southern Yukon (Dickie and Hein, 1995) shows a similar pattern: a predominance of sedimentary (likely

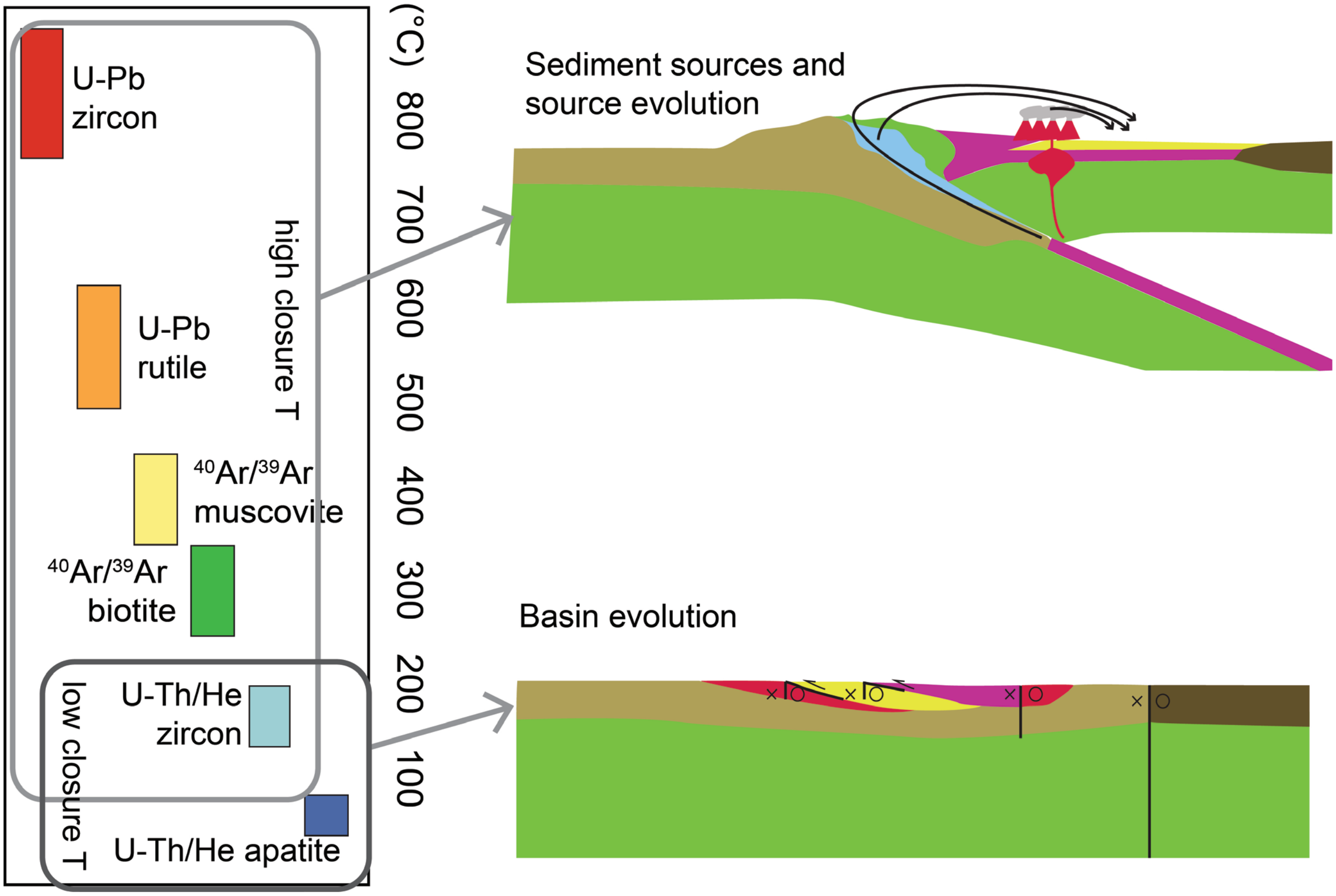

Figure 3. Approximate closure temperatures for geo- and thermochronometers reviewed in this paper of the Whitehorse trough (after Harrison et al. (1985); Cherniak (2000); Cherniak and Watson (2001); Farley and Stockli (2002); Reiners (2005); Harrison et al. (2009). Abbreviation: T, temperature; X/O, strike-slip fault.

Lewes River Group-derived) and volcanic clasts is characteristic of the basal Laberge Group, transitioning to more than 60% granitic clasts in Pliensbachian and younger strata. As noted above, conglomeratic units overlying the Laberge Group, in both the Bowser Lake Group in northern British Columbia and the Tantalus Formation in southern Yukon, are dominated by a return to sedimentary clasts; chert, in particular, becomes a major clastic component for the first time (Fig. 4). The shifting proportion of volcanic, plutonic, and sedimentary clasts through the Laberge Group stratigraphy has been interpreted as a shift in tectonic setting of the source regions: flank uplift (sedimentary clast dominated) during the Sinemurian, through transitional arc to dissected arc (plutonic clast dominated) by late Pliensbachian/early Toarcian age, and the Middle Jurassic arrival of chert-dominated sedimentary clasts interpreted to signal a return to flank uplift (Dickie and Hein, 1995; Johannson et al., 1997; Shirmohammad et al., 2011).

Metamorphic rocks provide short-lived sources of detritus to the Laberge Group. Two occurrences are well described in British Columbia. A diverse range of metamorphic clasts and minerals have been identified in upper Pliensbachian to lower Toarcian strata at 'Eclogite ridge' (unofficial name; *see* Fig. 1 for location), including eclogite, granulite, amphibolite, mica schist, and garnet peridotite (Canil et al., 2006; Kellett et al., 2018b). Upper Pliensbachian strata containing abundant garnet near Janus Point (Atlin Lake) are thought to represent the same stratigraphic horizon (Canil et al., 2006; Kellett et al., 2018b). Higher in the Laberge Group stratigraphy, metamorphic clasts are a major component of upper Toarcian conglomerate at Lisadele Lake (Fig. 4), where they include primarily quartzofeldspathic schist and gneiss (Shirmohammad, 2006). The Lisadele Lake section sits in the footwall of the King Salmon Fault, where the presence of gneissic metamorphic clasts in the Toarcian conglomerate in the footwall at the foot of the Llewellyn glacier (Atlin Lake) was also noted by these authors (*see* also Mihalynuk et al., 2006; Kellett and Iraheta-Muniz, 2019). Metamorphic clasts are more rarely reported from the Yukon portion of the Laberge Group, but they do form a minor component (<5%) in probable Middle Jurassic strata west of Whitehorse, and include quartzite, quartz-mica schist, chlorite schist, orthogneiss, and marble (Hart et al., 1995), as well as possible eclogite clasts in the northernmost part of the Laberge Group (Colpron et al., 2015). In all cases described above, the source of the metamorphic clasts is uncertain (e.g. Hart et al., 1995), although new geochronological data from

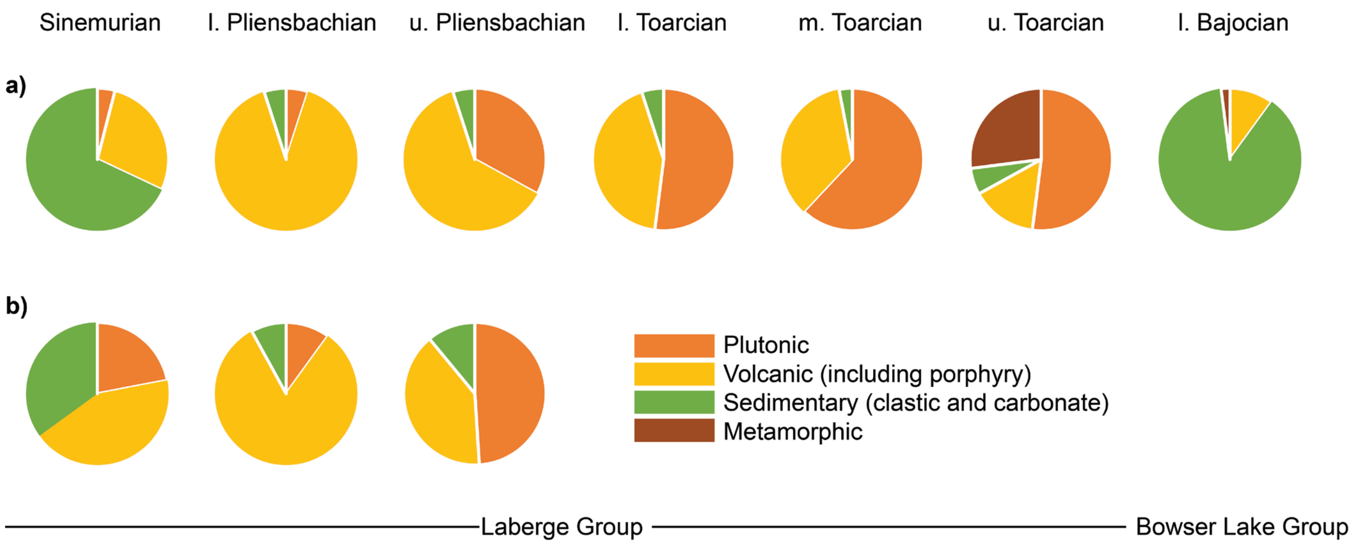

Figure 4. Clast-composition distribution for conglomerates of the Laberge and Bowser Lake (lower Bajocian only) groups compiled from **a)** Lisadele Lake (Shirmohammad, 2006) and **b)** Atlin Lake (Johannson et al., 1997). Abbreviations: l, lower; u, upper.

detrital metamorphic minerals (discussed below) is providing some constraints. Although the presence of metamorphic clasts has been noted in the potentially coeval Cache Creek argillite-greywacke units (Mulligan, 1963), they remain unstudied.

Detrital mineral geo- and thermochronology data sets

Detrital zircon U-Pb

Published detrital zircon U-Pb data are shown in Figure 5; they include 24 Laberge Group samples spanning the strike length of the basin, a few samples from the underlying Stuhini and Lewes River groups as well as overlying Tantalus Formation and Bowser Lake Group, and one Cache Creek sample (Shirmohammad et al., 2011; Colpron et al., 2015; Kellett et al., 2018b; Bordet et al., 2019; Kellett and Iraheta-Muniz, 2019). Some salient features of the data set are summarized in Table 1. The detrital mineral U-Pb age distributions are displayed in stacked-kernel density-estimate plots and a cumulative-age distribution diagram (Fig. 5a, b), as well as in a lag-time plot of youngest age peak versus maximum depositional age (Fig. 5c). There are different possible ways of estimating the maximum depositional age of a stratigraphic layer based on a detrital zircon U-Pb age population, with the weighted-mean age of all grains within 1σ error of the youngest grain being among the more robust, particularly when near-depositional age zircons are anticipated (Dickinson and Gehrels, 2009; Coutts et al., 2019). That weighted-mean age method is used here, in line with previous detrital zircon U-Pb studies of these rocks (Colpron et al., 2015). The abundance of volcanic and plutonic clasts in Laberge Group strata indicates proximal, active magmatic systems, providing a continual source of contemporary zircon. Regardless, maximum depositional ages are not true depositional ages, and should not be treated as such. However, direct comparisons of detrital zircon U-Pb ages with biostratigraphic constraints at Lisadele Lake suggest that maximum depositional ages for Laberge Group samples can approach the true depositional age, as expected for sedimentation adjacent to an active arc (Table 1; Shirmohammad et al., 2011). Maximum depositional ages determined in this way also trend quite closely to the youngest age peaks in all Laberge Group samples, and are within 2% of chemical-abrasion thermal ionization mass spectrometry ages for the youngest zircon grain analyzed (Table 1; Colpron et al., 2015; Bordet et al., 2019), two other common methods for determining maximum depositional age.

The coverage and density of the detrital zircon U-Pb data set reveal spatial and temporal patterns in source zircon/rock ages. To illustrate those trends, the northern Laberge Group results (Yukon) have been separated from those of the southern Laberge Group (British Columbia) in Figure 5. The northern Laberge Group ranges in maximum depositional age from ca. 204 to 180 Ma and has dominant age peaks between 212 and 186 Ma, whereas the southern Laberge Group ranges in maximum depositional age from ca. 188 to 178 Ma, with dominant age peaks between 191 and 182 Ma. The maximum depositional-age pattern appears to suggest that Laberge Group deposition progressed southward from Yukon to British Columbia. However, as indicated above, maximum depositional age is not equivalent to true depositional age and several of the dated samples from the Yukon were selected specifically as representing basal strata of the Laberge Group (Colpron et al., 2015; Bordet et al., 2019), whereas none of the British Columbia samples were collected specifically from basal strata. The earliest maximum depositional age for the southern Laberge Group, sample S1 from Lisadele Lake, was collected about 250 m stratigraphically above the basal Laberge Group (Shirmohammad et al.,

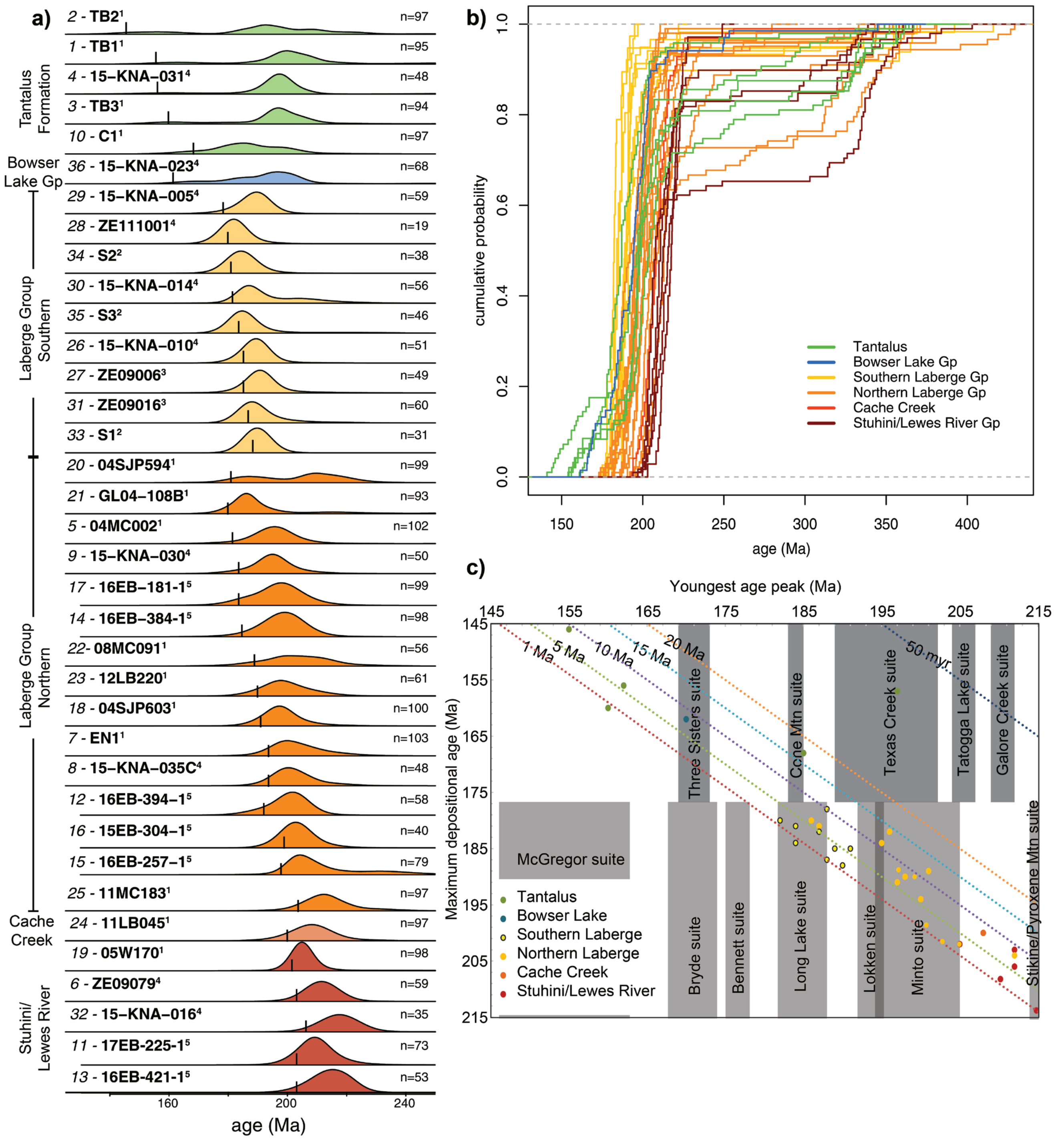

Figure 5. a) Kernel density estimates (KDE) for all detrital zircon U-Pb data ($^{206}Pb/^{238}U$ ages), grouped by formation, with northern (Yukon) Laberge Group samples separated from southern (B.C.) Laberge group samples, and sorted within each group by maximum depositional age. Note that only <250 Ma data are shown, for clarity. Tick marks indicate maximum depositional ages as listed in Table 1. **b)** Cumulative age distribution (CAD) plot showing data from (a) coloured by formation. Data sources: 1 - Colpron et al. (2015); 2 - Shirmohammad et al. (2011); 3 - Kellett et al. (2018a); 4 - Kellett and Iraheta-Muniz (2019); 5 - Bordet et al. (2019). **c)** Plot of maximum depositional age vs. youngest age peak. Dashed lines show lag times in millions of years. Light shaded boxes indicate age ranges of plutonic suites of southern Yukon: 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; M. Colpron, pers. comm., 2019). Dark shaded boxes indicate age ranges of plutonic suites for northern B.C.: 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) (B.I. van Straaten, J. Nelson, R. Creaser, and R. Friedman, BCGS Open House presentation, 2018). KDE and CAD plots were constructed using IsoplotR (Vermeesch, 2018).

Table 1. Summary of U-Pb detrital zircon data for the Laberge Group and select underlying and overlying units.

Sample	Unit	Youngest age peak (Ma)	Maximum depositional age[1] (Ma)	Reference no.[2]; sample location no.[3]
05W170	Lewes River Gp.	205	202; -	1; 19
ZE09079	Mandanna (Aksala)	212	203; -	4; 6
15-KNA-016	Stuhini Gp.	212	206; -	4; 32
17EB-225-1	Aksala	210	208; 211.33±0.01	5; 11
16EB-421-1	Aksala	215	214; 214.75±0.07	5; 13
11LB045	Cache Creek	208	200; -	1; 24
04SJP594	Laberge Gp. (N)	187	181; -	1; 20
GL04-108B	Laberge Gp. (N)	186	180; -	1; 21
04MC002	Laberge Gp. (N)	196	182;-	1; 5
15-KNA-030	Laberge Gp. (N)	195	184; -	4; 9
16EB-181-1	Laberge Gp. (N)	197	189; 186.22±0.09	5; 17
16EB-384-1	Laberge Gp. (N)	199	190; 186.38±0.07	5; 14
08MC091	Laberge Gp. (N)	201	189; -	1; 22
12LB220	Laberge Gp. (N)	198	190; -	1; 23
04SJP603	Laberge Gp. (N)	197	191; -	1; 18
EN1	Laberge Gp. (N)	200	194; -	1; 7
15-KNA-035C	Laberge Gp. (N)	200	194; -	4; 8
16EB-394-1	Laberge Gp. (N)	201	199; 199.78±0.06	5; 12
15EB-304-1	Laberge Gp. (N)	203	202; 202.4±1.5	5; 16
16EB-257-1	Laberge Gp. (N)	205	202; 203.46±0.14	5; 15
11MC183	Laberge Gp. (N)	212	204; -	1; 25
15-KNA-005	Laberge Gp. (S)	188	178; -	4; 29
ZE111001	Laberge Gp. (S)	182	180; -	4; 28
S2	Laberge Gp. (S)	184	181; *Lower Toarcian*[4]	2; 34
15-KNA-014	Laberge Gp. (S)	187	182; -	4; 30
S3	Laberge Gp. (S)	184	184; *Upper Toarcian*[4]	2; 35
15-KNA-010	Laberge Gp. (S)	189	185; -	4; 26
ZE09006	Laberge Gp. (S)	191	185; -	3; 27
ZE09016	Laberge Gp. (S)	188	187; -	3; 31
S1	Laberge Gp. (S)	190	188; *Pliensbachian*[4]	2; 33
TB2	Tantalus Fm.	155	146; 148.51±0.06	1; 2
TB1	Tantalus Fm.	162	156; 159.20±0.08	1; 1
15-KNA-031	Tantalus Fm.	197	157; -	4; 4
TB3	Tantalus Fm.	160	160; -	1; 3
C1	Tantalus Fm.	185	168; -	1; 10
15-KNA-023	Bowser Lake Gp.	170	162; -	4; 36

[1]Maximum depositional age (MDA) determined as the weighted mean age of grains within 1σ of youngest grain; both youngest age peaks and calculated maximum depositional age are shown rounded to nearest Ma (2σ errors for calculated MDAs are typically 1%). Where CA-TIMS ages for youngest zircon grains are available, they are listed subsequently to the calculated maximum depositional age for comparison, with their 2σ errors.

[2]References: 1 - Colpron et al. (2015); 2 - Shirmohammad et al. (2011); 3 - Kellett et al. (2018a); 4 - Kellett and Iraheta-Muniz (2019); 5 - Bordet et al. (2019).

[3]Sample location numbers are shown on Figure 1.

[4]Where precise biostratigraphic constraints are available, they are also listed for comparison Biostratgraphic ages from Shirmohammad et al., 2011.

2011). This sampling bias may explain the apparent transgression and should be tested by sampling basal sections of the Laberge Group in British Columbia.

Whereas all nine samples from the southern Laberge Group are dominated by Pliensbachian zircon, only two of the southwesternmost samples from the northern Laberge Group (Yukon) captured significant Pliensbachian zircon (04SJP594 and GL04–108B). The remaining thirteen samples are dominated by Norian to Sinemurian zircon, even though a few have maximum depositional ages young enough that they could feasibly capture Pliensbachian zircon (04MC002, 15-KNA-030). Since the Nordenskiöld tuffs interbedded with the Laberge Group in Yukon are Pliensbachian (Tempelman-Kluit, 2009), either sampling bias has affected these apparent age patterns, or source catchments for the Laberge Group may have been restricted, potentially due to topography of the underlying Lewes River and Stuhini groups (van Drecht and Beranek, 2018). In Figure 5c, the maximum depositional age is compared against the youngest zircon age peak for each sample. From this plot, it is evident that the northern Laberge Group zircons are dominated by Minto/Texas Creek suite-aged zircons of Rhaetian through Pliensbachian strata, with generally longer lagtimes from crystallization to deposition of 5 to 15 Ma, whereas the southern Laberge Group zircons are dominated by Texas Creek/Long Lake suite-aged zircons during the Pliensbachian, with generally shorter lagtimes of 0 to 10 Ma.

At the level of the available maximum depositional-age data, there is little to no gap in depositional age between Laberge Group and Stuhini/Lewes River sediments, at least for the northern part of the Whitehorse trough. The maximum depositional ages for Lewes River Group samples 05W170 and ZE9079 overlap with Laberge Group sample 11MC183. The data show an apparent temporal gap of approximately 10 Ma between the latest Laberge Group deposition and the onset of both Bowser Lake Group and Tantalus Formation deposition; however, local transgression likely plays a role. Regionally, the Bowser Lake Group deposition started during the Bajocian (Evenchick et al., 2010; Shirmohammad et al., 2011), so there is little to no time gap between the two at the regional scale.

There is a paucity of published detrital zircon U-Pb data for Cache Creek clastic units. However, sample 11LB045 is close in age to the youngest strata of the Stuhini and Lewes River groups as well as possibly younger than the oldest Laberge Group sample (11MC183), and the Cache Creek units contain a range in source zircon ages similar to both (Fig. 5).

Laberge group samples also contain relatively fewer Paleozoic grains compared to both older (Stuhini) and younger (Tantalus) strata (Fig. 5b). A likely explanation for this is that the dissecting Stikine Arc was the main source of Laberge Group sediments (as evidenced by clast compositions), such that the sediment was swamped by local arc-volcanic, porphyry, and plutonic zircon sources relative to other possible zircon sources (e.g. Colpron et al., 2015).

In addition to the detrital zircon age data discussed above, zircon has been isolated from igneous clasts in conglomeratic units of the Laberge Group in southern Yukon, and in the Lisadele Lake transect. Uranium-lead dating of multigrain zircon fractions from the Yukon clasts by thermal ionization mass spectrometry (TIMS) yielded crystallization ages of 215 to 208 Ma (Hart et al., 1995), suggesting derivation from the Late Triassic Stikine suite plutons such as the Willison Bay pluton near Atlin (Mihalynuk et al., 2006) and Tally-Ho leucogabbro in southernmost Yukon (Hart, 1995). Dating of the Lisadele Lake clasts using the TIMS method yielded crystallization ages of 186.6 ± 0.5 Ma and 221 ± 1 Ma (Shirmohammad et al., 2011). The latter coincides in age with the Stikine plutonic suite, whereas the former is not represented in igneous rocks of northern British Columbia but does coincide with the Long Lake suite of southern Yukon (Colpron et al., 2016a; M. Colpron, pers. comm., 2019).

Detrital rutile U-Pb

Pliensbachian Laberge Group strata trending from Atlin Lake to the south, including at ‘Eclogite ridge’, contain high metamorphic-grade minerals and clasts (English et al., 2002), and are likely the source of microdiamonds identified in nearby stream sediment surveys (Canil et al., 2005). Metamorphic clasts within this horizon include eclogite, granulite, amphibolite, and mica schist; igneous porphyry, volcanic and granitic clasts typical of the Laberge Group are also present. Detrital garnet, spinel, and pyroxene mineral chemistry indicates a probable ultrahigh-pressure (>2.8 GPa) garnet peridotite source rock (MacKenzie et al., 2005; Canil et al., 2006). Recent detailed petrochronology of pristine eclogite clasts, including in situ U-Pb dating of eclogitic rutile, yielded peak temperature and pressure conditions of equal or greater than 800°C and equal or greater than 2.2 GPa, and cooling of the rutile through more than 610°C during the Early Jurassic (Kellett et al., 2018b). To achieve deposition of the clasts into the basin by latest Pliensbachian, the source rock for the studied clasts must have been exhumed from approximately 80 km depth at a mean vertical rate of at least 4 km/Ma during the Early Jurassic (Kellett et al., 2018b). This rapid exhumation rate is typical for rocks exhumed in subduction zones: the clasts are interpreted to have been carried in a subduction channel between Yukon–Tanana and Stikinia terranes (Kellett et al., 2018b).

Detrital mica $^{40}Ar/^{39}Ar$

Muscovite is a rare detrital component of the Late Triassic to Early Cretaceous sedimentary basins of the northern Canadian Cordillera, likely because it is rare in the Triassic to Early Jurassic magmatic rocks that form a major sediment source. However, it is common in potential metamorphic source-rock units such as the Snowcap assemblage of the Yukon–Tanana terrane (e.g. Piercey and Colpron, 2009). Consequently, although there are few examples to study, detrital muscovite can provide thermochronological information (Ar in muscovite has a nominal closure temperature of ~400°C) about exclusively metamorphic sediment sources. Muscovite has been dated from a strongly foliated and lineated quartz-feldspar schist clast in an Upper Toarcian, metamorphic clast-bearing horizon of the Laberge Group at Lisadele Lake, British Columbia (Kellett and Iraheta-Muniz, 2019; depositional age based on biostratigraphy in Shirmohammad et al., 2011). Matrix detrital muscovite has also been dated from a horizon of the Tantalus Formation along the Klondike Highway of southern Yukon (Kellett and Iraheta-Muniz, 2019) that has an Aptian maximum depositional age, based on a ca. 120 Ma detrital zircon U-Pb population (L.H. van Drecht, pers. comm., 2017).

Step-heating results of individual muscovite crystals from the two sampled horizons indicates fairly homogeneous $^{40}Ar/^{39}Ar$ age populations for each (Fig. 6; Kellett and Iraheta-Muniz, 2019). The cobble from Toarcian Laberge Group strata at Lisadele Lake (sample 15-KNA-021B) yielded a muscovite cooling age of ca. 195 Ma, whereas detrital grains from the Aptian (maximum depositional age) Tantalus Formation sample 15-KNA-034 yielded an age peak of ca. 190 Ma. Both metamorphic muscovite $^{40}Ar/^{39}Ar$ age populations are well represented in Yukon–Tanana terrane rock units exposed today in southern Yukon (Fig. 6; Breitsprecher et al., 2004; Joyce et al., 2015). The close correspondence between these detrital muscovite age populations and bedrock metamorphic muscovite ages of present-day southern Yukon allows for a few observations. Firstly, Yukon–Tanana terrane metamorphic rocks are a possible source for the discrete horizons of metamorphic detritus in the Laberge Group and Tantalus Formation. Secondly, the metamorphic source rock that provided muscovite-bearing clasts to the Laberge Group was rapidly exhumed. Using a nominal closure temperature for muscovite of 400°C, a 25°C/km geothermal gradient, and a depositional age of ca. 180 Ma, a source rock containing ca. 195 Ma muscovite would have been exhumed at a mean rate of approximately 1 km/Ma during the Early Jurassic.

Detrital biotite grains isolated from two metamorphic clasts sampled from Upper Toarcian strata at Lisadele Lake, British Columbia, were also dated by the $^{40}Ar/^{39}Ar$ method (Shirmohammad, 2006). Results from both samples yielded hump-shaped spectra generally indicative of partial Ar loss, in this case likely postdepositional, and potentially a minor excess ^{40}Ar contribution (i.e. ^{40}Ar not produced by decay within the biotite), neither of which were addressed by Shirmohammad (2006). The final heating steps in these samples yielded poorly defined ca. 220 Ma and ca. 195 Ma ages, which are here interpreted to broadly represent maximum cooling ages. Further geochronological and petrological characterization of the muscovite-bearing metamorphic cobbles within Toarcian Laberge Group strata at the foot of the Llewellyn glacier and Lisadele Lake, as well as of muscovite- and biotite-bearing schist and gneiss in the adjacent metamorphic Nisling assemblage, may further the ability to make a more precise link with a particular source region.

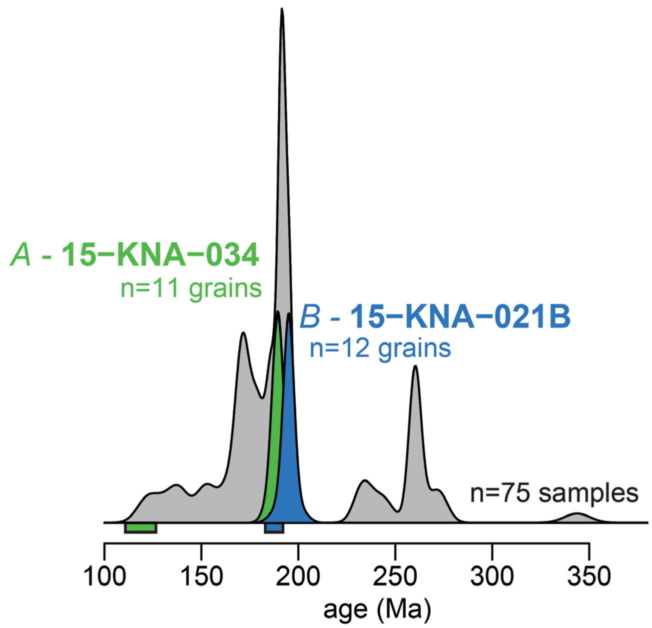

Figure 6. Kernel-density estimate (KDE) diagram for single crystal step-heat detrital muscovite ages from samples 15-KNA-034 (Tantalus Formation) in green and 15-KNA-021B (Toarcian strata of the Laberge Group) in blue. Sample locations are identified in Figure 1 as A and B, respectively. Data are overlain on a KDE that compiles all published muscovite $^{40}Ar/^{39}Ar$ metamorphic cooling ages (grey area) from southern Yukon (Breitsprecher et al., 2004; Joyce et al., 2015). Bars beneath the KDE plot show maximum depositional ages coloured by sample, as discussed in the text.

Cooling ages of metamorphic detritus of the Laberge Group indicate a source region, or regions, that experienced Early Jurassic Barrovian through to high-pressure metamorphism immediately followed by rapid exhumation, erosion, and deposition. The evidence for widespread Early Jurassic metamorphism in Yukon–Tanana terrane bedrock exposed today (Currie and Parrish, 1993; Dusel-Bacon et al., 2002; Berman et al., 2007; Joyce et al., 2015; Morneau, 2017) makes it a likely source for the metamorphic detritus (e.g. Canil et al., 2006; Kellett et al., 2018b). However, further petrochronological investigations of both the metamorphic clasts and adjacent metamorphic bedrock, such as the Florence Range in the Atlin area, could aid in making a definitive link.

Detrital zircon (U-Th)/He

Radiogenic He is a byproduct of alpha decay of U, Th, and Sm; the decay chain from ^{238}U to ^{206}Pb, for example, produces eight ^{4}He atoms. The nominal closure temperature for trapping and accumulating He atoms in zircon is approximately180°C (Reiners, 2005). Whereas the U-Pb age of zircon generally provides the timing of zircon crystallization, the (U-Th)/He age of zircon (ZHe) records the time at which the crystal last cooled through ~180°C. Depending on thermal conditions in the sedimentary basin, ZHe ages of detrital zircon may provide either a record of source exhumation ages (i.e. ages older than depositional age) or basin thermal history due to sedimentary burial, local heat sources such as fluids/contact metamorphism, and/or tectonics (i.e. ages younger than depositional age; Fig. 3).

Recently, ZHe dating was performed on zircon from eight Laberge Group samples (one plutonic clast, seven matrix samples). Age determinations were also made for two matrix samples from the overlying Tantalus Formation, one matrix sample from the overlying Bowser Lake Group, one matrix sample from the underlying Aksala formation, and one sample each from the Willison Bay pluton and Florence Range schist, both bedrock samples collected close to basal Laberge strata at the southwestern tip of Atlin Lake (Fig. 7; Kellett et al., 2017). Five of these samples were double-dated (i.e. U-Pb and He dates were obtained from the same individual zircon crystals); double-dating of detrital zircon is a powerful approach for studying sediment provenance (Reiners et al., 2005). Preliminary results were presented in Kellett et al. (2017) and additional preliminary data are displayed in Figures 7 and 8.

Two regions, northernmost Laberge Group and an area between the King Salmon and Nahlin faults, present ZHe ages of detrital zircon that are generally slightly older than, or within error of, their depositional ages (domains 1 and 5, respectively, in Fig. 8a–c), indicating that they preserve information about the exhumation/cooling history of their source rocks and the sediments in which they reside have not experienced postdepositional temperatures higher than approximately 180°C. There are also three regions of the Whitehorse trough in which ZHe dates have been reset by postdepositional heating. Samples northwest and southwest of Lake Laberge yielded postdepositional ZHe dates of ca. 150 Ma, whereas two intervening samples collected adjacent to Lake Laberge yielded postdepositional ZHe dates of ca. 80 Ma (domains 2 and 3, respectively, in Fig. 8a–c). Finally, all samples (n = 5) from the footwall of the King Salmon thrust (including bedrock and Bowser Lake Group samples) yielded postdepositional ZHe dates of 110 Ma or younger (Fig. 7).

Three of the samples for which zircon grains were double dated yielded ZHe dates within uncertainty of their U-Pb crystallization ages and/or within uncertainty of their maximum depositional ages (Fig. 9a–c). The remaining two samples are from the footwall of the King Salmon Fault and have been reset with respect to He by postdepositional heating (Fig. 9d, e).

Detrital apatite (U-Th)/He

As for zircon, He is produced in apatite due to alpha decay of U, Th, and Sm; however, with a significantly lower trapping temperature of approximately 60°C (Farley and Stockli, 2002). Thus, AHe is the most likely thermochronometer to be reset during basin burial/heating. Accordingly, all AHe dates obtained thus far from Mesozoic sedimentary rocks (Kellett et al., 2017; this paper) postdate deposition of their host sediments and range from latest Cretaceous to Oligocene. These results indicate that final cooling and exhumation of the postaccretionary basins following basin inversion occurred primarily during the Paleogene.

Basin-evolution constraints

Preliminary ZHe and AHe data, combined with constraints on timing of deposition from detrital zircon U-Pb results described above, suggest at least five domains with contrasting basin thermal histories (Fig. 8b). Inverse thermal models of representative samples from each of these domains illustrate possible thermal-history paths for each domain. These models emphasize the contrast in magnitude of postdepositional heating between domains 1 and 5 versus domains 2 and 4, and the delayed cooling of domain 3 compared to all other domains (Fig. 8c). The disparate thermal histories of domains 4 and 5 appear to have a structural control, as they are separated by the King Salmon Fault. Coincidence in U-Pb and He ages for double-dated zircon from samples not reset for He suggests these zircons either formed in, or were recycled through (in the case of Paleozoic U-Pb ages), local arc magmas (volcanic or rapidly exhumed plutonic rocks).

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 extents of these thermal-history domains are significant for basin petroleum evaluations: ZHe dates indicate which regions of the trough are overmature for oil and gas (regions 2 and 4), and will be used in future to identify when burial/heating occurred, to better constrain possible traps to oil and gas migration.

CONCLUSIONS

Sedimentary strata record a period of tectonism during Early Jurassic in present-day southern Yukon/northern British Columbia. As the Whitehorse trough formed during the Sinemurian to Toarcian, Stikinia experienced progressive erosion through its sedimentary flank and volcanic carapace, eventually exposing the arc's plutonic roots. At the same time, Yukon–Tanana rocks underwent regional metamorphism immediately followed by rapid exhumation. Some of this eroded metamorphic detritus, representing all crustal levels

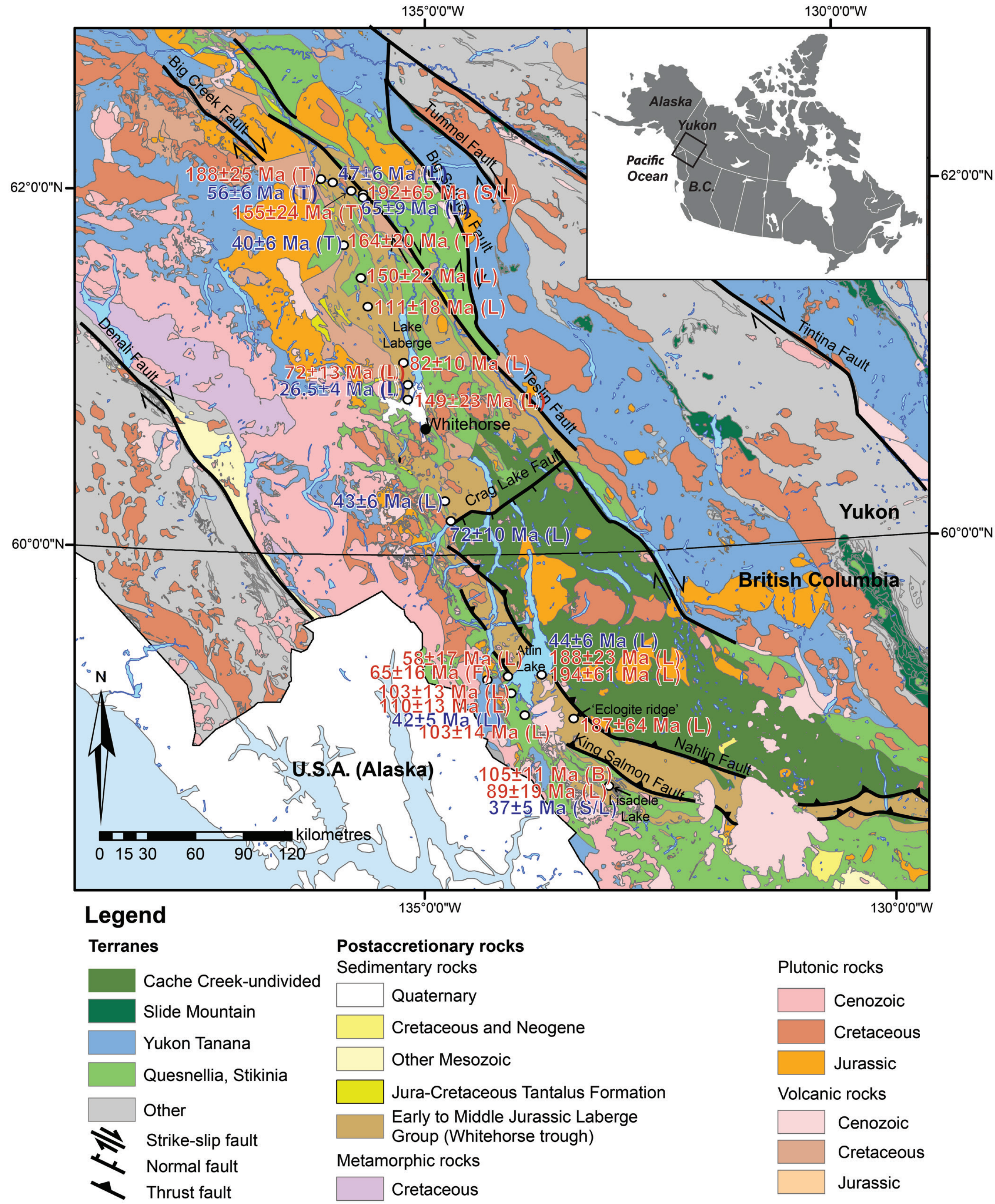

Figure 7. Geological map of the northern Cordillera showing preliminary detrital zircon (U-Th)He (red text) and detrital apatite (U-Th)He (blue text) mean-age and standard-error results for 3 to 8 grains from Bowser Lake Group (B), Florence Range (F), Laberge Group (L), Stuhini/Lewes River Group (S/L), and Tantalus Formation (T) rocks (*modified from* Colpron et al., 2016b; Cui et al., 2017).

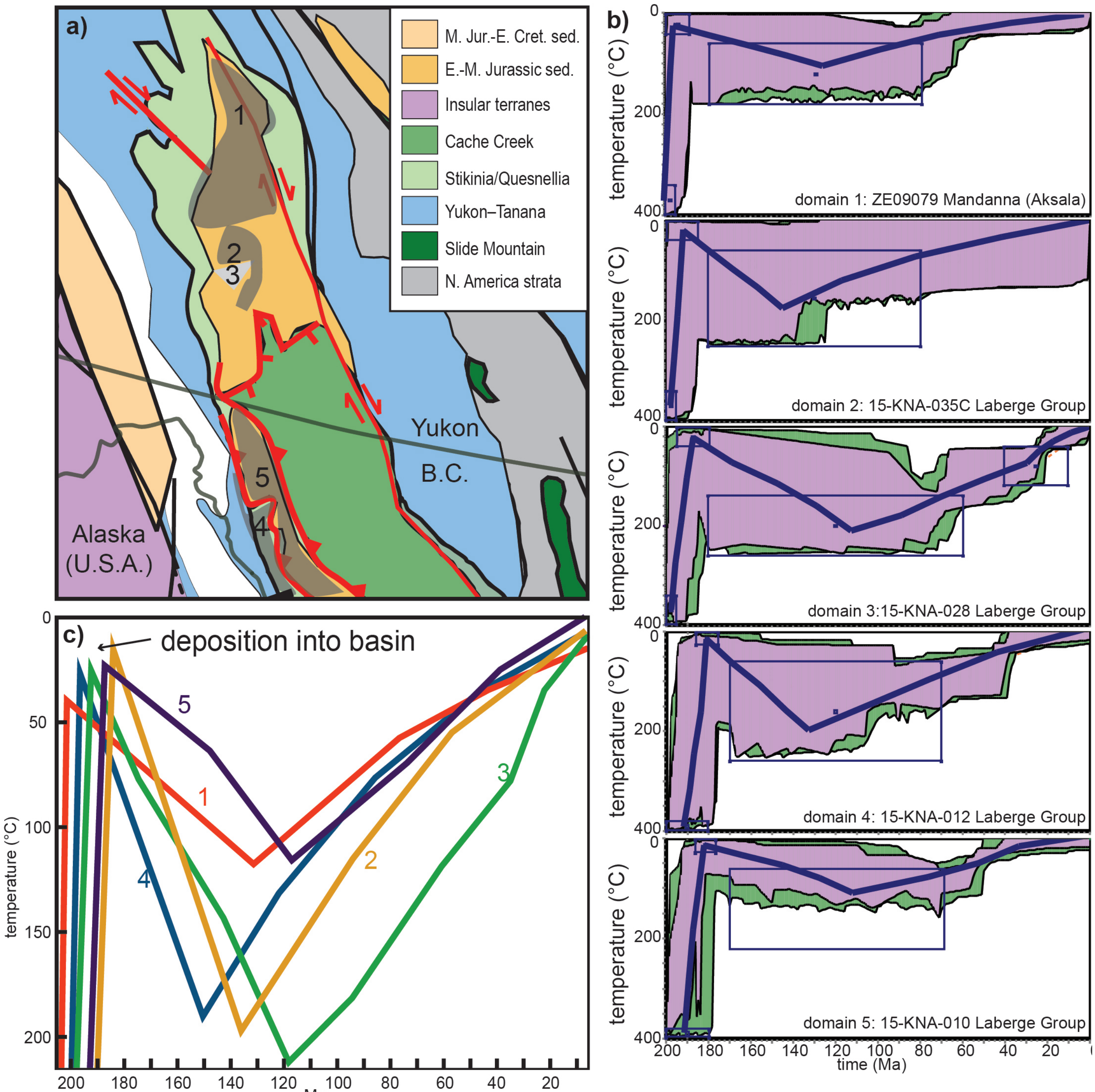

Figure 8. a) Terrane map of southern Yukon and northern British Columbia, showing five domains of the Whitehorse trough with different basin thermal-evolution histories, based upon preliminary detrital zircon and detrital apatite (U-Th)/He data shown in Figure 7. **b)** Inverse thermal models using the HeFTy software (Ketcham, 2005) for representative samples from each of the five domains defined in a), using the diffusion calibrations of Flowers et al. (2009) and Guenthner et al. (2013) for apatite and zircon, respectively. Each Monte Carlo simulation included 10 000 iterations. Temperature-time paths that yielded acceptable fits to user-imposed constraints and thermochronological data are shown by the green envelopes, while good fits are shown by the pink envelopes. Boxes represent user-imposed constraints. Blue lines are averages of the best-fit paths. Note that these are not unique solutions. All models are based upon both ZHe and AHe data except for 15-KNA-035C from domain 2, which is constrained by only ZHe data (hence the low temperature history is relatively unconstrained for this sample). **c)** Summary of the average best-fit path lines for each domain. Domains 1 and 5 have experienced significantly less postdepositional heating than domains 2 to 4; of those three latter domains, domain 3 cooled 20 to 30 Ma later than domains 2 and 4. Abbreviations: Cret., Cretaceous; E., Early; Jur., Jurassic; M., Middle; sed., sedimentary rocks.

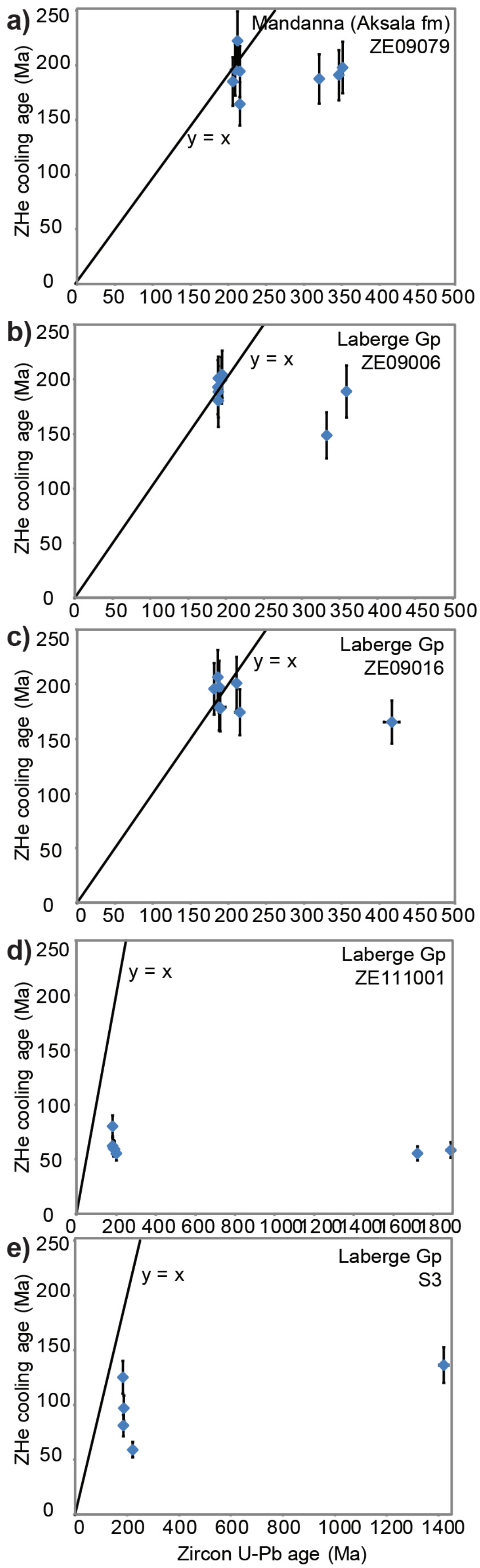

Figure 9. Double dating of detrital zircon crystals: **a), b), c)** samples yielding dates within error for all testing methods; **d), e)** samples reset with respect to postdepositional heating. Uranium-lead (U-Pb) ages for a) and c) are from Kellett and Iraheta-Muniz (2019), from Kellett et al. (2018b) for d) and e), and from Shirmohammad et al. (2011) for b), whereas detrital zircon (U-Th/He (ZHe) ages for the same crystals are preliminary data. Sample locations are shown on Figure 1. In terms of the thermal history domains defined in Figure 8, a) is from domain 1, b) and c) are from domain 5 and d) and e) are from domain 4. Data along the black line indicate the ZHe cooling age is within error of the zircon U-Pb age. Error bars are at the 1σ level for both U-Pb and ZHe data. Abbreviations: fm, formation; Gp, Group.

and including rapidly exhumed subduction-zone eclogite, was transported into the trough. This suggests Stikinia and Yukon–Tanana amalgamated or re-amalgamated during the Early Jurassic, with Yukon–Tanana as the lower plate. The relationship between Cache Creek and Stikinia during the Early Jurassic remains enigmatic, and the potential for relationships between Late Triassic and Early Jurassic clastic and volcanoclastic units requires further detailed study (e.g. zircon ages versus geochemistry and isotopic signatures; chert-clast chemistry; detrital-mineral populations)

By the Bajocian, the Laberge Group had begun to erode at its northern extent. Abundant chert clasts in both Tantalus Formation and Bowser Lake Group successor basins during Middle to Late Jurassic indicate a shift in sediment source. The shift in depositional setting from marine (Laberge Group) to restricted fluvial (Tantalus Formation) in Yukon and the widespread erosion of a chert source suggest closure and/or inversion of a marine basin. Successor Bowser Lake Group sediments were deposited on the southernmost part of the Laberge Group and Tantalus Formation sediments, on the northern Laberge Group. Though their depositional settings differed, both indicate an orogen-type setting with a foreland (Bowser) basin and mountainous topography, and both received abundant chert pebbles.

Subsequently, Bowser Lake Group and correlative rocks were inverted and shortened into an Early to Middle Jurassic(?) west-facing fold and thrust belt that included the King Salmon Fault (Tipper, 1978; English et al., 2002). Any westward overthrusting of Cache Creek onto Stikinia and the Laberge Group was limited, as Laberge Group rocks lying in the footwall of the Nahlin Fault (thermal-history domain 5) were not buried sufficiently to reach approximately 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 British Columbia were heated at temperatures exceeding 180°C sometime during the Late Jurassic to Early Cretaceous before eventually cooling, likely by exhuming into the shallow crust. Postaccretionary structures such as the King Salmon, Nahlin, and Teslin faults may have facilitated differential exhumation and cooling along the length of the Whitehorse trough during the Cretaceous, and to a minor extent through the Paleogene.

OUTSTANDING QUESTIONS AND FUTURE WORK

The above review of recent research on the Laberge Group under the Geoscience for Energy and Minerals program, as well as other programs, highlights the need for a series of targeted tests focussing on deposition of the Laberge Group and related sedimentary rocks in the Canadian Cordillera. Such tests are essential to improving the tectonic model for the Late Triassic/Early Jurassic amalgamation period of the Intermontane terranes (Zagorevski et al., this volume).

Further provenance discriminators should be applied to the Laberge Group and age equivalent strata in the proposed Atlin and Cache Creek terranes (Zagorevski et al., this volume) in conjunction with detrital zircon U-Pb populations, including zircon isotopic signatures such as Hf and O and detailed petrochronology of both detrital materials, and potential source regions (e.g. van Drecht and Beranek, 2017; Kellett et al., 2018b; Zagorevski et al., 2018). A detailed paleontological, geo- and thermochronological study of Jurassic Cache Creek clastic units is needed to expand the initial comparisons with the Laberge Group made by Mulligan (1963) (e.g. Bordet et al., 2019; Bickerton et al., 2020). Sampling of basal and uppermost sections of the Laberge Group in British Columbia, and uppermost Laberge Group in Yukon, is required to determine durations of unconformities, as well as to capture the full range of variability in detrital mineral and clast sources to the basin during deposition of the Laberge Group. Detailed detrital geochronology of a few key stratigraphic sections along the strike length of the basin, controlled by biostratigraphy (e.g. Lisadele Lake), are needed to better document the shift in source provenance through the Early Jurassic. Finally, a deepening of the thermochronological data set will better define the extent of the thermal domains identified above (Kellett et al., 2018a) and can be used to explore the potential geological drivers for these contrasting basin thermal histories.

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