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Structure and kinematic evolution of the Duke River fault, Southwestern Yukon

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Abstract: In southwest Yukon, the boundary between the Alexander terrane and Wrangellia corresponds with the Duke River Fault. In this paper, we report on observations of the Duke River Fault from four localities in southwest Yukon, and provide new constraints on (1) Permian regional metamorphism within the Alexander terrane, (2) Cretaceous ductile deformation along the Duke River fault and (3) post-Miocene brittle deformation along the fault. Within these areas, the Duke River Fault juxtaposes imbricated, pervasively foliated and folded greenschist-facies rocks of the Alexander terrane southwest of the fault against sub-greenschist-facies, less deformed rocks of Wrangellia. Multiple lines of evidence from this region indicate the Alexander terrane has been juxtaposed against Wrangellia along a southwest-dipping thrust fault. $^{40}\text{Ar}/^{39}\text{Ar}$ dates from muscovite, that grew during faulting or have been reset by motion along the Duke River Fault, range from 79 to 105 Ma, suggesting that ductile movement along the fault is at least as old as Cretaceous (Albian to Cenomanian). This phase of faulting is interpreted as the local expression of Cretaceous shortening which has been documented the length and width of the Cordillera. Cretaceous structures along the Duke River Fault are overprinted by brittle deformation that affects rocks as young as Miocene (or Pliocene?). The Duke River Fault appears to be accommodating present day transpression through uplift and reactivation of the thrust fault.

Key words: Duke River Fault, Insular terranes, southwest Yukon, Cretaceous, transpression

INTRODUCTION

The northern Cordillera of western Canada and Alaska is composed of a number of terranes that were accreted to the North American continental margin primarily during the Mesozoic and subsequently disrupted by Mesozoic and younger strike-slip faults (Fig. 1; Monger and Price 1979; Coney et al. 1980; Gabrielse and Yorath 1991; Gabrielse et al. 2006; Nelson et al. 2013). The Alexander terrane and Wrangellia, together with the Peninsular terrane, make up the Insular composite terrane (Colpron et al. 2007). Although some debate on the exact timing of accretion remains, it is accepted by most that

the Insular terranes accreted to the terranes to the east and the ancient continental margin by Middle Jurassic time (McClelland and Gehrels 1990; Gehrels 2001; van der Heyden 1992; Plafker and Winkler 1994; Manuszak et al. 2007; Israel et al. 2014). The geologic ties between the component terranes of the Insular terranes are not fully understood, however studies focusing on these terranes in Yukon, British Columbia and Alaska have furthered our understanding of their evolution. For example, Gardner et al. (1988) mapped a Pennsylvanian pluton that stitches the basements of Wrangellia and the Alexander terrane, suggesting that the two evolved together since at least that time, and Israel et al. (2014) documented Late Devonian gabbros that intrude both terranes represent initiation of extension in a back arc to the Pennsylvanian-Permian Skolai/Sicker arc which was in part built on the Alexander terrane beginning in the Late Devonian.

In southwest Yukon, the contact between the Alexander terrane and Wrangellia is defined by the Duke River Fault (Fig. 1), which is one of several large faults that dissect the Canadian and Alaskan Cordillera. Other nearby regional-scale faults are the Denali and Totschunda faults (Fig. 1). The Denali fault system is one of the most prominent structural features in southwest Yukon, and is interpreted to have accommodated approximately 300-400 kilometres of right-lateral displacement during the Cenozoic (Eisbacher 1976; Lowey 1998; Murphy et al. 2009). The fault strikes northwest in Yukon and juxtaposes Wrangellia against Yukon-Tanana terrane and various Mesozoic overlap assemblages and plutonic rocks (Fig. 1). The Totschunda fault is a 200 km-long, Late Cenozoic, dextral strike-slip fault that splays south-southeastwardly off the Denali fault in eastern Alaska and may link up with the Duke River Fault near the Yukon-Alaska border (Fig. 1; Plafker 1977; Dodds and Campbell 1992). The currently active segment of the Totschunda fault may connect directly with the northwestern end of the Fairweather fault (the strike-slip portion of the Pacific-North American plate boundary) via an undocumented structure, defined mainly by present seismicity (Fig. 1; Kalbas et al. 2008).

Muller (1967) mapped the Duke River Fault in Yukon as a moderately to steeply southwest-dipping thrust fault along which the Alexander terrane was emplaced over Wrangellia. MacKevett and Jones (1975) interpreted rocks now mapped as the Alexander terrane as being emplaced over those called Wrangellia along a regionally significant thrust fault that accommodated the emplacement of the Taku-Skolai terrane (Wrangellia) over the Alexander terrane in a southwesterly direction. Read and Monger (1976) suggested that the Duke River Fault was a splay off the Denali fault and accommodated some dextral strike-slip movement. More recently, Power (1988) analyzed microseismicity along the Duke River Fault and inferred that shortening was being accommodated by high-angle reverse and thrust faulting. Kalbas et al. (2008), using best-fit models of slip rate estimates along faults in Alaska and southwest Yukon, inferred 1mm/a of modern contractional deformation across the northwestern portion of the Duke River Fault.

In this paper we describe the structural and lithologic character of the Duke River Fault and adjacent rocks at four locations in southwest Yukon. Petrographic data from deformed samples from within the fault zone and accompanying geochronological data indicates there were two main phases of displacement across the fault, one in the Albian to Cenomanian and the other probably post-Miocene. We discuss the regional implications of these data and relate Cretaceous fault movement to the final accretion of the Insular terranes to North America and link post-Miocene movement to the subduction of the Yakutat microplate beneath the North American plate.

GEOLOGIC FRAMEWORK

Stratified Rocks in Alexander terrane

The Alexander terrane is exposed in eastern and southeastern Alaska, southwestern Yukon and parts of northwestern British Columbia (Fig. 1). In Yukon, the Alexander terrane comprises siliciclastic, carbonate and volcanic rocks ranging in age from Cambrian to Upper Triassic (Fig. 2; Read and Monger

1976; Dodds and Campbell 1992; Beranek et al. 2012). Rock units, ages and detailed lithologic descriptions of the Alexander terrane rocks exposed near the Duke River Fault are provided in the map legend (Fig. 3).

Stratified Rocks in Wrangellia

Wrangellia is the larger of the two Insular terranes covering an area extending from southern Alaska to south-westernmost British Columbia (Fig. 1). It is characterized by Late Paleozoic rocks of island arc affinity that are overlain by Mesozoic flood basalts and sedimentary rocks (Fig. 1 and 2).

The oldest succession of layered rocks in Wrangellia in southwest Yukon is the Skolai Group. The Skolai Group consists of Mississippian to Pennsylvanian volcanic and volcanoclastic rocks of the Station Creek Formation gradationally overlain by Permian sedimentary rocks of the Hasen Creek Formation (Smith and MacKevett 1970; Read and Monger 1976; Israel et al. 2007; Israel and Cobbett 2008). The Skolai Group is unconformably overlain by Upper Triassic volcanic and marine sedimentary rocks. Rock units, ages and detailed lithologic descriptions of this terrane are provided in the map legend (Fig. 3).

Links between Alexander terrane and Wrangellia

Intrusive rocks with a wide range of ages and compositions crop out throughout southwest Yukon and occur in both the Alexander terrane and Wrangellia. The oldest of these found in Yukon are Late Devonian (364 Ma) gabbros that intrude the Goatherd and Bullion assemblages of Alexander terrane and sit unconformably below the Early Permian Hasen Creek Formation of Wrangellia (Fig. 2; Sharp 1943; Dodds and Campbell 1992; Israel et al. 2014). The Pennsylvanian to Permian Icefield Ranges Suite (306-285 Ma) consists of biotite-hornblende syenite, quartz monzodiorite and diorite (Dodds and Campbell 1992) and intrudes both Wrangellia and the Alexander terranes (Gardner et al. 1988; Beranek

et al. 2014). Locally, near the Duke River and Denali faults, mafic and ultramafic bodies of the Early Cretaceous Pyroxenite Creek Suite intrude strata of Alexander and Wrangellia terranes (Gordey and Makepeace, 2001; Cobbett 2013a). Small volumes of intermediate to felsic intrusions of the Oligocene Tkope Suite and the Miocene to Pliocene Wrangell Suite are found both in the Alexander terrane and Wrangellia (Dodds and Campbell 1992).

Several stratigraphic sequences overlie both the Alexander terrane and Wrangellia (Fig. 2). The oldest of these are Upper Jurassic to Lower Cretaceous sandstone, shale, conglomerate, limestone and volcanoclastic rocks of the Dezadeash Formation, which interpreted to unconformably overlap rocks of Wrangellia in Southwest Yukon. The Dezadeash Formation has been correlated with the Gravina belt in Southeast Alaska where similar aged marine clastic strata and mafic to intermediate rocks sit unconformably on Alexander terrane strata (Fig. 2). It has been hypothesized that these rocks were deposited in a basin (or basins) that developed between the Insular and Intermontane composite terranes (Smith and MacKevett 1970; Eisbacher 1976; Read and Monger 1976; Gehrels and Berg, 1992; Lowey 1992; McClelland et al. 1992; Kapp and Gehrels, 1998). Terrestrial clastic sedimentary rocks of the Oligocene Amphitheatre Formation occur near the Denali and Duke River Faults and have been interpreted as syntectonic basins developed along both fault systems (Read and Monger 1976; Ridgway et al. 1992, 2002). Miocene to Pliocene (and younger?) mafic to intermediate volcanic flows, breccias and tuffs of the Wrangell Volcanics outcrop extensively on both terranes, very near the trace of the Duke River Fault and in some places partly bury this structure (Richter et al., 1990).

Structure and Metamorphism

The structural evolution of Wrangellia is better constrained than that of the Alexander terrane in Yukon mainly because it is more accessible and better exposed. The structural history of the Alexander terrane rocks in Yukon is poorly understood and has traditionally been studied separately

from Wrangellia because historically, workers thought these two terranes evolved separately until the Jurassic (Israel et al. 2014). In general, northwest-southeast trending folds and faults make up the dominant structural trend in both terranes in southwest Yukon (Dodds and Campbell 1992).

Two generations of regional-scale folds deform lower Paleozoic rocks in the Alexander terrane and are inferred to be Pennsylvanian or older as they are cross-cut by the Icefield Ranges Suite (306-285 Ma) (Read and Monger 1976; Gardner et al. 1988; Dodds and Campbell 1992). The early folds are closed to isoclinal and are overprinted by more open to closed, late folds. Several phases of faulting, including thrust faults of uncertain age, steeply dipping strike-slip faults that are inferred to be related to the Denali fault, and normal faults that have been interpreted to be post-Oligocene (Dodds and Campbell 1992) are found throughout southwest Yukon.

Several phases of deformation, which began in pre-Middle Triassic and continued until the present day, deformed Wrangellian rocks (Read and Monger 1976; Power 1988; Israel and Cobbett 2008). A pre-Middle Triassic contractional event has been inferred on the basis of (1) folded Paleozoic strata overlain by Triassic strata that are less deformed than the older rocks, and (2) an unconformable contact between Triassic and Paleozoic stratigraphic units (Read and Monger 1976; Israel et al. 2007; Israel and Cobbett 2008). A second, post-Triassic, pre-Late Cretaceous contractional event is recorded by regionally extensive, northeast-verging folds and related thrust faults (Read and Monger 1976; Israel and van Zeyl 2005; Israel et al. 2007). Finally, rock units of Wrangellia are deformed by latest Cretaceous to Cenozoic strike-slip and associated second-order faults.

Wrangellia has undergone sub-greenschist- facies metamorphism indicated by prehnite and pumpellyite-bearing volcanic rocks (Read and Wheeler 1976). The Alexander terrane rocks have been metamorphosed to greenschist facies as indicated by the presence of chlorite and actinolite schists and strongly chloritized and epidotized basalt (Read and Monger 1976; Dodds and Campbell, 1992).

GEOLOGICAL OBSERVATIONS ACROSS THE DUKE RIVER FAULT ZONE

Detailed 1:10 000-scale mapping was carried out in four areas across the Duke River Fault in southwest Yukon but only three of these are discussed in detail (Fig. 3, 4, 5, 6; Cobbett 2013a, b, c, d). For each area, the geological description is divided into two sections; the footwall and hanging wall. The hanging wall has been imbricated creating a zone of deformation adjacent to the Duke River Fault that is bounded by brittle shear zones (termed 'the imbricate zone' below). The footwall in all areas comprises rocks that belong to Wrangellia as well as overlap assemblages, whereas the hanging wall includes a variety of rocks that belong mostly to the Alexander terrane. In most areas the Duke River Fault is defined as the leading edge of the imbricate zone and marks the boundary between the Alexander terrane and Wrangellia (and rocks that overlap Wrangellia). Figure 3 includes a legend that describes rock units and symbology for all the mapped areas presented in figures 3, 4, 5, and 6.

Dollis Creek Area

The Duke River Fault in the Dollis Creek area is exposed along an approximately six kilometre-long, steep-sided, northwest-trending canyon located near the Yukon-British Columbia border (Fig. 1, 3). In this area, the Duke River Fault is a low angle, south-southwest dipping thrust fault that places older, and higher metamorphic grade rocks of the Alexander terrane over younger, lower grade rocks that have been interpreted as overlap assemblages to Wrangellia (Fig. 3). The imbricate zone is approximately 100-300 metres thick and the Duke River Fault is a brittle shear zone. Deformation within the imbricate zone affects Icefield Assemblage rocks and the Pyroxenite Creek diorite with only minor deformation affecting the overlying Wrangell Volcanics. Deformation is characterized by both brittle and ductile fabrics (Fig. 3).

Wrangellia Footwall

Footwall rocks in the Dollis Creek area include intermediate to mafic intrusions of the Pyroxenite Creek Suite and volcanic rocks of the Miocene Wrangell Volcanics. Rocks lying directly along the fault in the central part of the map include altered diorite. In the northwest and southeast parts of the map rocks along the fault comprise basalt and crystal tuff. The diorite is green, medium-grained and actinolite-bearing, containing minor amounts of epidote and abundant chlorite. This body of diorite is inferred to intrude the Station Creek Formation, although the contact was not observed (Fig. 3). The Wrangell Volcanics are characterized by dark grey, fine-grained, amygdaloidal and magnetite-bearing basalt and beige rhyolitic tuffs with quartz crystals up to 3 mm in an aphanitic matrix. Both the basalt and the crystal tuff unconformably overlie Station Creek rocks and Pyroxenite Creek diorite. Near the Duke River Fault, this tuff contains post-lithification fabrics that include two closely-spaced fracture sets that dip steeply to the northeast and moderately to the east.

Away from the fault to the east, the Station Creek Formation includes augite-phyric basalt breccia, agglomerate and volcaniclastic sandstone overlain by light grey and light green, very fine-grained tuffs interbedded with volcaniclastic siltstone.

The Station Creek Formation rocks are deformed by open folds that plunge very shallowly to the northwest and have been interpreted as the product of a regional folding event that affects Wrangellia (Israel et al. 2008). These folds are intruded by latest Triassic granodiorite and both pre-date Duke River Fault deformation.

Alexander terrane hanging wall

Within the hanging wall of the Duke River Fault near Dollis Creek, the lowest thrust panel comprises imbricated, strongly sheared and fractured rocks of Alexander terrane overlain by less deformed rocks of the terrane. Rocks lying directly along the fault within this thrust panel are thin bedded, calcareous and carbonaceous siltstone and phyllite with rare muscovite-rich quartzite that

belong to the Icefield assemblage (DTrI2; Fig. 3). Overlying this unit in the northern part of the area is thin bedded limestone (DTrI4) and carbonaceous muscovite $\pm$ feldspar $\pm$ quartz schist (DTrI1). In the central and southern parts of the map sheet the bedded limestone is absent. In the structurally highest thrust panel, beige-orange altered marble of the Bullion assemblage forms steep, blocky outcrops. This unit, where it crops out several hundred metres away from the Duke River Fault, is a grey weathered, laminated to thinly foliated silty limestone. In the southwest corner of the map area, calcareous and carbonaceous siltstone, chlorite schist and banded limestone of undifferentiated Icefield assemblage (DTrI4b) cores a northwest-trending antiform (Fig. 3). The Bullion assemblage carbonate is intruded by a green, medium-grained hornblende gabbro body of unknown age (Fig. 3).

Regional foliation and bedding within the Alexander terrane rocks (outside the imbricate zone) strike northwest and dip to the southwest and northeast. Regional northwest-trending folds occur west of the Duke River Fault and are consistent with regional-scale structures mapped by Dodds and Campbell (1992). Outcrop-scale folding was not observed in the Alexander terrane rocks outside the imbricate zone of the Duke River Fault. The gabbro body that crops out in the southwest part of the map ranges from undeformed to deformed by closely spaced brittle fractures with random orientations.

The Duke River Fault penetratively deforms a diorite body in the footwall of the fault. The penetrative foliation strikes southeast and dips steeply to the southwest and becomes less intense away from the fault. The weakly-developed foliation is defined by flat aggregates of actinolite needles (commonly radial), elongate chlorite grains and dynamically recrystallized quartz grains that anastomose between larger blocky amphibole grains.

In the lowest thrust panel of the imbricate zone, the main foliation strikes approximately southeast and dips moderately to the southwest; however, there is a large variation in orientation of this foliation and associated dips (Fig. 3). The main foliation within the schist and quartzite is defined by

microlithons comprising quartz and rarely feldspar between seams of muscovite (Fig. 7a). Within the siltstone of the Icefield assemblage the main foliation is defined by quartz stringers and graphitic layers. Elongation lineations on the main foliation, which are defined by elongated calcite and quartz grains, plunge approximately 50° towards 200° (Fig. 3). Rare C'-S shear fabrics are observed in thin sections cut parallel to these lineations and indicate hanging wall motion towards the north-northeast on a foliation plane dipping moderately towards the southwest.

The main foliation in the lowest thrust panel is folded by tight, moderately to steeply plunging folds with an axial planar cleavage that strikes between 270° and 280° and dips between 64° and 70° . They are close, asymmetric folds with angular hinges and thinned limbs. Icefield assemblage siltstone has been locally deformed by a penetrative crenulation cleavage. Kink folds are common in schistose rocks within the imbricate zone (Fig. 7b).

Brittle deformation overprints the ductile fabrics described above. A 10-20 m-wide, discrete gouge zone is observed within siltstone, phyllite and schist of the Icefield assemblage and is the boundary between the lower thrust panel and its hanging wall. Fault gouge comprises finely-milled rock (dominantly quartz and feldspar) in a clay matrix that has developed a pervasive planar fabric that strikes 125° and dips approximately 30° towards the southwest. Locally within the Dollis Creek canyon, this planar fabric has been folded into northeast-verging tight, asymmetric, chevron folds with hinges plunging shallowly to the southeast (Fig. 7c). No lineations or kinematic indicators (aside from the folding mentioned above) were found within the gouge zone. Bullion assemblage marble sits structurally above the gouge zone and remains relatively undeformed (Fig. 7d); however, the marble has been cut by a number of quartz and calcite veins that form three dominant sets. Two of these sets are steeply dipping and range in thickness from 1-5 cm and the third set is moderately dipping, closely spaced, with an average thickness of < 1 cm.

Jessie Creek Area

The Duke River Fault near Jessie Creek is exposed in a narrow valley between steep-sided mountains of the Kluane Ranges (Fig. 1, 4). In this area, the fault is a steep south-dipping structure exhibiting reverse motion. It is the leading edge of an approximately 1500 metre- wide zone of deformation (imbricate zone; Fig. 4) where brittle shear zones overprint ductile deformation. The imbricate zone is developed within the Icefield assemblage and can be divided into two thrust panels, each characterized by a distinct set of structures and map units, and separated by brittle shear zones (Fig. 4).

Wrangellia footwall

In the Jessie Creek area the footwall of the Duke River Fault comprises light grey, thinly bedded Upper Triassic Chitistone Limestone. The limestone unconformably overlies dark grey to black siltstone and brown sandstone of the Lower Permian Hasen Creek Formation that is exposed in the core of a west plunging antiform (Fig. 4).

Alexander terrane hanging wall

The geology of the hanging wall of the Duke River Fault in the Jessie Creek area includes two distinct, thrust-bounded stratigraphic successions that make up the imbricate zone and a third succession that comprises Alexander terrane rocks that have not been deformed by the fault. The Silver Creek member of the Icefield assemblage comprises calcareous siltstone interbedded with Triassic ribbon chert (Campbell and Dodds 1990), foliated, maroon and green volcanic conglomerate and rare fossiliferous limestone of unknown age (Cobbett, 2011). These rocks together occupy the lowest thrust panel in the imbricate zone and lie directly above the Duke River Fault (Fig. 4). Rocks in the overlying thrust panel include quartz-feldspar-chlorite phyllonite and schist, calcareous to carbonaceous feldspar-

muscovite-quartz schist, banded and massive marble and locally micaceous quartzite that have been assigned to the older units of the Icefield assemblage. Rocks occupying both thrust panels are intruded by hornblende-epidote gabbro and ultramafic rocks of probable Early Cretaceous age. In thin sections, the gabbro shows a plagioclase, hornblende, actinolite and epidote mineral assemblage. Rocks that belong to the Alexander terrane south of the imbricate zone include grey, banded marble that contains Ordovician fossils (Cobbett 2011) interlayered with fine- to medium-grained, dark green, basalt composed of plagioclase, actinolite (partly altered to chlorite), clinopyroxene (partly altered to actinolite) and epidote. These rocks have been assigned to the Donjek assemblage and are exposed along a cliffy ridge in the southwestern part of the map sheet (Fig. 4; Cobbett, 2011).

Within the lowest thrust panel of the Duke River Fault imbricate zone (Domain 1), foliation is best displayed in the conglomerate by clasts flattened in a plane that mostly dips moderately to steeply north and northeast. The foliation is not observed in the chert; instead bedding is observed dipping steeply in a variety of directions. The foliation and bedding are tightly folded by west-southwest plunging folds that are subsequently deformed by a later phase of open, north- and northwest-plunging folds (Fig. 4). Dome and basin fold interference patterns are developed where the hinges of these two fold sets intersect. Within the overlying thrust panel (Domain 2), the dominant phase of deformation is defined by a foliation characterized by seams of muscovite separating microlithons of dominantly dynamically recrystallized quartz and feldspar in quartzite and schist, respectively, and is the main layering seen in marble. The dominant foliation strikes mainly to the east-southeast and dips moderately to the south and is deformed by at least three phases of folding. Rare, rootless, isoclinal folds observed within a single microlithon are evidence of an early phase of folding that has been mostly overprinted by younger structures. Shallow to moderately plunging tight to isoclinal, asymmetric folds are the prominent phase of folds observed within Domain 2. Northwest-plunging crenulation lineations, commonly observed when schistose rocks break along the mica seams, are related to the second phase

of folding. Late, open folds of a third phase deform the second phase folds and the crenulation lineations. Where crenulation lineations are not folded they plunge moderately towards 295° . Elongation lineations measured on the dominant foliation are defined by elongated calcite, quartz and mica and plunge moderately towards 110° . Rare C'-S shear fabrics are seen in thin sections cut parallel to elongation lineations (Fig. 8a) indicating top to the northwest, dextral reverse shear. Muscovite grains grow along the dominant foliation and also grow along shear bands (Fig. 8b)

Brittle damage zones comprising closely spaced-fracture sets and discrete zones of cataclasite overprint the ductile structures described above. The Duke River Fault, separating Chitistone Limestone from Icefield assemblage conglomerate, is a zone of fault breccia several metres wide with seams of fault gouge (Fig. 8c). Another brittle feature that separates Domain 1 from Domain 2 roughly parallels Jessie Creek and is best exposed in the far western edge of the map (Fig. 4). Here it is characterized by several cataclastic zones comprising sub-rounded, pebble-sized clasts of siltstone and volcanic material in a clay matrix (Fig. 8d). These zones dip both north-northeast, where Jessie Creek occurs north of the structure, and to the southwest very near where Jessie Creek crosses this structure and begins running south of it.

The upper structural contact of Domain 2 (corresponding with the contact between the Donjek and Icefield assemblages) is characterized by a section of broken up, dark grey, carbonaceous siltstone sitting below cliffy outcrops of laminated marble. The laminations in the marble, the foliations in the siltstone and the contact between these two rock types all dip moderately southwest. Strongly damaged zones characterized by highly folded and fractured rock are common within the Duke River Fault imbricate zone. At Jessie Creek, in the southeast corner of the map, within the upper thrust panel (Domain 2), carbonaceous feldspar-muscovite schist is folded on a centimetre-scale, with near vertical plunging, tight folds and near horizontal, open to tight folds. In the most damaged areas, single layers

within the schist are not traceable for more than one metre. Crenulation lineations within mica layers are commonly obliquely folded around tight folds. In one location, doubly plunging folds deform a quartzite layer.

Hoge Creek

Approximately 55 km to the northwest of the Jessie Creek area, the Duke River Fault is very well exposed in a steep valley occupied by Hoge Creek (Fig. 1, 5). In the Hoge Creek area, the Duke River Fault is the leading edge of a one kilometre wide zone of brittle and ductile deformation that is bound to the north and south by brittle shear zones (Fig. 5). In the Hoge Creek area the hanging wall rocks are imbricated into several thrust panels and one thrust fault cuts up into Wrangellian strata.

Wrangellia footwall

The footwall of the Duke River Fault in the Hoge Creek area includes conglomerate, limestone and fine to coarse clastic rocks of the Permian Hasen Creek Formation and two gabbro bodies inferred to be Devonian and Early Cretaceous (Fig. 5). The stratigraphically lowest exposed unit in the Hasen Creek Formation is a boulder conglomerate dominated by clasts of medium-grained diorite and gabbro that grades upward into a volcanic breccia comprising very angular volcanic derived clasts in a sandy maroon matrix. The volcanic breccia grades upwards into a grey and brown, pebble conglomerate, then into a medium- to coarse-grained, lithic sandstone, a fossiliferous wackestone, and finally into a banded to massive marble. A strongly deformed gabbro (DSC), observed only in the far western part of the map, is interpreted to be Devonian in age based on lithologic similarities with gabbro bodies that have been dated in the region (Israel et al. 2014). The gabbro is unconformably overlain by the boulder conglomerate of the Hasen Creek Formation. An undeformed medium-grained hornblende gabbro intrudes Hasen Creek conglomerate in the eastern part of the map and is interpreted to be Early

Cretaceous based on lithologic similarities with the Pyroxenite Creek Suite (Gordey and Makepeace, 2001).

The footwall rocks are deformed by upright, tight folds with hinges oriented northwest/southeast and by an unnamed thrust fault that lies partially below the Duke River Fault. These folds are sub-parallel to the Hoge Creek syncline, a large regional structure found just north of the Hoge Creek area (Read and Monger 1976).

Alexander terrane hanging wall

The hanging wall of the Duke River Fault is predominantly made up of phyllite, phyllonite, siltstone, marble and basalt of the Icefield assemblage. Beige-colored, medium-grained hornblende-biotite diorite of the Miocene Wrangell suite crops out in the southeast part of the mapped area and roughly delineates the southern boundary of the imbricate zone. The lowest thrust panel in the Duke River Fault zone includes a massive, strongly deformed marble (DTrI4) in the western half of the map (and Hasen Creek rocks in the eastern half). The overlying thrust panel comprises phyllonite characterized by recrystallized feldspar and quartz (DTrI1) and dark grey carbonaceous and calcareous siltstone and phyllite (DTrI2). In the overlying thrust panel, carbonaceous, calcareous, muscovite-feldspar-quartz phyllite and lozenges of grey, banded marble are well exposed south of Hoge Creek. To the south in the structurally highest thrust panel, volcanic breccia and plagioclase-phyric basalt flows (DTrI3) occur with siltstone (DTrI2) and are intruded by diorite (MW) (Fig. 5).

Calcareous and carbonaceous siltstone exhibits a foliation that is dominantly made up of calcite and quartz crystals between layers of clay and other dark, insoluble minerals. A foliation within the phyllite is defined by microlithons of feldspar and dynamically recrystallized quartz between seams of muscovite and within phyllonite by very fine-grained, mildly elongated feldspar, quartz and mica. Siltstone, phyllite and phyllonite are commonly tightly to isoclinally folded within the Duke River Fault

imbricate zone. Fold hinges are oriented in a variety of directions but broadly can be grouped into northwest-plunging and east-southeast-plunging folds (Fig. 5). Within the east-southeast-plunging group, some folds are asymmetric and verge to the north-northeast but many are symmetric. Within the northwest-plunging group no patterns of vergence or fold style could be ascertained. Crenulation lineations are common within phyllite and are folded around tight and isoclinal folds. Also within phyllite an early foliation is rarely seen within the dominant foliation (Fig. 9a). Four distinct, brittle shear zones overprint the foliation within the imbricate zone and bound the thrust panels. The lowest thrust panel is bounded by a brittle shear zone that separates Hasen Creek conglomerate from Alexander terrane limestone in the western half of the mapped area. This shear zone cuts up into Hasen Creek Formation eastward across the map (Fig. 5). Where this structure deforms Hasen Creek Formation rocks it is characterized as a cataclastic zone that ranges in width from 1 to 5 metres and is composed of well-rounded pebble- and sand-sized clasts of volcanic material. A planar fabric is defined by interlayered sandy sections between coarser-grained layers developed within the cataclastic zone and strikes southeast and dips moderately to the southwest (Fig. 5). Locally at the top of this lowermost thrust panel is a small dike of Wrangell Volcanics (Fig. 5). The overlying thrust panel is bounded by a brittle shear zone that separates phyllite and phyllonite (DTr11) from limestone (DTr14) in the west and phyllite and siltstone (DTr12) of the Icefield assemblage from Hasen Creek sandstone (PHC) in the east (Fig. 5). This shear zone is characterized by clay and sub-angular, pebble-sized fragments of dominantly calcareous siltstone that exhibits planar fabrics that strike southeast and dip moderately to the southwest. The next highest thrust panel is bounded at its base by a 5 to 50 metre thick section of fault gouge that cuts through Icefield assemblage siltstone (DTr12). The boundary of the structurally highest thrust panel is marked locally by a thrust contact between diorite of the Miocene Wrangell suite and siltstone of the Icefield assemblage (DTr12), and in part by a thrust contact between basalt (DTr13) and siltstone (DTr12; Fig. 5) of the Icefield assemblage. The contact between diorite and siltstone is

characterized by gouge composed of sub-rounded, sand sized fragments of dominantly quartz in a clay matrix (Fig. 9b). Field observations indicate deformation only affected rocks within ten metres of the contact. Away from the gouge zone, to the south, the diorite body is undeformed (Fig. 9c). This gouge zone strikes approximately 100° and dips shallowly to the south and lacks any well-developed planar fabrics. Away from the Wrangell suite diorite to the east, the boundary of the structurally highest thrust panel is inferred to follow the contact with the basalt (DTrI3) and siltstone (DTrI2), and to the west is inferred to cut through the basalt. Neither of these sections of the boundary was examined in the field.

Locally, in the west-central part of the map area, a thick section of calcareous siltstone and phyllite is intruded by dikes that are folded, pulled apart and in places completely dismembered (Fig. 9d). In some locations the dikes cross cut the main foliation but are pulled apart parallel to the main foliation in other areas.

Klutlan Glacier Area

The westernmost exposure of the Duke River Fault in Yukon occurs near the Yukon-Alaska border, approximately 60 km west-northwest of Hoge Creek (Fig. 1). In the mapped area, the Duke River Fault is a steeply south-dipping reverse fault that places Late Paleozoic, higher metamorphic grade rocks of the Alexander terrane over Wrangellia (Fig. 6). Detailed information is limited due to rugged topography and glaciers and therefore only a brief description and sketch of the geology is provided (Fig. 6).

In the Klutlan Glacier area the footwall of the fault comprises folded basalt and sandstone that have been assigned to the Pennsylvanian Station Creek and Permian Hasen Creek Formations, respectively. The hanging wall of the fault comprises a panel of gabbro and foliated leucocratic gabbro that has been assigned to the Devonian Steele Creek Suite and mica schist that has been assigned to the

Bullion assemblage. South of this panel and in fault contact with the leucocratic gabbro, folded micaceous quartzite and marble have been assigned to the Bullion assemblage.

TIMING OF DEFORMATION ALONG THE DUKE RIVER FAULT

Seven samples were collected for geochronological analysis to determine timing of deformation along the Duke River Fault. One sample of deformed diorite in the hanging wall of the Duke River Fault zone was dated by the U-Pb zircon CA-TIMS method at Boise State University described in Appendix I. $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of muscovite were performed at the University of British Columbia's Pacific Centre for Isotopic and Geochemical Research (five samples) and at the Geological Survey of Canada in Ottawa, Ontario (one sample). Detailed descriptions of the $^{40}\text{Ar}/^{39}\text{Ar}$ methodologies from both laboratories are presented in Appendix II.

U-Pb Geochronology

Numerous samples were collected from igneous rocks deformed by the Duke River Fault in order to constrain the minimum age of deformation. One of these samples proved to be dateable using the U-Pb geochronological techniques. Sample 09RC151 is from a medium-grained, biotite-hornblende-pyroxene diorite that crops out near Hoge Creek in the hanging wall of the Duke River Fault zone and is deformed into clay and crushed rock within ten metres of the fault (Fig. 9b). Six single zircon grains were analysed, and the four youngest $^{206}\text{Pb}/^{238}\text{U}$ dates are equivalent with a weighted mean of 15.463 ± 0.013 Ma (Fig. 10a; Tables I and II). Two other slightly older dates of 15.500 ± 0.034 and 15.504 ± 0.031 Ma are interpreted as being from grains with a prolonged magma residence history or that contained inherited components.

$^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology

$^{40}\text{Ar}/^{39}\text{Ar}$ age determinations on rocks along and nearby the Duke River Fault yielded several different ages. Samples were collected in order to constrain the timing of regional metamorphism in the Alexander terrane and ductile movement along the Duke River Fault. Two samples were collected near Klutlan Glacier in the hanging wall of the Duke River Fault in Bullion assemblage mica schist and micaceous quartzite (Cobbett 2011d; Fig. 6). Muscovite that defines the main regional foliation in the mica schist (from sample 08-RC-060-1b) shows a $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum with a plateau age of 256.5 ± 3.7 Ma defined by 76.5% of the gas released over 5 steps (Fig. 6 and 10b; Tables I and III). Muscovite within the quartzite defines the dominant foliation (from sample 08-RC-071-1) and yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum with a plateau age of 254.7 ± 5.3 Ma defined by 88% of the gas released over 8 steps (Fig. 6 and 10c; Tables I and III).

Muscovite that defines the dominant foliation within the Icefield assemblage rocks in the Duke River Fault imbricate zone near Dollis Creek gave a plateau age of 79.3 ± 2.5 Ma comprising 78.3 % of the gas released over 6 steps (sample 08-RC-024-1A) (Fig. 3 and 10d; Tables I and III). Two other muscovite-bearing samples from the imbricate zone at Dollis Creek were also analyzed. Sample 08-RC-024-1B yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ spectrum showing significant ^{40}Ar -loss in the low- to mid-temperature heating steps. These steps ranged in age between 62 and 98 Ma. The high-temperature steps yielded a pseudoplateau age of 103.5 ± 1.7 Ma (30 % of the total ^{39}Ar gas released over 6 steps) (Fig. 3 and 10e; Table I and III). Sample 08-RC-028-1 gave a plateau age of 90.9 ± 2.1 Ma (80.8 % of the gas released over 7 mid- to high-temperature steps) (Fig. 3 and 10f; Table I and III). Weak foliation in a calcite-altered rock is defined dominantly by muscovite near the Duke River Fault at Jessie Creek (from sample 09-RC-063C01). This sample gave a hump-shaped release spectrum from which no plateau age could be determined. On the inverse isochron diagram, the majority of data points plotted along a line

intersecting the y-axis at a $^{40}\text{Ar}/^{36}\text{Ar}$ composition of 2797 ± 1552 . The inverse isochron age for the muscovite 104.8 ± 3.7 Ma defined by 58% of the ^{39}Ar released (7 of 9 heating steps) (Fig. 4 and 10g; Tables I and III).

DISCUSSION

Kinematic Interpretation

In all areas, the Duke River Fault zone in its present configuration juxtaposes older rocks of higher metamorphic grade above younger rocks of lower metamorphic grade. Elongation lineations at both Dollis and Jessie creeks are interpreted to record transport direction of ductile movements along the fault. Near Dollis Creek the lineations plunge towards the south-southwest. The C'-S shear fabrics associated with the lineations suggest a thrusting motion. This, together with the orientation of the fault, indicates a nearly orthogonal (slightly dextral oblique) direction of transport (Fig. 11). Near Jessie Creek the lineations plunge shallowly to moderately to the east-southeast and, coupled with associated C'-S shear fabrics, suggest strike-slip motion with a reverse component or an oblique thrust (Fig. 11). Therefore, we interpret that the earlier, ductile phase of Duke River Fault deformation is associated with thrusting that places the Alexander terrane over Wrangellia towards the north-northeast near Dollis Creek and towards the west-northwest near Jessie Creek along the elongation lineation axes. At Hoge Creek, no ductile elongation lineation was observed; therefore, a transport direction was not ascertained. However, Alexander terrane rocks sit structurally above Wrangellia rocks along the Duke River Fault and there are north-northeast vergent asymmetric folds. Both suggest a thrust relationship that is consistent with relationships elsewhere.

Conditions of faulting

Evidence collected at several locations along the fault provides insight into the conditions of faulting in both the ductile and brittle regimes. Ultramafic bodies that intrude schist within Domain 1 near Jessie Creek have developed a fabric defined by bands of muscovite and elongate grains of dynamically recrystallized feldspar suggesting deformation at approximately 450° C (Price and Cosgrove, 1990).

In both the Dollis Creek and Hoge Creek areas some brittle shear zones and sections of fault gouge are nearly completely altered to clay. For example, in a diorite from within the structurally highest gouge zone at Hoge Creek, all minerals except quartz have been altered to clay. The foliation within siltstone at Dollis Creek is interpreted to have formed by pressure solution processes because it appears that the soluble material has been removed, leaving behind layers of dark insoluble minerals and clay during the forming of stylolites. This suggests fluids percolated through the fault zone when it was active at shallow crustal levels (Warr and Cox 2015; Renard et al. 2000).

Ages of fabric development near the Duke River Fault

Permian

Permian ages (ca. 257 to 255 Ma) obtained from samples near Klutlan Glacier are interpreted to record the age of a regional metamorphic event that affected the Alexander terrane in Yukon. These ages are indistinguishable from Permian (ca. 273 to 260 Ma) $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages from metamorphic rocks within the Alexander terrane in southeast Alaska that have been interpreted by Karl et al. (2010) to date a regional metamorphic event. Near Klutlan Glacier the muscovite probably formed during Permian regional metamorphism of the Alexander terrane and was not subsequently recrystallized during deformation along the Duke River Fault. Younger ages in the low-temperature heating steps of

the Klutlan Glacier samples may reflect partial resetting that could be attributed to fault deformation (Fig. 10b and c). One explanation for this is that the Duke River Fault in this area has not been as deeply exhumed as in the more southern locations. Another possibility is that deformation along the Duke River Fault is represented by several strands, none of which at the Klutlan locality saw enough shear-heating or fluid-flow in the Cretaceous to reset the $^{40}\text{Ar}/^{39}\text{Ar}$ system.

Cretaceous

The Duke River Fault underwent a protracted period of ductile deformation, which, based on several $^{40}\text{Ar}/^{39}\text{Ar}$ ages, is interpreted to have occurred in the Cretaceous. The dominant foliation preserved in the Duke River Fault imbricate zone is interpreted to be formed by pressure solution processes, growth and/or recrystallization of muscovite and dislocation creep which has resulted in dynamically recrystallized quartz and feldspar grains (Fig. 7a and 8a, b). In all locations mapped along the fault, the fabric developed by these processes has been folded and this folding is interpreted to be a result of movement along the fault.

Near Dollis Creek the main penetrative foliation, asymmetric folds and associated axial planar cleavage developed within the quartz-feldspar schist and crenulation cleavage developed within siltstone are attributed to a phase of ductile deformation along the Duke River Fault. Similarly, near both Jessie and Hoge creeks, metamorphic fabrics, crenulation lineations and folding that deformed both of these structures are all attributed to deformation along the fault. Near Hoge Creek, phyllonite is interpreted to have formed through extensive grain size reduction in response to ductile deformation processes being active over extended periods of time. Muscovite from Dollis and Jessie Creek areas that are interpreted, because of their proximity to the fault zone, to have formed during Duke River Fault deformation give a range of cooling ages from 105 to 79 Ma; this suggests ductile motion along the fault is Cretaceous in age (Albian to Cenomanian).

Near Hoge Creek the dominant foliation, northwest plunging and east-southeast plunging folds are attributed to a phase of ductile deformation along the Duke River Fault. The variation in the orientation of the folds at Hoge Creek suggests they were formed by more than one phase of folding (Fig. 5). This could be explained if the Duke River Fault was active in pulses throughout its ductile phase. In the same area, dikes that have been pulled apart and dismembered are interpreted to be syn- to late kinematic because they cross-cut the ductile foliation in some places and have been pulled apart parallel to the foliation in other places (Fig. 9d).

The Cretaceous $^{40}\text{Ar}/^{39}\text{Ar}$ ages (ca. 105 to 79 Ma) obtained for muscovite from rocks of the Icefield assemblage within the Duke River Fault imbricate zone are interpreted to date movements along the fault. Muscovite that has grown parallel to both S and C' surfaces likely grew during movement along the fault. The presence of dynamically recrystallized feldspar indicates heat from shearing reached 450° C or higher which is well above the $^{40}\text{Ar}/^{39}\text{Ar}$ closure temperature for muscovite (Purdy and Jäger 1976; Jäger 1979; Price and Cosgrove 1990).

Based on the quality of the $^{40}\text{Ar}/^{39}\text{Ar}$ spectra for the four Cretaceous samples, 103.5 +/- 1.7 Ma (from sample 08-RC024-1b) is the preferred minimum age for the main phase of ductile movement along the fault. Although it is based on only 30% of the total released ^{39}Ar for the sample, the age is not a true plateau age; however, the age is calculated from all high temperatures steps (except for the fusion step) which gave more precise results compared to the other two samples (Fig. 10e). Sample 09-RC-063C01 did not yield a plateau age but the inverse isochron age of ca. 105 Ma is indistinguishable from the 103.5 +/- 1.7 Ma pseudoplateau age from sample 08-RC024-1b.

The spectra for muscovite from samples 08-RC-024-1a and 08-RC-028-1 were slightly hump-shaped with relatively lower precision, and yielded much younger Late Cretaceous plateau ages. In both samples, high-temperature steps dropped off significantly from the main plateau. The younger ages

obtained from these samples, and from the low- to mid-temperature steps of 08-RC-024-1b may be attributed to 1) argon loss related to fluids percolating through the deformation zone during or following movement along the Duke River Fault, 2) thermal resetting of fine-grained muscovite that may be related to episodes of high heat flow in and near the Duke River Fault after the main phase of movement (Scaillet et al. 1990), 3) mica growth at various times during prolonged deformation within the Duke River Fault imbricate zone (Kirschner et al. 1996; Hames and Cheney 1997; Dunlap and Kronenberg 2001), or 4) slower cooling of these rocks. The presence of secondary calcite and quartz in most samples collected along the fault suggests that syn- or post-kinematic circulation of fluid within the Duke River Fault imbricate zone may explain the argon loss.

Miocene and later

Brittle features observed along the Duke River Fault zone overprint ductile fabrics suggesting a reactivation of the fault at shallow crustal levels, above the brittle-ductile transition subsequent to the development of the ductile fabrics. In the Dollis Creek canyon, where Wrangell Volcanics are overridden by the thrust, there are good exposures of fault gouge that overprint and completely destroy earlier structures. Here, the schistose rocks of the Icefield assemblage localize the brittle deformation and have been deformed into crushed rock and locally fault gouge (Fig. 7c). Fracture sets within the Miocene tuff are interpreted to be associated with this late movement along the Duke River Fault as these features are only found within approximately 300 metres of the fault. This suggests that at least some post-Miocene brittle faulting took place. Similarly, Miocene (?) crystal tuff northeast of the Bullion Creek area exhibits clay gouge and brecciated zones near the Duke River Fault (Cobbett 2011) and northwest of Hoge Creek, the Wrangell Volcanics are folded above the Duke River Fault (Dodds and Campbell 1992).

Within the Jessie Creek area cohesionless damage zones composed of fault breccia, cataclasite and gouge overprint the ductile foliation and are interpreted to be a result of movement along thrust and reverse faults. Near Hoge Creek, brittle shear zones deform the base of a Miocene diorite body, Icefield assemblage and Hasen Creek rocks and clearly overprint ductile fabric.

Furthur evidence that indicates that the Duke River Fault was reactivated in the Cenozoic includes pull-apart basins filled with Oligocene conglomerates that have been mapped near the fault in southwest Yukon (Ridgway et al. 1992; Ridgway and DeCelles 1993). Northwest of Hoge Creek, the Burwash basin occurs between the Duke River Fault and the Denali fault and the Bates Lake basin occurs right along the Duke River Fault north of Dollis Creek (Fig. 1, 11). Our study yielded little evidence that pointed to purely strike-slip movement along the Duke River Fault. These basins may be attributed to other, unidentified strike-slip faults in the area or strike-slip motion along the Denali fault.

Whether or not the Duke River Fault was active continuously or intermittently is not known. It is interpreted as being a deep, crustal scale structure that extended below the brittle-ductile transition zone in the Albian to Cenomanian because of the nature of the fault fabrics and the width and extent of the fault zone. The ductile portions of the fault were exhumed into the brittle regime by the Miocene. Either the fault was progressively deforming from Cretaceous to Miocene time and was gradually exhumed or there was a pulse of ductile deformation in the Cretaceous and then a period of erosion and exhumation with a reactivation at higher level in the crust in the Miocene.

Regional considerations

From northern Washington to Juneau, Alaska, regional Cretaceous (Albian to Cenomanian) transpression affected a 1200 km long section of the Cordillera mainly along the western edge of the Coast Plutonic Complex (Crawford et al. 1987; Rubin et al. 1990; McClelland and Mattinson 2000; Rusmore et al. 2000; Angen et al. 2014). Evidence includes west-vergent thrust faults and sinistral strike

slip shear zones mapped at numerous locations along the western edge of the Coast Plutonic Complex that are coeval with east-vergent thrust faults that occur east of the Coast Plutonic Complex (Crawford et al. 1987; Evenchick, 1991; Journeay and Friedman 1993; Rusmore and Woodsworth 1994; McClelland and Mattinson 2000; Evenchick et al., 2007; Israel et al. 2013; Angen et al. 2014).

Similarities in the age of deformation along both the east and west-verging thrust faults with the $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Duke River Fault zone suggest the fault may form part of the northern end of this phase of oblique shortening and is best correlated with the structures that represent the phase of tectonism characterized by dextral transpression. The timing of this phase may be slightly younger in the south than movement along the Duke River Fault. In all cases, as with the Duke River Fault, the thrust faults juxtapose rocks of relatively higher metamorphic grade with rocks characterised by lower grade.

Several workers have identified large-scale sinistral strike-slip and sinistral oblique thrust faults of Cretaceous age within the Coast Plutonic Complex, separating the Insular terranes from the Intermontane terranes (Scharizza et al., 1997; Umhoefer et al., 2002; Chardon et al., 2003; Evenchick, 2006; Israel et al., 2006; 2013; Angen et al., 2014). Similarly aged dextral faults are observed separating the Intermontane terranes from more inboard terranes (Gabrielse et al., 2006 and references therein). This dichotomy in kinematics led some researchers to propose a model involving large-scale tectonic escape, where the Intermontane terranes (as a coherent block) moved northward with respect to the bounding North American plate to the east and the Insular terranes to the west (Fig. 12a; Umhoefer, 2003; Nelson et al., 2013; Angen et al., 2014). A problem with this model is that tectonic escape is generally associated with continent-continent type collisional orogens (Molnar and Tapponnier, 1975; Burke and Sengor, 1986), and as Angen et al., (2014) point out, there is a lack of evidence for large-scale Cretaceous accretionary events. The new data from the Duke River fault suggests that there was a dramatic compressional event that provides further evidence for the escape model.

Several large sedimentary basins (Gravina-Nutzotin-Kahiltna-Dezadeash) developed between the Insular and Intermontane terranes in the Middle to Late Jurassic following initial accretion of the Insular terranes, presumably during a period of transtensional tectonics (McClelland et al., 1992; van der Heyden, 1992; Umhoefer et al., 2002; Evenchick, 2006). This period of transtension was followed by Early Cretaceous sinistral transpression that slowly transitioned into more orthogonal compression and dextral transpression later in the Cretaceous (Engelbreton et al., 1985; Schiarizza et al., 1997; McClelland and Mattinson, 2000; Israel et al., 2013; Angen et al., 2014). We suggest that deformation observed along the Duke River fault is the result of orthogonal, dextral transpressive tectonic interaction between the Insular and Intermontane terranes. The 're-accretion' of the Insular terranes to the margin of the Intermontane terranes would be the accretionary event that appears to be lacking in the tectonic escape model (Fig. 12b). The overall kinematics at the time would have been dextral transpressive; however, sinistral kinematics on faults between the Insular and Intermontane terranes existed likely in response to the elevated thermal environment of the Coast Plutonic Complex, due to the voluminous Cretaceous plutons (Woodsworth et al., 1991; Hollister and Crawford, 1996; Hollister and Andronikos, 2006). The Coast Plutonic Complex was a thermally weakened zone that allowed for escape of the Intermontane terranes northward between two coherent tectonic blocks, the Insular terranes and North America (Fig. 12b). The Duke River fault, and associated structures, accommodated the dextral transpressive kinematics within the 'colder' and stiffer tectonic collider

Reactivation of the Duke River Fault occurs during the collision of the Yakutat microplate with North America. The Yakutat microplate has been shown to have moved northwestwards with the Pacific Plate along margin-parallel strike-slip faults until it reached the Gulf of Alaska in the Miocene at which point it began to underthrust beneath the North American Plate in southern Alaska (Plafker 1994; Bruhn 2004). Global Positioning System (GPS) motion vectors show that some of the present day deformation related to the Yakutat microplate collision is causing the southwest corner of the Yukon to move

towards the north-northeast (Mazzotti 2002). The Duke River Fault is favourably oriented to accommodate northeast-southwest compression by reverse slip. Micro-seismicity recorded along the Duke River Fault in the southwest Yukon suggests the fault accommodates part of the active uplift of the St. Elias Mountains (Power 1988; Page 1991).

CONCLUSIONS

The Duke River Fault mostly separates the Alexander terrane from Wrangellia in southwest Yukon. The thrust fault places pervasively foliated Alexander terrane rocks over mildly deformed rocks of Wrangellia. Elongation lineations from within the fault zone suggest this fault was a dextral oblique to orthogonal thrust fault in the Cretaceous. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of muscovite grains from deformed rocks within the Duke River Fault zone range in age from 79 Ma to 105 Ma. Rocks at least as young as 15.5 Ma have been affected by brittle deformation clearly showing the Duke River Fault has accommodated shortening since the Miocene (Langhian).

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Tables:

Table I: Geochronology sample location and summary of ages

Table II: U-Pb Isotopic data for Wrangell Suite.

Table III: $^{40}\text{Ar}/^{39}\text{Ar}$ data from samples within the Duke River Fault imbricate zon

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Figures:

Figure 1. Terrane map of northern Cordillera in western Canada and Alaska. Inset map shows terranes of southwest Yukon highlighting the Duke River Fault. Red squares show approximate location of mapped areas.

Figure 2. Regional stratigraphy of southwest Yukon.

Figure 3. Geologic map and cross section of Duke River Fault near Dollis Creek. Map legend for Dollis Creek, Jessie Creek, Hoge Creek and Klutlan Glacier areas. Structural data from the Dollis Creek area presented in equal area, lower hemisphere projection stereonet. Map area included in the imbricate zone stereonet is shown on the cross sections. Poles to foliations from within the imbricate zone have been contoured using a 1% function. The footwall cross section includes the entire area to the northeast of the Duke River Fault. See stereonet legend for symbol explanation. Note: Contour lines in Yukon are every 100 feet and in British Columbia are every 20 metres.

Figure 4. Geologic map and cross section of Duke River Fault near Jessie Creek (see Figure 3 for legend). Structural data from the Jessie Creek area presented in equal area, lower hemisphere projection stereonets. See stereonet legend for symbol explanation.

Figure 5. Geologic map and cross sections of the Duke River Fault near Hoge Creek (see Figure 3 for legend). Structural data collected near Hoge Creek presented on equal area, lower hemisphere stereonets. See stereonet legend for symbol explanation.

Figure 6. Geologic sketch of Duke River Fault near Klutlan Glacier. Figure 3 can be used to identify age of units and map symbols.

Figure 7. Photos from Dollis Creek area. a) Microphotograph of calcareous, quartz-muscovite schist from within the Duke River Fault imbricate zone near Dollis Creek. Foliation is made up of seams of muscovite between microlithons of dominantly quartz and calcite. b) Kink folds within Icefield assemblage schist from the imbricate zone. Photo is looking north and green tool in the right of the photo is 12 cm long. c) Fault gouge within the Duke River Fault imbricate zone that has developed a planar fabric that was subsequently folded. Photo is looking south with a rock hammer for scale (head of hammer is 15 cm wide). d) Bullion assemblage (SDB) carbonate sitting structurally above Icefield assemblage siltstone and phyllite (DTrI) that has been in part deformed into fault gouge. Photo is looking southwest across Squaw Creek canyon.

Figure 8. Photos from Jessie Creek area. a) Microphotograph of sample collected from within the Duke River Fault imbricate zone of quartz-feldspar-muscovite phyllite deformed into shear bands. Dashed line traces S-fabric and solid line traces C'-fabric suggesting sinistral kinematics. b) Microphotograph of sample collected from within the Duke River Fault imbricate zone of quartz-muscovite-calcite schist deformed into shear bands. Dashed line traces S-fabric and solid line traces C'-fabric. White circle highlights grain of muscovite that has grown along the C' fabric. c) Duke River Fault (black line)

juxtaposing Icefield assemblage (DTrI) volcanic conglomerate against Chitistone Limestone (uTrC) along steep, south-dipping reverse fault. View looking to the east. White arrow points to fault gouge. d) Photo looking west at Icefield assemblage. Cataclastic zone on the left (black outline) deforms volcanic conglomerate (DTrI7). Cataclastic zone on the right (white outline) deforms siltstone (DTrI8) and a felsic dike. Note the lozenge-shaped sections of the pulled apart dike. Person near the bottom and middle of the photo, circled to show scale.

Figure 9. Photos from Hoge Creek area. a) Early foliation traced with red lines between dominant foliation traced with white lines in phyllite of unit DTrI1. b) Photo looking southeast at gouge zone comprising rounded-quartz grains in clay matrix. Blocky rock above gouge is part of the undeformed Miocene Wrangell diorite. Contact between gouge and diorite strikes approximately 100° and dips shallowly to the south. c) Microphotograph of undeformed Miocene Wrangell diorite approximately 1 kilometre away from the gouge zone. Bt- biotite, fsp-feldspar, px-pyroxene. d) Felsic dike cutting foliation (white solid line) and pulled apart by foliation (white arrow).

Figure 10. a) Plot of $^{206}\text{Pb}/^{238}\text{U}$ dates from single grains of zircon analyzed by the CA-TIMS method. Plotted with Isoplot 3.0 (Ludwig, 2003). Error bars are at 2 sigma. Weighted mean date is shown by the grey box behind the error bars. Error bars in white are not included in the weighted mean calculation. MSWD = mean square weighted deviation. pof = probability of fit. b) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum for muscovite that defines the regional foliation in schist found at Klutlan Glacier (sample 08-RC-060-1b). c) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum for muscovite that defines the main regional foliation in micaceous quartzite at Klutlan Glacier (sample 08-RC-071-1). d) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum for muscovite that defines the main foliation in schist found within the Duke River Fault at Dollis Creek (sample 08-RC-024-1A). e) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum for muscovite that defines the main foliation in schist found within the Duke River Fault at Dollis Creek (sample 08-RC-024-1B). f) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum for muscovite that defines the main foliation in schist found within the Duke River Fault at Dollis Creek (sample 08-RC-028-1). g) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum and inverse isochron plot for muscovite that defines the main foliation in phyllite found within the Duke River Fault at Jessie Creek (sample 09-RC-063C01). Note: for all $^{40}\text{Ar}/^{39}\text{Ar}$ samples, plateau steps are light, rejected steps are dark, box heights are 2σ , line with double arrows indicates plateau or pseudoplateau regions.

Figure 11. Map of southwest Yukon showing study areas (red boxes), transport direction of the Duke River Fault (orange and black arrows) and Eocene-Oligocene strike-slip basins in the vicinity of the Duke River Fault (red polygons). AX – Alexander terrane, WR – Wrangellia, KS – Kluane Schist, YT – Yukon Tanana terrane, CG – Chugach, YA- Yakutat, TrJ – metamorphic rocks, Nab – North America basinal, SM – Slide Mountain, ST – Stikinia, QN – Quesnellia.

Figure 12: a) Map of Canadian and Alaskan Cordillera showing mid-Cretaceous tectonics and 'escape' of Intermontane terranes to the northwest (modified from Nelson et al, 2013). b) Schematic drawing that outlines change in regional kinematics of the Canadian Cordillera from Middle Jurassic to Cretaceous (Albian to Cenomanian). Closure of the Jura-Cretaceous basins was and 're-accretion' of the Insular

terrane was the driving mechanism for the northward escape of the Intermontane terranes during dominantly orthogonal dextral transpression.

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Table 1. Geochronology Sample Location and Summary of Ages							
Area	Sample	Map No.	Easting	Northing	UTM Zone	Mineral	Age (Ma)
Hoge Creek	09-RC-151-1	n/a	577447	6795148	7	Zircon	15.45 ± 0.01
Klutlan Glacier	08-RC-060-1b	1	517200	6808953	7	Muscovite	267.5 ± 6.4
Klutlan Glacier	08-RC-071-1	2	517701	6808546	7	Muscovite	256.8 ± 6.6
Dollis Creek	08-RC-024-1A	3	382803	6653051	8	Muscovite	82.8 ± 2.7
Dollis Creek	08-RC-024-1B	4	382803	6653051	8	Muscovite	104.6 ± 2.2
Dollis Creek	08-RC-028-1	5	381293	6654588	8	Muscovite	90.1 ± 4.3
Jessie Creek	09-RC-063-C1	6	639353	6758477	7	Muscovite	104.1 ± 3.7

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U-Pb isotopic data.

Sampl e	Radiogenic Isotope Ratios														Isotopic Ages					
	Th	²⁰⁶ Pb*	mol %	Pb*	Pb _c	²⁰⁶ Pb	²⁰⁸ Pb	²⁰⁷ Pb		²⁰⁷ Pb		²⁰⁶ Pb		corr.	²⁰⁷ Pb	±	²⁰⁷ Pb	±	²⁰⁶ Pb	±
	U	x10 ⁻¹³ mol	²⁰⁶ Pb*	Pb _c	(pg)	²⁰⁴ Pb	²⁰⁶ Pb	²⁰⁶ Pb	% err	²³⁵ U	% err	²³⁸ U	% err	coef.	²⁰⁶ Pb		²³⁵ U		²³⁸ U	
(a)	(b)	(c)	(c)	(c)	(c)	(d)	(e)	(e)	(f)	(e)	(f)	(e)	(f)		(g)	(f)	(g)	(f)	(g)	(f)
09RC151																				
z1	0.43		96.31					0.04697		0.01556		0.002403				31.6		0.2		0.02
	1	0.1065	%	7.7	0.34	489	0.139	0	1.327	6	1.414	6	0.162	0.577	47.69	2	15.68	2	15.476	5
z2	0.46		91.76					0.04685		0.01555		0.002407				53.2		0.3		0.03
	3	0.1439	%	3.3	1.07	219	0.150	1	2.231	1	2.393	4	0.222	0.750	41.63	0	15.67	7	15.500	4
z3	0.45		93.40					0.04721		0.01560		0.002396				49.7		0.3		0.03
	2	0.0917	%	4.2	0.54	273	0.146	7	2.093	3	2.234	6	0.195	0.741	60.22	6	15.72	5	15.431	0
z4	0.37		94.73					0.04633		0.01534		0.002402				36.4		0.2		0.02
	1	0.1100	%	5.2	0.51	342	0.120	0	1.521	6	1.634	4	0.161	0.727	14.81	7	15.46	5	15.468	5
z5	0.36		91.96					0.04686		0.01556		0.002407				46.8		0.3		0.03
	1	0.1463	%	3.3	1.06	224	0.117	8	1.966	0	2.123	9	0.201	0.797	42.52	9	15.68	3	15.504	1
z6	0.35		93.06					0.04651		0.01540		0.002402				44.8		0.3		0.02
	1	0.1308	%	3.9	0.81	260	0.113	3	1.875	8	2.015	6	0.187	0.765	24.27	6	15.53	1	15.469	9

(a) z1, z2, etc. are labels for analyses composed of single zircon grains that were annealed and chemically abraded (Mattinson, 2005). Fraction labels in bold denote analyses used in the weighted mean calculation.

(b) Model Th/U ratio calculated from radiogenic $^{208}\text{Pb}/^{206}\text{Pb}$ ratio and $^{207}\text{Pb}/^{235}\text{U}$ date.

(c) Pb^* and Pb_c are radiogenic and common Pb, respectively. mol % $^{206}\text{Pb}^*$ is with respect to radiogenic and blank Pb.

(d) Measured ratio corrected for spike and fractionation only. Fractionation correction is 0.15 ± 0.03 (1 sigma) %/amu (atomic mass unit) for single-collector Daly analyses, based on analysis of EARTHTIME ^{202}Pb - ^{205}Pb tracer solution.

(e) Corrected for fractionation, spike, common Pb, and initial disequilibrium in $^{230}\text{Th}/^{238}\text{U}$. Common Pb in analyses was assigned to laboratory blank with a composition of $^{206}\text{Pb}/^{204}\text{Pb} = 18.04 \pm 0.61\%$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.54 \pm 0.52\%$; $^{208}\text{Pb}/^{204}\text{Pb} = 37.69 \pm 0.63\%$ (1 sigma).

$^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios corrected for initial disequilibrium in $^{230}\text{Th}/^{238}\text{U}$ using $\text{Th}/\text{U} [\text{magma}] = 3.0 \pm 0.3$ (1 sigma).

(f) Errors are 2 sigma, propagated using algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).

(g) Calculations based on the decay constants of Jaffey et al. (1971). $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ dates corrected for initial disequilibrium in $^{230}\text{Th}/^{238}\text{U}$ using $\text{Th}/\text{U} [\text{magma}] = 3.0 \pm 0.3$ (1 sigma).

08RC024-1b Muscovite								
Laser	Isotope Ratios							
Power(%)	40Ar/39Ar	2σ	36Ar/39Ar	2σ	39Ar/40Ar	2σ	36Ar/40Ar	2σ
2.00	181.44	21.27	0.57992	0.16286	0.00550	0.00065	0.00319	0.00083
2.20	89.84	6.01	0.33121	0.02327	0.01113	0.00074	0.00368	0.00035
2.40	91.87	3.81	0.27038	0.01159	0.01088	0.00045	0.00294	0.00013
2.60	49.33	1.35	0.14003	0.00976	0.02026	0.00055	0.00283	0.00021
2.90	41.70	1.72	0.11821	0.00516	0.02386	0.00099	0.00279	0.00016
3.20	26.70	1.38	0.05895	0.00548	0.03729	0.00193	0.00214	0.00023
3.50	19.88	0.25	0.03199	0.00293	0.05037	0.00063	0.00161	0.00015
3.80	20.59	0.54	0.03757	0.00122	0.04863	0.00129	0.00183	0.00007
4.00	12.66	0.27	0.00296	0.00081	0.07918	0.00170	0.00023	0.00006
4.30	12.89	0.21	0.00221	0.00156	0.07777	0.00125	0.00017	0.00012
4.60	12.90	0.20	0.00229	0.00184	0.07768	0.00119	0.00018	0.00014
5.00	12.23	0.28	0.00179	0.00115	0.08198	0.00185	0.00015	0.00009
5.40	12.68	0.15	0.00323	0.00178	0.07902	0.00095	0.00025	0.00014
5.80	12.87	0.29	0.00240	0.00262	0.07787	0.00177	0.00018	0.00020
6.20	13.71	0.17	0.00865	0.00150	0.07307	0.00088	0.00063	0.00011

$$J = 0.00489900 \pm 0.00000735$$

Volume 39ArK =

0.259 x E-13 cm3 NPT

Integrated Date =

 100.04 ± 1.45

Ma

Plateau age = 84.9 ± 4.3 Ma

(2s, including J-error of .2%)

MSWD = 1.6, probability=0.21

Inverse isochron (correlation age) results, plateau steps: Model 1 Solution ($\pm 95\%$ -conf.) on 7 points

Age = 85 ± 12 Ma

Initial $^{40}\text{Ar}/^{36}\text{Ar} = 293 \pm 23$

MSWD = 2.0

Probability = 0.0

Inverse isochron (correlation age) results, plateau steps: Model 1 Solution ($\pm 95\%$ -conf.) on 7 points

$$\text{Age} = 104.2 \pm 4.0 \text{ Ma}$$
Initial $^{40}\text{Ar}/^{36}\text{Ar} = 195 \pm 110$

MSWD = 1.8

Probability = 0.

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<i>Rho</i>	<i>K/Ca</i>	<i>%40Ar rad</i>	<i>f 39Ar</i>	<i>40Ar*/39ArK</i>	<i>Age</i>	<i>2 σ</i>
0.026	0.20	4.79	0.03	8.709	76.48 ± 385.83	
0.672	1.01	-10.01	0.21	8.997	-82.52 ± 84.24	
0.512	0.63	12.21	1.42	11.226	98.00 ± 33.18	
0.337	0.46	15.45	3.45	7.629	67.17 ± 27.42	
0.647	0.09	16.77	5.73	7.036	62.03 ± 19.30	
0.453	0.09	36.19	7.55	9.714	85.10 ± 18.15	
0.001	9.38	51.88	18.45	10.314	90.24 ± 7.48	
0.591	22.66	45.43	30.71	9.355	82.03 ± 5.39	
0.004	5.97	92.89	4.67	11.758	102.52 ± 2.97	
0.013	15.72	94.68	5.87	12.201	106.27 ± 4.30	
0.003	10.11	94.52	5.89	12.195	106.21 ± 4.90	
0.001	14.47	95.43	6.52	11.667	101.75 ± 3.67	
0.002	15.66	92.20	4.08	11.694	101.98 ± 4.66	
0.001	7.74	94.27	2.93	12.132	105.69 ± 7.02	
0.009	5.49	81.04	2.48	11.115	97.05 ± 3.98	

Includes 56.7% of the 39Ar

steps 6 through 8

first 8 steps

08

last 7 steps

10

<i>Rho</i>	<i>K/Ca</i>	<i>%40Ar rad</i>	<i>f 39Ar</i>	<i>40Ar*/39ArK</i>	<i>Age</i>	<i>2 σ</i>
0.199	0.58	20.13	0.25	12.797	110.98 ± 103.13	
0.261	2.02	27.89	1.51	8.246	72.28 ± 14.74	
0.330	0.65	27.84	2.36	6.981	61.37 ± 15.41	
0.415	0.10	52.37	7.09	8.726	76.39 ± 6.14	
0.246	0.05	55.99	9.29	9.638	84.20 ± 4.86	
0.365	0.57	53.96	19.24	8.577	75.11 ± 6.48	
0.354	9.10	57.36	24.97	9.304	81.35 ± 7.72	
0.357	6.33	52.10	11.14	8.890	77.80 ± 6.12	
0.503	9.53	51.46	6.60	8.942	78.24 ± 5.70	
0.172	11.09	63.75	7.15	9.717	84.88 ± 3.96	
0.477	8.05	39.08	4.13	7.587	66.61 ± 7.95	
0.058	8.05	22.33	2.18	3.657	32.41 ± 15.97	
0.017	5.92	52.07	2.16	8.774	76.80 ± 11.24	
0.498	5.72	35.04	1.94	8.066	70.73 ± 15.97	

of the ^{39}Ar

steps 4 through 9

12

<i>Rho</i>	<i>K/Ca</i>	<i>%40Ar rad</i>	<i>f 39Ar</i>	<i>40Ar*/39ArK</i>	<i>Age</i>	<i>2 σ</i>
0.237	3.49	23.92	0.10	5.598	49.40 ± 131.52	
0.565	4.01	41.38	0.75	7.750	68.04 ± 29.58	
0.495	13.51	63.58	1.92	6.393	56.31 ± 11.29	
0.075	10.55	88.24	7.03	8.392	73.56 ± 3.54	
0.246	13.83	80.10	15.42	9.961	87.00 ± 5.35	
0.127	12.29	82.96	15.11	10.733	93.57 ± 4.39	
0.060	20.94	79.45	10.92	10.316	90.02 ± 8.11	
0.160	11.38	76.76	9.48	10.262	89.56 ± 5.14	
0.112	14.59	81.13	11.31	10.731	93.55 ± 5.26	
0.184	6.76	73.60	13.85	10.198	89.02 ± 6.98	
0.193	5.98	77.60	4.69	10.465	91.29 ± 5.83	
0.191	2.03	57.30	3.45	7.798	68.45 ± 7.30	
0.253	1.15	55.95	2.32	7.427	65.25 ± 8.67	
0.425	0.58	48.43	1.48	6.990	61.48 ± 10.45	
0.490	0.28	49.13	1.25	8.011	70.29 ± 20.82	
0.296	0.15	34.14	0.91	4.888	43.21 ± 28.84	

PT

Includes 80.8% of the 39Ar

steps 5 through 11

42

08RC035-1 Muscovite								
Laser	Isotope Ratios							
Power(%)	40Ar/39Ar	2σ	36Ar/39Ar	2σ	39Ar/40Ar	2σ	36Ar/40Ar	2σ
2.00	22.34	5.11207	0.03908	0.00952	0.04476	0.01024	0.00175	0.00058
2.20	10.15	0.88992	0.02188	0.00563	0.09857	0.00865	0.00215	0.00058
2.40	9.42	0.54401	0.01605	0.00230	0.10623	0.00614	0.00170	0.00026
2.70	10.49	0.15755	0.00218	0.00058	0.09563	0.00144	0.00021	0.00006
3.00	11.56	0.13950	0.00549	0.00183	0.08676	0.00105	0.00048	0.00016
3.10	16.84	0.96751	0.02037	0.00180	0.05949	0.00342	0.00121	0.00013
3.30	12.56	0.22471	0.00679	0.00165	0.07967	0.00143	0.00054	0.00013
3.50	12.76	0.33054	0.01029	0.00148	0.07843	0.00203	0.00081	0.00012
3.70	13.28	0.51123	0.01171	0.00234	0.07549	0.00291	0.00088	0.00018
3.90	13.95	0.73377	0.02629	0.00524	0.07171	0.00377	0.00188	0.00039
4.20	13.44	0.57493	0.02262	0.00190	0.07444	0.00319	0.00168	0.00016
4.60	13.30	0.62499	0.02065	0.00181	0.07520	0.00353	0.00155	0.00015
5.10	12.32	0.40462	0.01621	0.00183	0.08117	0.00267	0.00131	0.00015
5.60	12.61	0.54256	0.01661	0.00350	0.07935	0.00342	0.00132	0.00028
6.10	13.20	0.46308	0.01970	0.00247	0.07580	0.00266	0.00149	0.00019

J = 0.00488240 ± 0.00000732

Volume 39ArK = 0.541 x E-13 cm3 NPT

Integrated Date = 80.20 ± 1.35 Ma

Plateau age = 86.5 ± 1.6 Ma (2s, including J-error of .2%) MSWD = 1.8, probability=0.10 Includes 81.6%

Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±95%-conf.) on 7 points

Age = 83.7 ± 2.4 Ma Initial 40Ar/36Ar =336 ± 45 MSWD = 1.3 Probability = 0.

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<i>Rho</i>	<i>K/Ca</i>	<i>%40Ar rad</i>	<i>f 39Ar</i>	<i>40Ar*/39ArK</i>	<i>Age</i>	<i>2 σ</i>
0.682	6.69	47.87	0.38	10.697	93.19 ± 49.60	
0.314	36.95	35.72	0.76	3.625	32.12 ± 16.63	
0.367	24.12	49.15	1.31	4.629	40.91 ± 7.61	
0.048	71.46	93.53	6.37	9.807	85.61 ± 1.99	
0.018	178.82	85.56	22.74	9.886	86.29 ± 4.80	
0.529	28.54	63.71	9.08	10.727	93.44 ± 9.29	
0.069	35.63	83.85	13.39	10.529	91.76 ± 4.60	
0.167	20.81	75.91	16.65	9.683	84.56 ± 4.69	
0.179	17.33	73.47	13.37	9.754	85.16 ± 7.36	
0.246	6.77	43.79	3.67	6.108	53.79 ± 14.93	
0.435	6.00	49.81	2.64	6.694	58.87 ± 6.91	
0.455	6.32	53.72	2.35	7.146	62.78 ± 7.05	
0.224	7.22	60.77	2.71	7.489	65.74 ± 5.70	
0.133	8.24	60.68	2.63	7.650	67.13 ± 9.84	
0.264	13.49	55.44	1.96	7.317	64.26 ± 7.50	

of the ^{39}Ar

steps 4 through 9

08RC57-3 Muscovite								
Laser	Isotope Ratios							
Power(%)	40Ar/39Ar	2σ	36Ar/39Ar	2σ	39Ar/40Ar	2σ	36Ar/40Ar	2σ
2.00	33.49	1.81	0.04639	0.07690	0.02984	0.00161	0.00137	0.00230
2.20	42.47	1.04	0.12559	0.01094	0.02354	0.00058	0.00295	0.00026
2.40	44.97	0.94	0.06655	0.01011	0.02223	0.00047	0.00147	0.00022
2.70	35.83	4.81	0.05604	0.00628	0.02789	0.00374	0.00155	0.00027
3.00	37.79	2.70	0.03098	0.00488	0.02634	0.00188	0.00078	0.00014
3.30	51.18	6.86	0.07062	0.00877	0.01939	0.00260	0.00133	0.00025
3.50	53.31	2.65	0.07945	0.00864	0.01868	0.00093	0.00146	0.00017
3.70	33.16	0.67	0.00973	0.00286	0.03016	0.00061	0.00029	0.00009
4.00	29.24	0.56	0.00621	0.00357	0.03420	0.00066	0.00021	0.00012
4.40	22.68	0.44	0.01015	0.00793	0.04409	0.00085	0.00044	0.00035
4.80	19.78	0.59	0.01107	0.00733	0.05054	0.00151	0.00054	0.00037
5.30	25.22	0.75	0.01412	0.00566	0.03964	0.00118	0.00054	0.00022
5.90	24.32	0.54	0.02257	0.00544	0.04109	0.00091	0.00090	0.00022
J = 0.00488640 ± 0.00000733					Volume 39ArK =		0.096	x E-13 cm3 Nf
Integrated Date =		210.33 ± 4.57		Ma				
Plateau age = 251.8 ± 7.5 Ma		(2s, including J-error of .2%)		MSWD = 0.18, probability=0.91		Includes 67.3%		
Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±95%-conf.) on 4 points								
Age = 248.4 ± 9.8 Ma		Initial 40Ar/36Ar =297 ± 49		MSWD = 0.26		Probability = 0.		

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<i>Rho</i>	<i>K/Ca</i>	<i>%40Ar rad</i>	<i>f 39Ar</i>	<i>40Ar*/39ArK</i>	<i>Age</i>	<i>2 σ</i>
0.008	0.70	58.96	0.22	19.762	168.74 ± 187.64	
0.220	1.64	12.02	1.55	5.108	45.12 ± 29.44	
0.019	2.23	56.18	2.67	25.268	213.11 ± 24.30	
0.761	0.52	53.74	8.96	19.273	164.75 ± 42.05	
0.388	0.11	76.83	27.21	29.165	243.88 ± 24.04	
0.716	0.07	60.42	23.36	31.164	259.46 ± 57.25	
0.374	0.12	56.37	10.04	30.177	251.78 ± 28.26	
0.036	3.27	91.28	6.68	30.274	252.54 ± 8.31	
0.001	2.46	93.74	4.54	27.414	230.12 ± 9.39	
0.003	1.30	86.87	3.83	19.708	168.30 ± 19.57	
0.004	0.95	83.84	3.23	16.592	142.70 ± 18.56	
0.053	0.88	83.88	3.99	21.167	180.16 ± 14.90	
0.006	0.86	73.12	3.70	17.796	152.63 ± 13.73	

PT

of the ^{39}Ar

steps 5 through 8

77

08RC60-1B Muscovite								
Laser	Isotope Ratios							
Power(%)	40Ar/39Ar	2σ	36Ar/39Ar	2σ	39Ar/40Ar	2σ	36Ar/40Ar	2σ
2.00	108.05	46.24	0.44597	0.39341	0.00925	0.00396	0.00413	0.00329
2.20	46.16	3.72	0.09943	0.06874	0.02167	0.00175	0.00215	0.00148
2.40	44.01	2.13	0.10387	0.04152	0.02270	0.00110	0.00235	0.00094
2.70	28.12	0.80	0.06065	0.00877	0.03555	0.00102	0.00215	0.00031
3.00	34.76	0.67	0.05559	0.00707	0.02870	0.00056	0.00157	0.00020
3.30	39.97	0.43	0.05948	0.00586	0.02496	0.00027	0.00146	0.00015
3.60	51.40	2.16	0.07195	0.00342	0.01944	0.00082	0.00140	0.00006
3.90	38.72	0.48	0.02519	0.00158	0.02583	0.00032	0.00065	0.00004
4.20	39.12	0.44	0.02925	0.00375	0.02557	0.00029	0.00075	0.00010
4.60	37.52	0.33	0.02555	0.00478	0.02665	0.00024	0.00068	0.00013
5.10	42.74	1.40	0.04199	0.00374	0.02340	0.00077	0.00098	0.00009
5.70	38.06	0.54	0.02758	0.00385	0.02627	0.00037	0.00072	0.00010
J = 0.00488480 ± 0.00000733								
Integrated Date =			Volume 39ArK =			0.074 x E-13 cm3 NPT		
245.35 ± 3.24			Ma					
Plateau age = 256.5 ± 3.7 Ma			(2s, including J-error of .2%)			MSWD = 1.2, probability=0.30		Includes 76.5%
Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±95%-conf.) on 5 points								
Age = 255.5 ± 9.3 Ma			Initial 40Ar/36Ar =283 ± 39			MSWD = 1.6		Probability = 0.

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<i>Rho</i>	<i>K/Ca</i>	<i>%40Ar rad</i>	<i>f 39Ar</i>	<i>40Ar*/39ArK</i>	<i>Age</i>	<i>2 σ</i>
0.058	1.01	-23.18	0.05	25.057	-239.00 ± 1080.68	
0.004	-2.53	35.73	0.34	16.489	141.80 ± 169.11	
0.013	0.50	29.86	0.65	13.156	114.01 ± 103.88	
0.048	0.74	35.91	2.82	10.102	88.17 ± 22.36	
0.081	0.21	53.01	4.80	18.474	158.16 ± 17.86	
0.022	0.20	56.26	7.81	22.544	191.23 ± 14.27	
0.405	0.79	58.34	10.18	30.007	250.38 ± 14.62	
0.007	19.87	80.57	21.31	31.200	259.66 ± 4.72	
0.046	7.72	77.69	22.35	30.391	253.37 ± 9.23	
0.032	2.25	79.73	12.19	29.917	249.68 ± 11.40	
0.301	8.31	70.68	10.45	30.207	251.94 ± 13.59	
0.027	3.03	78.41	7.04	29.850	249.15 ± 9.62	

of the ^{39}Ar

steps 7 through 11

18

08RC071-1 Muscovite								
Laser	Isotope Ratios							
Power(%)	40Ar/39Ar	2σ	36Ar/39Ar	2σ	39Ar/40Ar	2σ	36Ar/40Ar	2σ
2.00	267.18	222.88	0.78	0.91	0.00	0.00	0.00	0.00
2.20	85.67	23.38	0.07	0.06	0.01	0.00	0.00	0.00
2.40	51.44	6.69	0.09	0.03	0.02	0.00	0.00	0.00
2.70	39.81	2.65	0.04	0.00	0.03	0.00	0.00	0.00
3.00	37.42	1.18	0.03	0.00	0.03	0.00	0.00	0.00
3.40	41.55	6.38	0.06	0.02	0.02	0.00	0.00	0.00
3.70	36.45	2.07	0.02	0.01	0.03	0.00	0.00	0.00
3.80	37.44	2.24	0.02	0.00	0.03	0.00	0.00	0.00
4.00	35.18	1.35	0.02	0.00	0.03	0.00	0.00	0.00
4.20	36.89	1.59	0.02	0.00	0.03	0.00	0.00	0.00
4.50	36.30	0.79	0.02	0.00	0.03	0.00	0.00	0.00
4.90	39.02	1.94	0.03	0.01	0.03	0.00	0.00	0.00
5.30	45.72	2.29	0.07	0.01	0.02	0.00	0.00	0.00
5.80	34.28	1.06	0.02	0.01	0.03	0.00	0.00	0.00
6.30	49.32	5.56	0.05	0.01	0.02	0.00	0.00	0.00

J = 0.00489130 ± 0.00000734

Volume 39ArK = 0.187 x E-13 cm3 Nf

Integrated Date = 251.52 ± 4.75 Ma

Plateau age = 254.7 ± 5.3 Ma (2s, including J-error of .2%) MSWD = 1.01, probability=0.42

Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±95%-conf.) on 12 points

Age = 259 ± 15 Ma Initial 40Ar/36Ar =237 ± 79 MSWD = 1.6 Probability = 0.

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<i>Rho</i>	<i>K/Ca</i>	<i>%40Ar rad</i>	<i>f 39Ar</i>	<i>40Ar*/39ArK</i>	<i>Age</i>	<i>2 σ</i>
0.122	0.03	13.86	0.02	37.716	309.91 ± 1706.55	
0.244	0.13	77.57	0.09	66.718	516.97 ± 193.91	
0.302	1.83	47.03	0.46	24.199	204.77 ± 86.34	
0.519	4.78	70.95	2.29	28.248	236.90 ± 22.86	
0.153	4.22	78.92	5.26	29.537	247.02 ± 13.34	
0.364	6.44	57.19	8.82	23.765	201.29 ± 68.15	
0.167	18.05	82.41	19.62	30.039	250.94 ± 21.46	
0.316	5.57	84.73	11.38	31.729	264.08 ± 18.03	
0.147	16.11	85.00	14.99	29.902	249.87 ± 14.10	
0.188	12.54	81.37	10.05	30.023	250.82 ± 15.75	
0.107	16.59	85.82	10.18	31.152	259.61 ± 8.35	
0.160	13.32	78.65	7.68	30.690	256.01 ± 23.02	
0.320	4.93	57.17	3.59	26.141	220.25 ± 27.24	
0.040	8.42	82.64	3.97	28.327	237.53 ± 15.68	
0.465	2.29	68.56	1.61	33.821	280.23 ± 49.48	

▷T

Includes 88% of the 39Ar

steps 5 through 12

10

APPENDICES

Appendix I

Geochronological Methods

U-Pb TIMS – Boise State University – Isotope Geology Laboratory

CA-TIMS Methods

U-Pb dates were obtained by the chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-TIMS) method from analyses composed of single zircon grains (Table I), modified after Mattinson (2005). Zircon was separated from rocks using standard techniques and mounted in epoxy and polished until the centers of the grains were exposed.

Zircon was placed in a muffle furnace at 900°C for 60 hours in quartz beakers. Single grains were then transferred to 3 ml Teflon PFA beakers and loaded into 300 µl Teflon PFA microcapsules. Fifteen microcapsules were placed in a large-capacity Parr vessel and the grains partially dissolved in 120 µl of 29 M HF for 12 hours at 180°C. The contents of the microcapsules were returned to 3 ml Teflon PFA beakers, HF removed, and the residual grains immersed in 3.5 M HNO₃, ultrasonically cleaned for an hour, and fluxed on a hotplate at 80°C for an hour. The HNO₃ was removed and grains were rinsed twice in ultrapure H₂O before being reloaded into the 300 µl Teflon PFA microcapsules (rinsed and fluxed in 6 M HCl during sonication and washing of the grains) and spiked with the Boise State University mixed ²³³U-²³⁵U-²⁰⁵Pb tracer solution. Zircon was dissolved in Parr vessels in 120 µl of 29 M HF with a trace of 3.5 M HNO₃ at 220°C for 48 hours, dried to fluorides, and re-dissolved in 6 M HCl at 180°C overnight. U and Pb were separated from the zircon matrix using an HCl-based anion-exchange chromatographic procedure (Krogh, 1973), eluted together and dried with 2 µl of 0.05 N H₃PO₄.

Pb and U were loaded on a single outgassed Re filament in 5 μl of a silica-gel/phosphoric acid mixture (Gerstenberger and Haase, 1997), and U and Pb isotopic measurements made on a GV Isoprobe-T multicollector thermal ionization mass spectrometer equipped with an ion-counting Daly detector. Pb isotopes were measured by peak-jumping all isotopes on the Daly detector for 100 to 160 cycles, and corrected for $0.15 \pm 0.03\%$ /a.m.u. (1 sigma error) mass fractionation. Transitory isobaric interferences due to high-molecular weight organics, particularly on ^{204}Pb and ^{207}Pb , disappeared within approximately 60 cycles, while ionization efficiency averaged 10^4 cps/pg of each Pb isotope. Linearity (to $\geq 1.4 \times 10^6$ cps) and the associated deadtime correction of the Daly detector were monitored by repeated analyses of NBS982, and have been constant since installation. Uranium was analyzed as UO_2^+ ions in static Faraday mode on 10^{11} ohm resistors for 300 cycles, and corrected for isobaric interference of $^{233}\text{U}^{18}\text{O}^{16}\text{O}$ on $^{235}\text{U}^{16}\text{O}^{16}\text{O}$ with an $^{18}\text{O}/^{16}\text{O}$ of 0.00206. Ionization efficiency averaged 20 mV/ng of each U isotope. U mass fractionation was corrected using the known $^{233}\text{U}/^{235}\text{U}$ ratio of the Boise State University tracer solution.

U-Pb dates and uncertainties were calculated using the algorithms of Schmitz and Schoene (2007), $^{235}\text{U}/^{205}\text{Pb}$ of 77.93 and $^{233}\text{U}/^{235}\text{U}$ of 1.007066 for the Boise State University tracer solution, and U decay constants recommended by Jaffey et al. (1971). $^{206}\text{Pb}/^{238}\text{U}$ ratios and dates were corrected for initial ^{230}Th disequilibrium using a $\text{Th}/\text{U}[\text{magma}] = 3.0 \pm 0.3$ using the algorithms of Crowley et al. (2007), resulting in an increase in the $^{206}\text{Pb}/^{238}\text{U}$ dates of ~ 0.09 Ma. All common Pb in analyses was attributed to laboratory blank and subtracted based on the measured laboratory Pb isotopic composition and associated uncertainty. U blanks are estimated at 0.07 pg.

A weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date was calculated from equivalent dates using Isoplot 3.0 (Ludwig, 2003). The error of ± 0.013 Ma on the weighted mean date is the internal error based on analytical uncertainties only, including counting statistics, subtraction of tracer solution, and blank and initial

common Pb subtraction. Including the tracer calibration uncertainty propagated in quadrature increases the error to ± 0.016 Ma. Including the the ^{238}U decay constant uncertainty propagated in quadrature increases the error to ± 0.023 Ma. Internal error should be considered when comparing our date with $^{206}\text{Pb}/^{238}\text{U}$ dates from other laboratories that used the same Boise State University tracer solution or a tracer solution that was cross-calibrated using EARTHTIME gravimetric standards. Error including the uncertainty in the tracer calibration should be considered when comparing our date with those derived from other geochronological methods using the U-Pb decay scheme (e.g., laser ablation ICPMS). Error including uncertainties in the tracer calibration and ^{238}U decay constant (Jaffey et al., 1971) should be considered when comparing our date with those derived from other decay schemes (e.g., $^{40}\text{Ar}/^{39}\text{Ar}$, ^{187}Re - ^{187}Os). Error for the weighted mean date and dates from individual grains are given at 2σ .

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Appendix II

Geochronological Methods

Pacific Centre for Isotope and Geochemical Research - UBC

$^{40}\text{Ar}/^{39}\text{Ar}$ data presented in Table 2 and Appendix III were generated using the following methodology. Each sample was crushed and sieved to obtain fragments ranging in the size range from 0.5 to 1 mm. A hand magnet was passed over the samples to remove magnetic minerals and metallic crusher fragments/spall. The samples were washed in deionized water, rinsed and then air-dried at room temperature.

Mineral separates were hand-picked, wrapped in aluminum foil and stacked in an irradiation capsule with similar-aged samples and neutron flux monitors (Fish Canyon Tuff sanidine; apparent age = 28.201 ± 0.023 Ma; 1σ , Kuiper et al., 2008); MAC-83 biotite, 2 (Sandeman et al. 1999). The decay constant used was $^{40}\text{K} \lambda_{\text{total}} = 5.463 \pm 0.214 \times 10^{-10}/\text{a}$ (2σ) from Min et al. (2000).

The samples were irradiated at the McMaster Nuclear Reactor in Hamilton, Ontario, for 72 MWH, with a neutron flux of approximately 3×10^{16} neutrons/cm². Analyses ($n=33$) of 11 neutron flux monitors irradiated with the samples produced errors of $<0.25\%$ in the J value (2σ).

The samples were analyzed at the Noble Gas Laboratory at the Pacific Centre for Isotopic and Geochemical Research, University of British Columbia. The separates were step-heated at incrementally higher powers in the defocused beam of a 10W CO₂ laser (New Wave Research MIR10) until fused. The gas evolved from each step was analyzed by a VG5400 mass spectrometer equipped with an ion-counting electron multiplier. All measurements were corrected for total system blank, mass spectrometer sensitivity, mass discrimination, radioactive decay during and subsequent to irradiation, as well as interfering Ar from atmospheric contamination and the irradiation of Ca, Cl and K. The plateau and correlation ages were calculated using Isoplot ver.3.09 (Ludwig 2003). Errors are quoted at the 2-sigma (95% confidence) level and are propagated from all sources except mass spectrometer sensitivity and age of the flux monitor. The term plateau age is defined as an age based on at least three

consecutive steps that are within 2σ error of each other, and together comprise at least 60% of the released ^{39}Ar for the aliquot.

Geological Survey of Canada - Ottawa

Selected samples were processed for $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of muscovite by standard preparation techniques, including hand-picking of unaltered grains in the size range 0.25 to 0.50 mm. Individual mineral separates were loaded into aluminum foil packets along with grains of Fish Canyon Tuff Sanidine (FCT-SAN) to act as flux monitor (apparent age = 28.201 ± 0.023 Ma; 1σ , Kuiper et al., 2008). The sample packets were arranged radially inside an aluminum can. The samples were submitted for a 60 MWh irradiation in high flux position 5c at the research reactor of McMaster University in Hamilton, Ontario, Canada.

Laser $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating analysis was carried out at the Geological Survey of Canada geochronology laboratories in Ottawa, Ontario. Upon return from the reactor, the sample was loaded into a 1.5 mm-diameter hole in a copper planchet. The planchet was then placed in the extraction line and the system evacuated. Heating of individual sample aliquots in steps of increasing temperature was achieved using a Merchantek MIR10 10W CO_2 laser equipped with a 2 mm x 2 mm flat-field lens. The released Ar gas was cleaned in the extractions line over two hot SAESTM NP-10 getters of St 707 alloy (Zr-V-Fe) held at $\sim 400^\circ\text{C}$ (to remove nitrogen, oxygen, hydrocarbons, water and other active gases) and a room-temperature getter containing HY-STOR[®] 201 calcium-nickel alloy pellets (to remove hydrogen), and then analyzed isotopically using a Nu Instruments Noblesse noble gas mass spectrometer, equipped with a Faraday detector and three ion counters. For the analyses, a single ion counter peak-hopping mode was used for small signals, ('SC' mode as described in Kellett and Joyce, 2014) and in cases where the ^{40}Ar signal exceeded ion counting tolerance, a Faraday plus single ion counter peak-hopping routine was employed (^{38}Ar was not measured for these runs) Baselines were measured prior to each analysis. Blank measurements were made throughout the analytical sessions, the values for which are included in Appendix II. Mass fractionation and detector efficiencies were determined from repeated measurements of air aliquots, whereby ^{40}Ar and ^{36}Ar signals were measured on all collectors. The efficiency of the IC0 ion counter used in the measurements was determined to be $0.9359 \pm 0.006\%$ (1σ) relative to the Faraday collector. Deadtime of the IC0 collector was 20 ns. $^{40}\text{Ar}/^{36}\text{Ar}$ ratios were then determined for each collector individually, and for each combination of collectors (ex. ^{40}Ar on the Faraday/ ^{36}Ar on each ion counter). Raw data from the mass spectrometer was imported and processed

using in-house Excel® data handling macros that employ average, linear or non-linear regression protocols based on the equations of Koppers (2002).

Error analysis on individual steps follows numerical error analysis routines outlined in Scaillet (2000) and error analysis on grouped data follows algebraic methods of Roddick (1988). Corrected argon isotopic data are listed in Appendix II, and presented (Figure 9g) as a spectrum of gas release and inverse-isochron plot (Roddick et al. 1980).

Neutron flux gradients throughout the sample canister were evaluated by analyzing the sanidine flux monitors included with each sample packet and interpolating a linear fit against calculated J-factor and sample position. The error on individual J-factor values is conservatively estimated at $\pm 0.6\%$ (2σ). Because the error associated with the J-factor is systematic and not related to individual analyses, correction for this uncertainty is not applied until calculation of dates from isotopic correlation diagrams (Roddick 1988). The decay constant used was $^{40}\text{K } \lambda_{\text{total}} = 5.463 \pm 0.214 \times 10^{-10}/\text{a}$ (2σ) from Min et al. (2000). Nucleogenic interference corrections were $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.025 \pm 0.005$, $(^{38}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.011 \pm 0.010$, $(^{40}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.002 \pm 0.002$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.00068 \pm 0.00004$, $(^{38}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.00003 \pm 0.00003$, $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.00028 \pm 0.00016$. MSWD is defined as the mean square of weighted deviates. All errors are quoted at the 2σ level of uncertainty.

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Draft

Figure 1

Figure 2

INTRUSIVE ROCKS**MIOCENE***Wrangell Suite***MW**

fine to medium-grained, hornblende-biotite-pyroxene diorite; fine to medium-grained hornblende-biotite granodiorite to quartz monzonite occurring as dykes

EARLY CRETACEOUS*Pyroxenite Creek Suite***EKP**

medium-grained pyroxene +/- hornblende gabbro, and biotite-hornblende diorite; green medium-grained, foliated, pyroxene-epidote gabbro

EKP2

dark green to black pyroxene gabbro and pyroxenite

DEVONIAN*Steele Creek Suite***DSC**

green to purple medium- to coarse-grained hornblende-pyroxene gabbro that is locally highly altered

LAYERED ROCKS**MIOCENE***Wrangell volcanics***NW**

dark grey to black, fine-grained amygdaloidal basalt

NW2

biege, fine-grained crystal-lithic tuff

WRANGELLIA**TRIASSIC***Chitistone limestone***uTC**

grey massive limestone

*Skolai Group***PERMIAN-PENNSYLVANIAN***Hasen Creek Formation***PHc**

light grey to brown, calcareous, fossiliferous packstone; medium-grained litharenite sandstone grades into a poorly bedded pebble conglomerate with coarse-grained sandstone interbeds; light to medium grey, massive to bedded limestone; dark grey, thin-bedded siltstone

PHc2

light grey, laminated to massive limestone

PHc3

green and maroon boulder conglomerate dominated by well-rounded clasts of gabbro and diorite; locally maroon volcanic breccia with a sandy matrix

MISSISSIPPIAN TO PENNSYLVANIAN*Station Creek Formation***MPsv**

laminated to thinly bedded, light grey to light green volcanic tuff and volcanoclastic siltstone; local crystal-rich tuff interbedded with fine-grained volcanic ash

MPsb

interbedded volcanic breccia, agglomerate and volcanoclastic sandstone dominated by pyroxene-phyric volcanic breccia; rare light grey-weathered, dark green to black, pyroxene-phyric basalt flows

ALEXANDER TERRANE**DEVONIAN TO TRIASSIC***Icefield assemblage: Silver Creek member***DTN8**

dark grey to black, fine-grained, calcareous siltstone; brown to grey, thin-bedded chert; rare crinoidal limestone

DTN7

green and maroon, foliated conglomerate that grades upwards into maroon, medium-grained sandstone

*Icefield assemblage***DTI6**

light grey to white, massive marble

DTN4b

undifferentiated calcareous and carbonaceous siltstone; fine to medium-grained chlorite schist; grey banded limestone to marble

DTI4

massive to thin-bedded limestone and marble; calcareous siltstone

DTI3

dark grey, fine-grained, locally amygdaloidal, plagioclase-phyric basalt; green, volcanic breccia made up of basalt clasts; rare biege crystal tuff

DTI2

dark grey, thin-bedded, calcareous and carbonaceous siltstone and phyllite; carbonaceous, calcareous, feldspar-muscovite-quartz schist to phyllite; rare muscovite-rich quartzite

DTI1

light green, fine-grained feldspar-quartz (?) schist and phyllite; very fine grained phyllonite; fine-grained, calcareous, muscovite-feldspar +/- quartz schist and phyllite; fine-grained, carbonaceous muscovite-feldspar schist and carbonaceous quartz-muscovite schist

SILURIAN TO DEVONIAN*Bullion assemblage***SDB**

light grey, massive to well-bedded limestone or marble, dark grey, thin-bedded limestone or marble; minor dark blue-grey calcareous argillite or phyllite

ORDOVICIAN*Donjek formation***COD**

grey, laminated marble

COD1

dark green, fine to medium-grained basalt; basalt breccia

geologic contacts

(defined, approximate, inferred).....

fault (movement not known).....

thrust fault (defined, approximate).....

mapping limit.....

fold axial surface trace (upright - anticline, syncline; overturned anticline, syncline).....

lineation (elongation).....

crenulation lineation.....

fold axis (dominant phase).....

bedding.....

foliation (dominant).....

vein.....

fault plane.....

isotopic and fossil age sample locations
(U-Pb, Ar/Ar, fossil).....

cross section line.....

field station.....

Figure 3

<https://mc06.manuscriptcentral.com/cjes-pubs>

Figure 4

Figure 5

Hasen Creek Formation

- PHc** grey-brown, fine-grained sandstone interbedded with medium- to coarse-grained sandstone; locally contains beds of conglomerate

Station Creek Formation

- MPsv** laminated to thinly bedded, dark-grey to green volcanic tuff and volcanoclastic siltstone
- MPSb** dark green, fine-grained basalt; rare pillow basalt

Steele Creek Suite

- DSC** massive, locally foliated, grey-green hornblende-pyroxene gabbro; minor medium-grained gabbro diabase; locally leucocratic gabbro

Bullion assemblage

- SDB** fine-grained, carbonaceous mica schist; fine- to medium-grained greenschist; thin-bedded marble; muscovite-bearing quartzite

Figure 6.

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12