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Tectonics of the Intermontane and Insular terranes, and development of Mesozoic synorogenic basins in southern Yukon: Carmacks to Kluane Lake

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INTRODUCTION

This three-day geological excursion across southwestern Yukon will examine the geology of the Intermontane and Insular terranes, and of synorogenic sedimentary basins that developed during Mesozoic terrane accretion in the northern Canadian Cordillera (Fig. A1). The trip will take us from the rolling hills of the Yukon Plateau in central Yukon, through the Coast Mountains, and end in the rugged Kluane Ranges, at the front of the St. Elias Mountains in southwest Yukon (Fig. A2). The selected roadside exposures we will visit will provide the backdrop for discussion of models of Cordilleran evolution and the mineral and hydrocarbon resources of Yukon. We present brief overviews in this guidebook; for more in depth recent syntheses the reader is referred to Nelson *et al.* (2013), Israel *et al.* (2014), and Colpron *et al.* (2015).

The 1:500 000-scale geological map for part of southwest Yukon provided with this guidebook (Plate 1) is derived from the online Digital Bedrock Geology database of the Yukon Geological Survey (http://www.geology.gov.yk.ca/update_yukon_bedrock_geology_map.html). Map units are described in the full legend for the Yukon Bedrock Geology map (Colpron *et al.*, 2016; http://ygsftp.gov.yk.ca/publications/openfile/2016/OF2016-1.zip). The PDF version of the geological map is georeferenced and the user is encouraged to view this map and follow the field trip route with the free Avenza PDF Maps app for smartphones and tablets with GPS (http://www.avenza.com/pdf-maps).

Structure of this guidebook

This guidebook begins with a brief introduction to northern Cordilleran geology and tectonics. Details of the geology of the accreted terranes and major crustal structures are further elaborated in the introduction to each segment of the field trip (Days 1-3). Parts of this guidebook are adapted from previous field guides by Johnston *et al.* (1993) and Colpron *et al.* (2007a). The tectonic and paleogeographic evolution of the northern Cordilleran terranes, and their bearing on metallogeny, are considered in the review paper by Nelson *et al.* (2013).

Regional geological overview

Within the northern Cordillera, Proterozoic to Triassic miogeoclinal, mainly sedimentary, platformal to basinal strata of the western Laurentian continental margin (NAp and NAb on Figure A1) extend into eastern British Columbia, Yukon and east-central Alaska. Farther west, most of British Columbia, Yukon and Alaska are made up of Paleozoic to Mesozoic volcanic, plutonic, sedimentary and metamorphic assemblages that represent magmatic arcs, microcontinents and ocean basins accreted to western Laurentia in Mesozoic and younger time. These, along with the parautochthonous deformed belt and the undisturbed platform of western Canada, are overlain by syn and post-accretionary clastic deposits. The western and inner parts of the orogen are pierced by post-accretionary plutons and in places overlain by thick accumulations of relatively young volcanic strata.

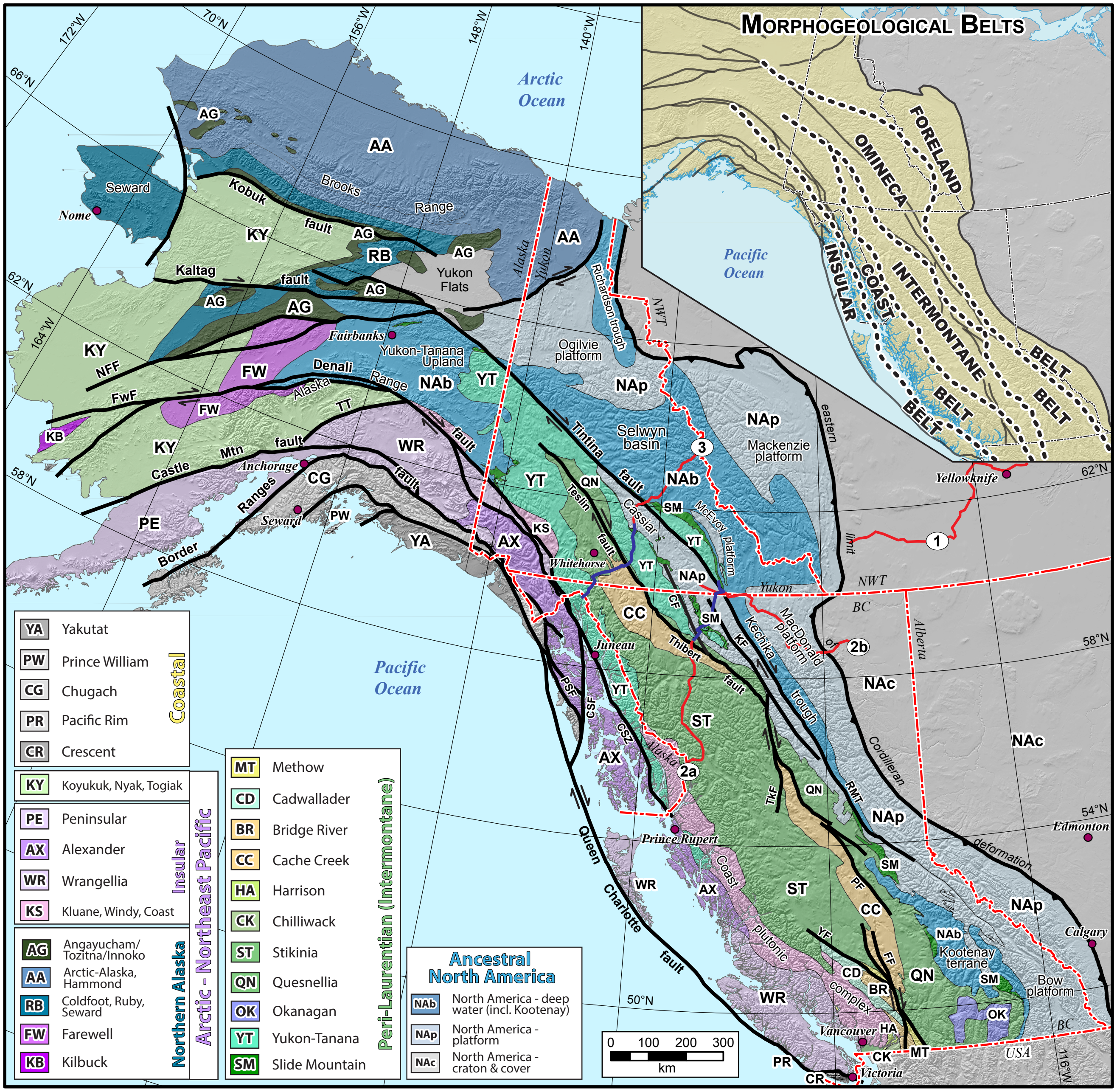


Figure A1. *Terranes of the Canadian-Alaskan Cordillera (after Colpron and Nelson, 2011a). Terranes are grouped in the legend according to paleogeographic affinities shown in Figure A3. Inset shows morphogeological belts of the northern Cordillera after Gabrielse et al. (1991). Red and blue lines overlain on the terrane map show approximate locations of Lithoprobe SNORCLE seismic transects (lines 1, 2a, 2b and 3; Cook et al., 2004); blue segments correspond to part of lines 2a and 3 reproduced in Fig. A4. Fault abbreviations: CF – Cassiar fault; CSF – Chatham Strait fault; FF – Fraser fault; FwF – Farewell fault; KF – Kechika fault; NFF – Nixon Fork-Iditarod fault; PF – Pinchi fault; PSF – Peril Strait fault; NMRT – northern Rocky Mountain trench; TkF – Takla-Finlay-Ingenika fault system; TT – Talkeetna thrust; YF – Yalakom fault.*

Figure A2. *Physiographic map of northern B.C., Yukon and eastern Alaska. HJ = Haines Junction; LP = Liard Plain. Shaded relief base map is from Amante and Eakins (2009).*

Although the northern Cordillera has been subdivided into a multiplicity of terranes (cf. Coney *et al.*, 1980; Wheeler *et al.*, 1991; Colpron and Nelson, 2011a, Fig. A1), it can be viewed more globally as consisting of four first-order tectonic entities (Fig. A3):

1) Ancestral North America (western Laurentia), including the Yukon-Tanana upland, Alaska Range, Cassiar Terrane and Kootenay Terrane – the autochthonous and parauthochthonous western Laurentian realm;

2) the allochthonous marginal pericratonic terranes (Intermontane terranes) – the peri-Laurentian realm;

3) the Insular and Northern Alaska terranes, which evolved in the Arctic and NE Pacific realms in Paleozoic time; and

4) Mesozoic and younger arc and accretionary terranes that form a western and southern outer fringe to the older elements – the Coastal realm in Figure A3.

Ancestral North America (Laurentia) includes the western craton margin, the miogeocline with its platforms and basins and its fringing, parautochthonous terranes (Cassiar, Kootenay, Selwyn basin; Fig. A1). Until recently, metamorphic rocks of the Yukon-Tanana upland and Alaska Range in east-central Alaska were considered a part of the allochthonous Yukon-Tanana terrane (see below); they are now interpreted as part of the parautochthonous Laurentian continental margin (Dusel-Bacon *et al.*, 2006; Nelson *et al.*, 2006). The western, outboard boundary of this autochthonous to parautochthonous belt is marked by discontinuous slivers and slices of the Slide Mountain oceanic terrane. These rocks were formed in a marginal rift basin of Late Devonian to Permian age that once lay between the continent and a belt of rifted pericratonic fragments upon which successive Devonian through Jurassic arcs were formed (Yukon-Tanana terrane, Quesnellia and Stikinia; Colpron *et al.*, 2006a; Nelson *et al.*, 2006, 2013). The belt of pericratonic terranes was originally bounded on its outer, oceanward margin by an accretionary complex, the Cache Creek terrane that includes slivers of high-pressure/low-temperature metamorphic assemblages, as well as blocks of limestone with exotic Permian fusulinid and coral faunas of Tethyan (Asian) affinity (Ross and Ross, 1983). The present position of the exotically derived Cache Creek terrane, enclosed within the pericratonic belt, is a constructional anomaly that may be best explained by oroclinal enclosure that developed as the Intermontane terranes amalgamated and accreted to the continent in Jurassic time (Mihalynuk *et al.*, 1994).

Monger *et al.* (1982) defined the Intermontane Superterrane as a collage of many of the peri-Laurentian and oceanic terranes that amalgamated during Triassic-Jurassic accretion. Colpron *et al.* (2007b) describe initial and ongoing relationships that span the entire period of the existence of these terranes. The first half of this field trip will focus primarily on the Intermontane terranes (Fig. A1) and examine sedimentary basins and plutonic belts that characterized the Mesozoic development of the northern Cordilleran orogen.

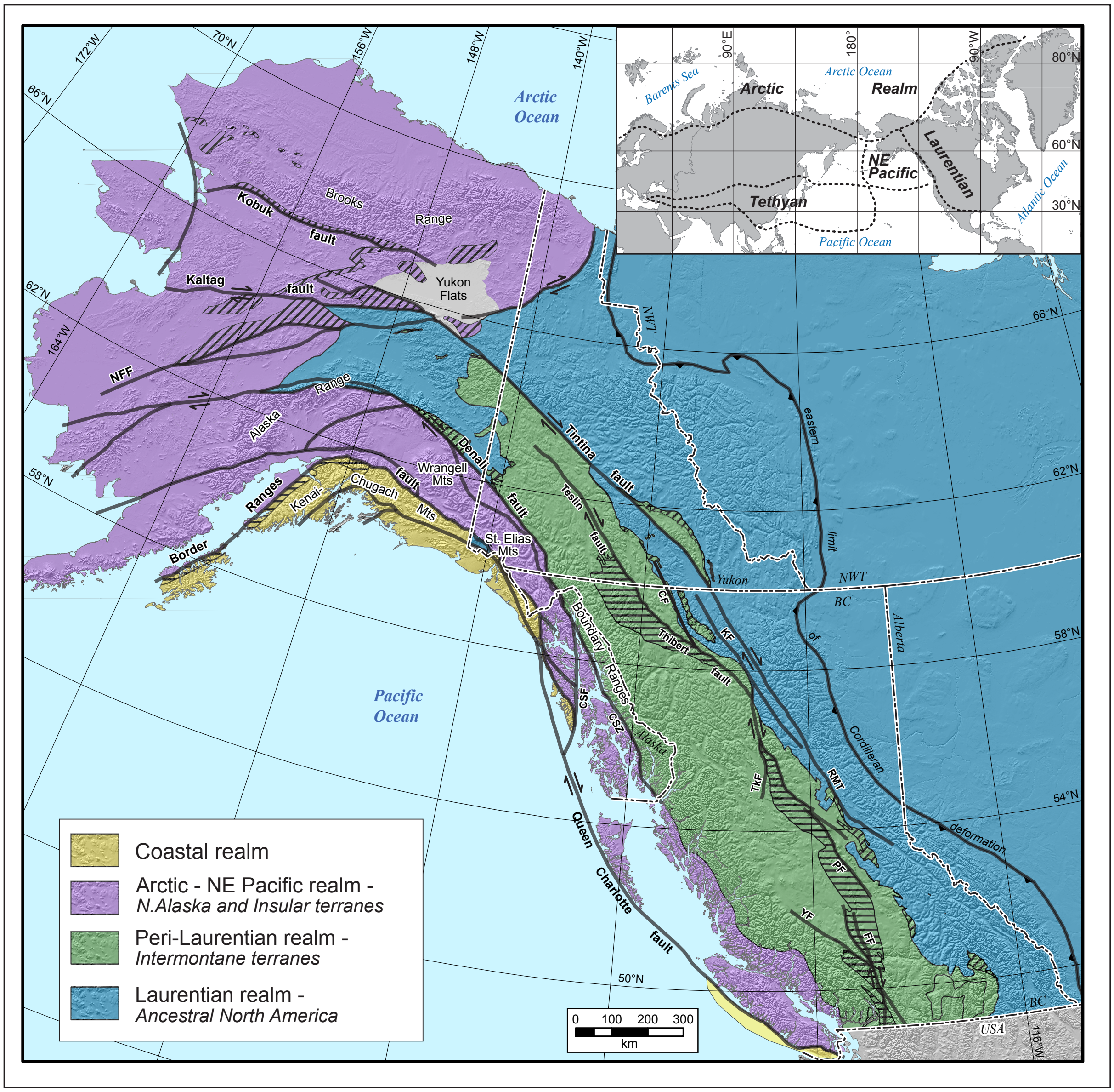


Figure A3. *Cordilleran terranes grouped by paleogeographic affinities (after Nelson et al., 2013). Paleogeographic affinity is assigned according to region of origin in Paleozoic time, except for the Coastal terranes, which originated along the late Mesozoic-Cenozoic eastern Pacific plate margin. Inset shows the main distribution of Paleozoic paleogeographic realms in the circum-Pacific region. Diagonal hatching indicates oceanic terranes in the peri-Laurentian and Arctic realms; horizontal hatching indicates accretionary complex containing elements of Tethyan affinity (e.g. Cache Creek terrane). Fault abbreviations: CF – Cassiar fault; CSF – Chatham Strait fault; FF – Fraser fault; KF – Kechika fault; NFF – Nixon Fork-Iditarod fault; PF – Pinchi fault; NMRT – northern Rocky Mountain trench; TkF – Takla-Finlay-Ingenika fault system; YF – Yalakom fault.*

In fundamental contrast to the Intermontane terranes, the Insular terranes (Wrangellia and Alexander; Insular Superterrane of Monger *et al.*, 1982; and the Peninsular terrane of southwestern Alaska; Plafker *et al.*, 1989a) and the Farewell terrane of central Alaska (Bradley *et al.*, 2003), although in part long-lived (Precambrian to Triassic) and in part of pericratonic origin, show no evidence of early relationships to the western margin of Laurentia. Instead, their early faunal and isotopic affinities are consistently with Siberia and Baltica (Bazard *et al.*, 1995; Nokleberg *et al.*, 2000; Bradley *et al.*, 2003; Colpron and Nelson, 2009). The Arctic-Alaska terrane appears to comprise Neoproterozoic-early Paleozoic continental to pericratonic crustal elements with affinities to Baltica, the northern Caledonides or northern Laurentia that were amalgamated by the Carboniferous (Moore *et al.*, 1994; Miller *et al.*, 2011; Strauss *et al.*, 2013; Till *et al.*, 2014). It bears stratigraphic similarities to the Chukotka peninsula of the Russian Far East (Patrick and McClelland, 1995; Till *et al.*, 2014); Miller *et al.* (2006) proposed that Arctic-Alaska and Chukotka were contiguous throughout most of their history and displaced and/or rotated into their current position in Cretaceous time. More recently Till *et al.* (2014) favour a model where Chukotka and Arctic Alaska evolved separately until their Early Cretaceous (Aptian) assembly. Together, the Insular, Farewell and Arctic-Alaska terranes constitute an original set of mobile to detached crustal fragments, along with subsequent Paleozoic and Mesozoic arcs and basins, which developed mainly within the Arctic realm (Colpron and Nelson, 2009, 2011b): they are referred to here collectively as the Northern Alaska/Insular terranes (Figs. A1 and A3). We will end the second day of this this field trip in the Insular terranes at Kluane Lake, facing the majestic Kluane Ranges. On the third and last day, we will further explore the relationship between Alexander terrane and Wrangellia, and the overlapping Dezadeash sedimentary basin with two short hikes into the front of the Kluane Ranges.

The outermost belt of terranes contains relatively young, Mesozoic to Paleogene assemblages, including the accreted Koyukuk arc in western Alaska; the Paleocene-Eocene seamounts of the Crescent terrane; and the Chugach, Prince Williams, Pacific Rim and Yakutat terranes, which are accretionary complexes dominated by trench sediments. These arc and accretionary assemblages developed within the eastern Pacific realm near or on the developing Cordilleran margin. Monger and Nokleberg (1996) interpret them as paired accretionary prism-arc belts; the reader is referred to their work for a clear and useful synthesis. We will not see this group of terranes on this field trip.

Crustal structure

Terranes of the northern Canadian Cordillera were emplaced to their current positions, above the western edge of the ancestral North American craton, during Mesozoic to early Cenozoic orogenesis. From Jurassic to Early Cretaceous time, the accreted terranes were mainly converging (most likely obliquely) with western North America (cf. Nelson *et al.*, 2013). By mid-Cretaceous, the deformation was dominated by transcurrent faulting, predominantly dextral in the interior of the orogen and sinistral along the coast, leading to the suggestion of northwest escape of the Intermontane region at that time (Nelson *et al.*, 2013; Angen *et al.*, 2014; Staples *et al.*, 2016). By the Eocene dextral strike-slip became dominant along a few large faults in the northern Cordillera and accompanied by transtension in the south (Price and Carmichael, 1986). As a result, the crustal structure of the northern Canadian Cordillera, as imaged on SNORCLE seismic transects (Fig. A4), is one of a thin-skinned thrust belt, dissected by a few crust-penetrating transcurrent faults (Cook *et al.*, 2004). Prominent features in the SNORCLE seismic reflection profiles are:

1. fairly flat, well-defined Mohorovicic discontinuity (sharp decrease in reflectivity) at approximately 12 sec (35-40 km; Fig. A4);
2. westward-tapering layering (zero edge below Alaska border; Fig. A4) that is interpreted as Proterozoic rocks of ancestral North American affinity (LCLS in Fig. A4), but for which details of interpretation are controversial (see below);
3. eastward-tapering wedge of upper Proterozoic and Paleozoic parautochthonous strata of ancestral North American affinity (including Cassiar platform, Selwyn basin, and the northern Rocky Mountains) – the Laurentian miogeocline;
4. the accreted terranes are typically less than 15 km thick (<4-5 sec) and commonly only a few kilometres thick (~1 sec);
5. Stikinia (and its pericratonic roots – labeled Nisling terrane in Fig. A4) is a notable exception; its entire lithosphere appears to be juxtaposed against the western edge of ancestral North America (see Fig. A4; and Foldout 3 in Cook *et al.*, 2004); and
6. the mantle is generally devoid of reflections, with the exception of a series of well-defined, east-dipping reflectors at the west end of Line 3 (16-20 sec in Fig. A4) that are interpreted as a relict subduction surface of the Kula plate (Cook *et al.*, 2004).

The strong, westward-tapering middle- to lower-crustal layering (LCLS in Fig. A4) has been variably interpreted as 1) a sedimentary prism of Proterozoic strata (~1.8-0.7 Ga; Mackenzie Mountains Supergroup, Muskwa assemblage and Wernecke Supergroup; Snyder *et al.*, 2002; Cook *et al.*, 2004); or 2) a westward-tapering wedge of crystalline basement (~1.8 Ga and older; Evenchick *et al.*, 2005).

The thin-skinned nature of the accreted terranes imaged in seismic-reflection profiles confirms inferences of the crustal structure as derived from geological mapping (a prominent example is the Sylvester allochthon in northern BC; Nelson, 1993; see also the map of the Finlayson Lake area by Murphy *et al.*, 2001). It is also corroborated by a more recent seismic-reflection survey acquired along the Robert Campbell Highway, approximately 200 km north of the Alaska Highway (White *et al.*, 2012; to be discussed on Day 1). It is important to remember that many of the terranes that are interpreted to be only a few kilometres thick at present (*e.g.*, Yukon-Tanana terrane, Fig. A4) have been moderately to deeply exhumed since their accretion in early Mesozoic time. In places,

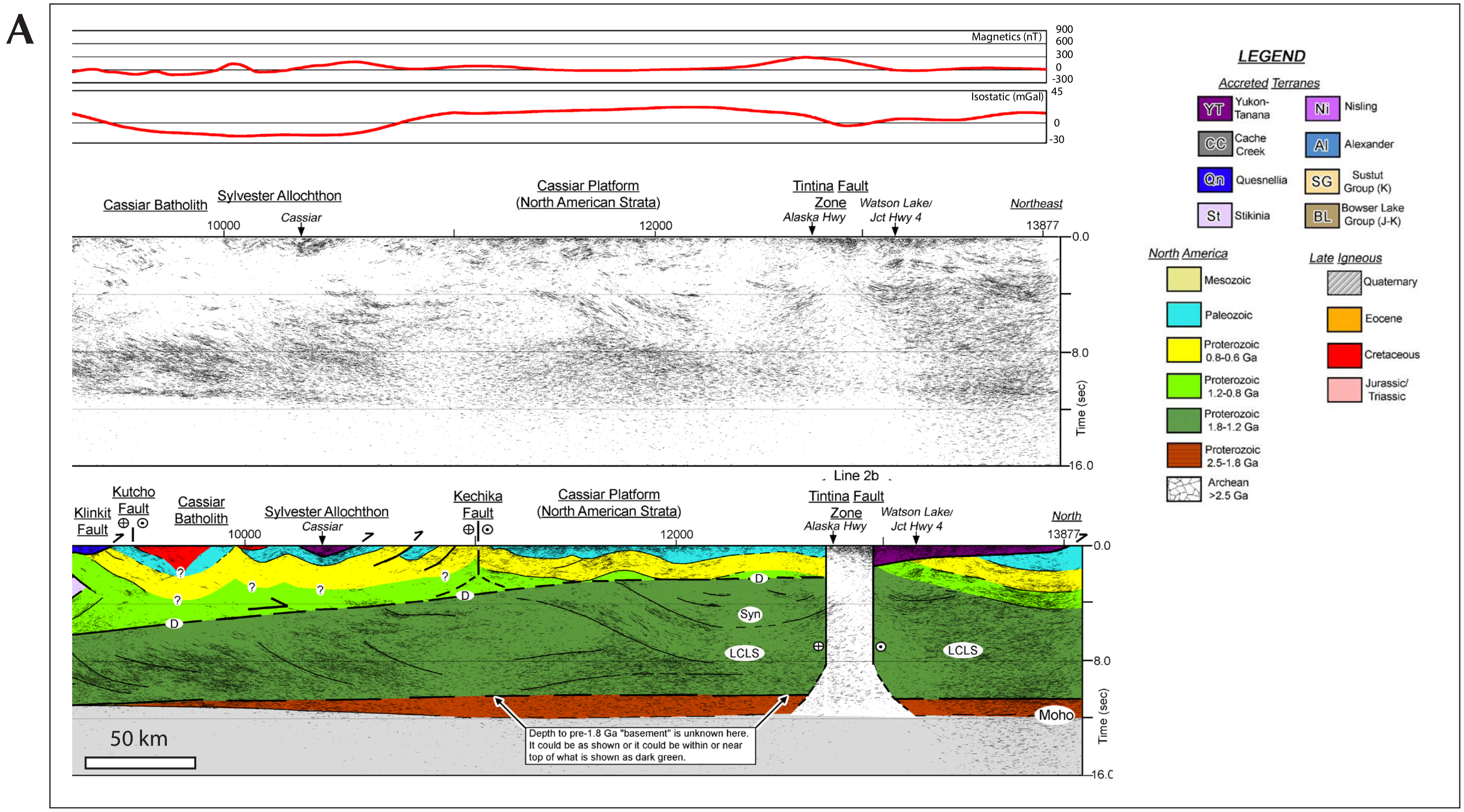
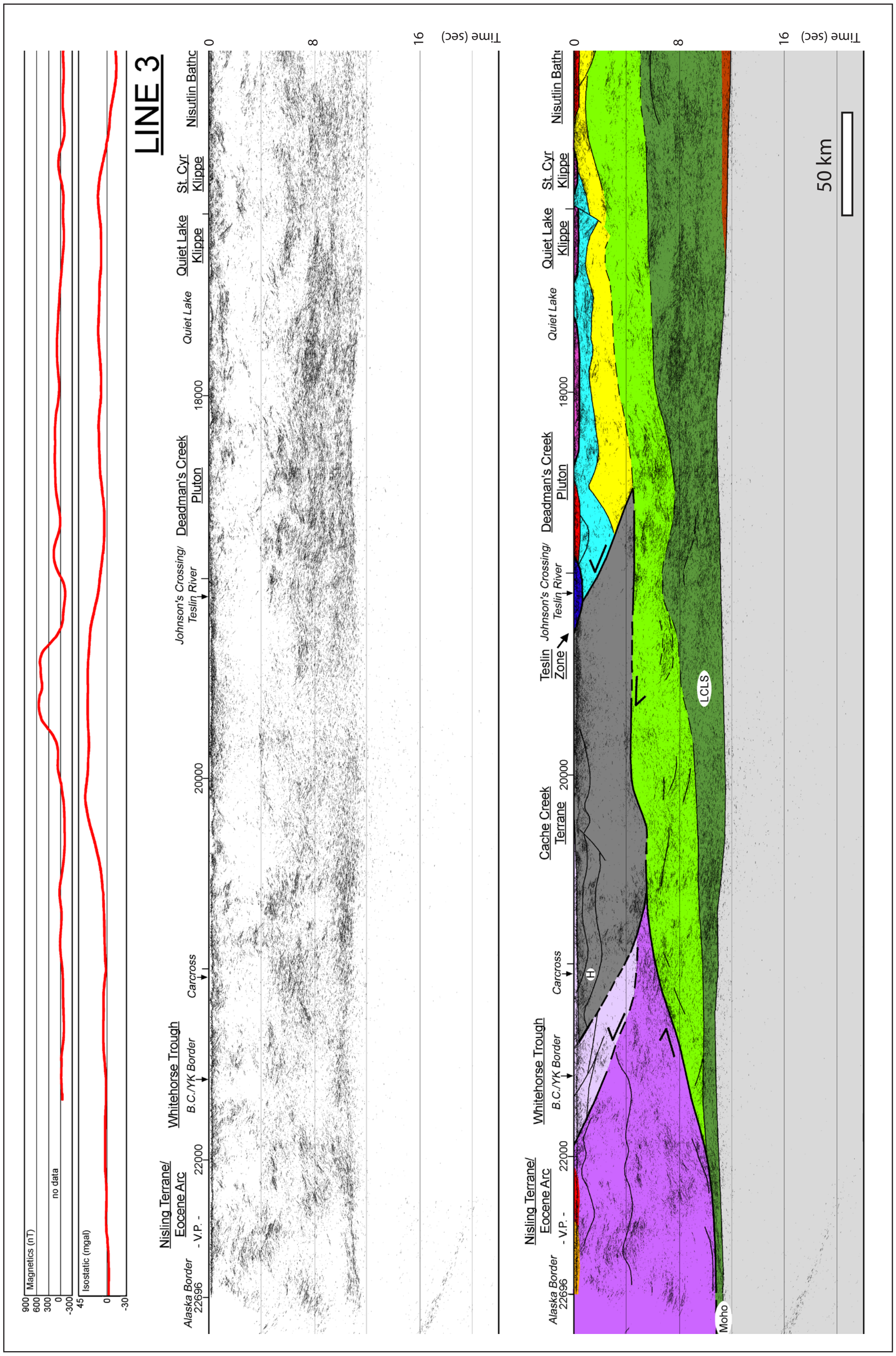


Figure A4. *A) Part of SNORCLE line 2a seismic transect along the Cassiar Highway (Cook et al., 2004). B) Part of SNORCLE line 3 seismic transect along South Canol road, part of the Alaska Highway, the Tagish road, and the South Klondike Highway (Cook et al., 2004). See Fig. A1 for approximate locations of these transects.*


LINE 3
Magnetics (nT)
900
600
300
0
-300
no data
Isostatic (mgal)
45
0
-30
Alaska Border
22696
- V.P. -
Nisling Terrane/
Eocene Arc
22000
Whitehorse Trough
B.C./YK Border
Carcross
Cache Creek
Terrane
20000
Teslin
Zone
Johnson's Crossing/
Teslin River
Deadman's Creek
Pluton
18000
Quiet Lake
Quiet Lake
Klippe
St. Cyr
Klippe
Nisutlin Batho
Time (sec)
0
8
16
H
LCLS
Moho
50 km

B

more than 15-20 km of rocks were removed by tectonic processes and/or erosion. Evidence for this lies in part in the rapid unroofing of Early Jurassic batholiths intruding the Yukon-Tanana terrane (*e.g.*, Aishihik, Granite Mountain and Tatchun batholiths; Johnston and Erdmer, 1995; Johnston *et al.*, 1996a; Colpron *et al.*, 2003) and in the widespread Early Jurassic mica cooling ages of surrounding metamorphic rocks (Fig. A5; Breitsprecher and Mortensen, 2004; Knight *et al.*, 2013; Joyce *et al.*, 2015; Colpron *et al.*, 2015). Recent work by Staples *et al.* (2013, 2014, 2016) related episodic and diachronous deformation, metamorphism and exhumation in Yukon to growth of the northern Cordilleran orogenic wedge and its subsequent collapse as a result of mid-Cretaceous extrusion.

The surface structures across the northern Cordilleran orogen vary from east-verging, thrust-and-fold structures in the northern Rockies and Cassiar Mountains, to recumbent, polyphase folds and ductile shear zones in the Yukon-Tanana terrane, and to west-verging thrust-and-fold structures in Quesnellia, Stikinia and Cache Creek terrane (Fig. A4; Cook *et al.*, 2004; Colpron, 2011; White *et al.*, 2012). The axis of this regional zone of structural divergence occurs in the eastern Yukon-Tanana terrane. The pattern of west-verging (or, at least, east-dipping) structures persists into southwestern Yukon to the Denali fault (*e.g.*, Johnston and Canil, 2007; Fig. A4).

Evidence for development of pre-accretionary structures is locally well-preserved in the Yukon-Tanana terrane. Deformational episodes of Devonian, late Early Mississippian, Pennsylvanian and Late Permian ages have been documented (Colpron *et al.*, 2006a,b; Murphy *et al.*, 2006; Mackenzie *et al.*, 2007; Berman *et al.*, 2007; Beranek and Mortensen, 2011). At least the Mississippian and Permian episodes appear to be of regional extent.

Dextral transcurrent faults and the Cordilleran paleomagnetic dilemma

The Canadian Cordillera is dissected by a series of late Early Cretaceous to Cenozoic, orogen-parallel, dextral strike-slip faults (Fig. A6; Gabrielse, 1985; Gabrielse *et al.*, 2006). The younger faults (mainly Eocene in age) are the most obvious as they correspond to well-defined morphogeological trenches; prominent examples being the Tintina-Northern Rocky Mountain Trench (NRMT), underlain by the fault of the same name, and the Shakwak Trench in southwest Yukon, which is underlain by the Denali fault (Fig. A2). The Tintina fault has a well-constrained post-Late Cretaceous dextral displacement of 400-430 km (Gabrielse *et al.*, 2006; see below for further description of the Tintina-NRMT fault). Eocene strike-slip displacement along the Tintina fault in the northern Cordillera was likely kinematically linked with widespread extension and exhumation of metamorphic core complexes in the southern Canadian Cordillera (Price and Carmichael, 1986). Eocene (to recent) dextral displacement on the Denali fault is not as well constrained but estimated at ~370 km (Lowey, 1998). The Denali fault will be further discussed at the end of Day 2 (Stop 2-6).

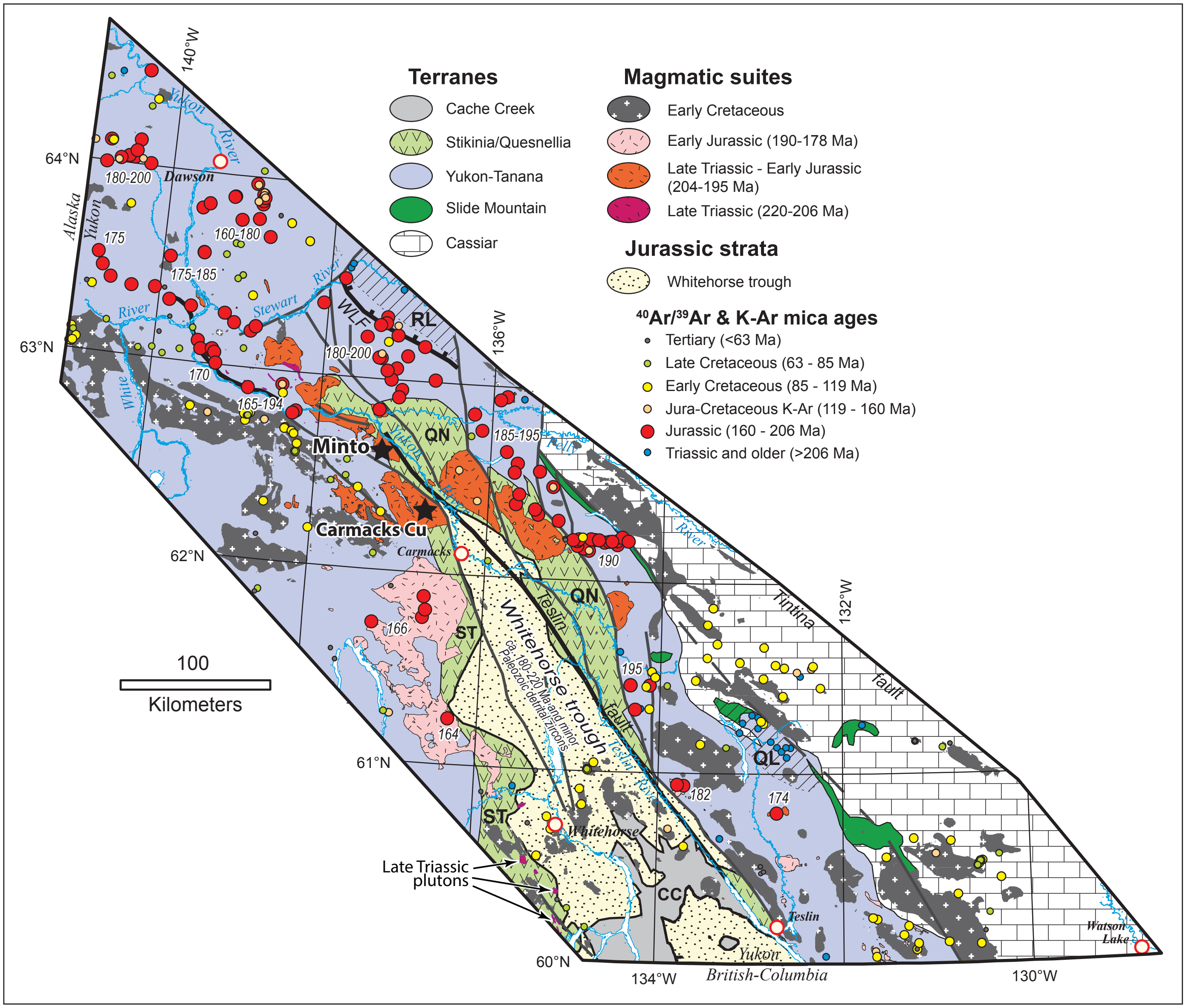


__Figure A5.__ Late Triassic – Early Jurassic elements of the Intermontane terranes in Yukon (after Colpron et al., 2015). Upper Triassic arc volcanic rocks and Late Triassic-Early Jurassic plutons of Stikinia (ST) and Quesnellia (QN) converge north of Carmacks and are enveloped by metamorphosed Paleozoic rocks of Yukon-Tanana terrane to the northwest. The Cache Creek terrane (CC) terminates near the latitude of Whitehorse, and Stikina and Quesnellia are separated by the Teslin fault along strike to the northwest. Mica cooling ages from the Yukon-Tanana terrane are predominantly ca. 200-180 Ma (emphasized with red dots) indicating that most of the terrane had exhumed to upper crustal levels (<300°C) by the Early Jurassic (sources: Breitsprecher and Mortensen, 2004; Knight __et al.__, 2013; Joyce __et al.__, 2015). Ranges for clusters of Jurassic ages are indicated. Distribution of Lower to Middle Jurassic clastic sedimentary strata of the Laberge Group (Whitehorse trough) is shown in yellow. The location of Early Jurassic copper mineralization at Minto and Carmacks Copper is shown by black stars. Note that Cretaceous and younger mica ages are typically near plutons or volcanic rocks of similar ages. Also note the occurrences of two domains in Yukon-Tanana terrane that were exhumed in the late Paleozoic (hatched regions): RL – Reid Lakes domain (Mississippian cooling); and QL – Quiet Lake domain (Late Permian-Triassic). WLF – Willow Lake fault.

The late Early Cretaceous transcurrent faults form a complex array of linked faults (as opposed to a few well-defined large Eocene faults) and are typically associated with voluminous syn-tectonic magmatism (Gabrielse *et al.*, 2006). These include the Kechika, Kutcho, Thibert and Teslin faults, and related splays such as the Cassiar, Big Salmon and d'Abbadie faults (Fig. A6). Prior to Eocene displacement on the Tintina fault, the late Early Cretaceous faults likely constituted a series of linear strike-slip faults which connected northward with a broad zone of extension and voluminous magmatism in southeast Yukon and northwesterly directed thrust faults (Tombstone and Robert Service faults) in western Yukon (Gabrielse *et al.*, 2006; Nelson *et al.*, 2013; Fig. A7). The NRMT fault was also likely the locus of Early Cretaceous displacement, although the total amount of offset is uncertain (Gabrielse, 1985). A coeval set of sinistral strike-slip faults (including the Grenville Channel, Tchaikazan and Pasayten faults; Figs. A6 and A7) bound the Intermontane belt to the west (see Angen *et al.*, 2014). The overall post-accretion northward translation (and extrusion) of the Intermontane terranes by dextral strike-slip faults, mainly in Cretaceous and younger times, is geologically constrained to be on the order of 860 km (Gabrielse *et al.*, 2006).

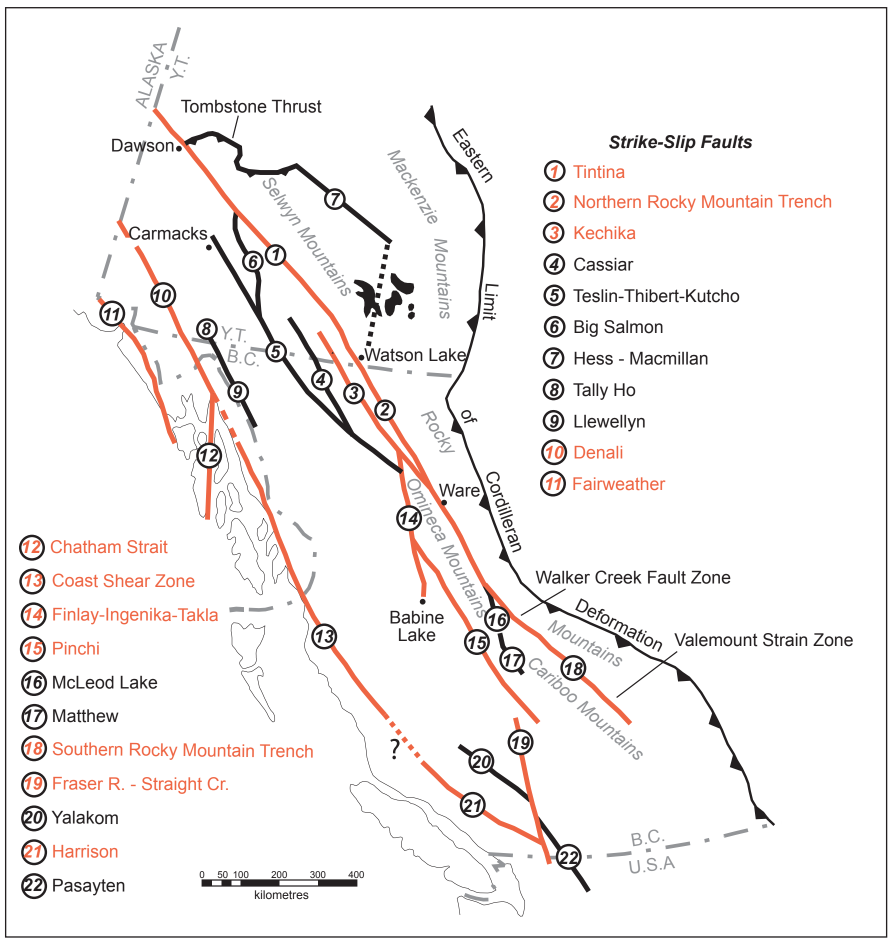


Figure A6. *Major transcurrent faults of the Canadian Cordillera (after Gabrielse et al., 2006). Faults with inferred Eocene displacement are shown in orange. Black areas north of Watson Lake represents voluminous mid-Cretaceous plutons inferred to be emplaced in a zone of late Early Cretaceous extension (dash line).*

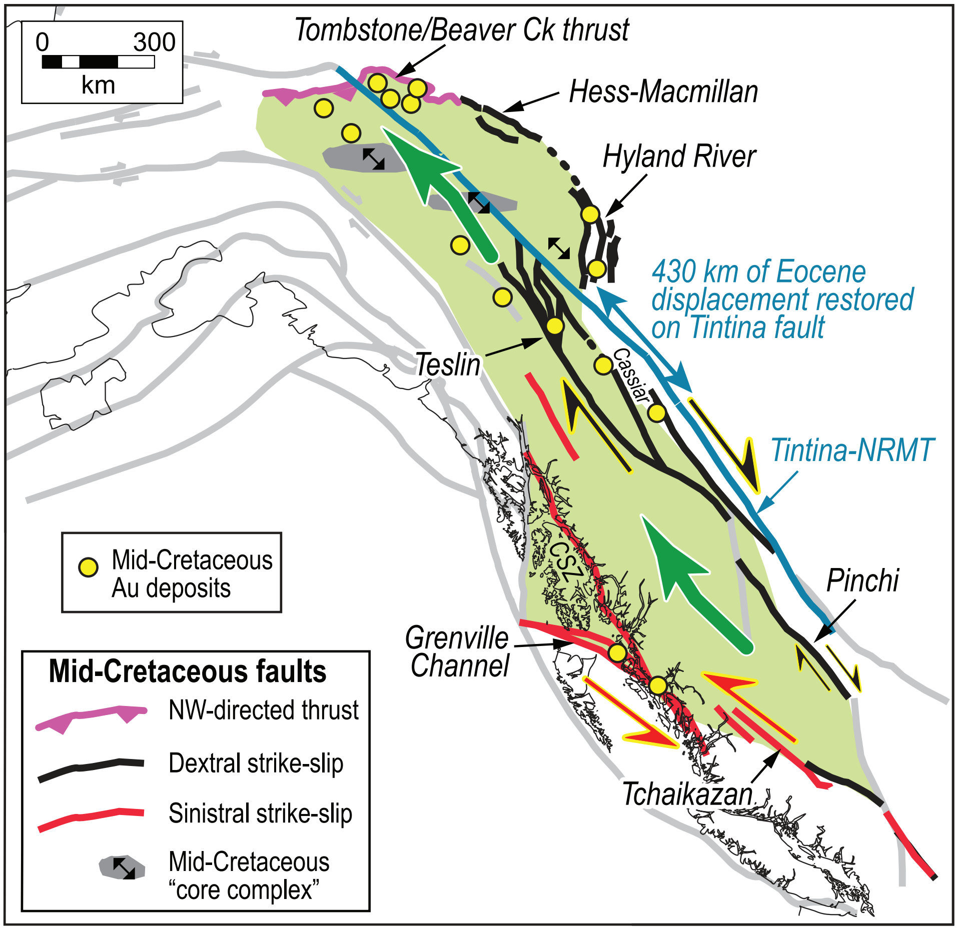


Figure A7. *Geometry of mid-Cretaceous northwest extrusion of an Intermontane crustal block (in green) with 430 km of displacement restored along the Eocene Tintina fault (in blue; after Nelson et al., 2013). The Intermontane block is bounded on the northeast by a series of dextral strike-slip faults, whereas sinistral strike-slip faults mark its southwestern edge in coastal and southern BC. The northwest-directed Tombstone and Beaver Creek thrusts in Yukon and Alaska form the leading edge of this extruding block. Major faults are identified; CSZ = Coast shear zone; NRMT = Northern Rocky Mountain Trench.. Note the close association of (inferred) mid-Cretaceous gold occurrences with major structures bounding the extruding wedge.*

In contrast, paleomagnetic data from Late Cretaceous rocks require northward latitudinal displacement on the order of 2000+ km (Irving *et al.*, 1996). Originally, anomalously shallow paleomagnetic inclinations from the Insular terranes were interpreted to require large latitudinal displacements on intra-Cordilleran faults such as the Coast shear zone (CSZ in Fig. A1; 13 in Fig. A6; Irving *et al.*, 1996). Subsequently, shallow paleomagnetic inclinations have been measured at more inboard sites along the eastern edge of the Intermontane terranes, such as the Upper Cretaceous Carmacks Group volcanic rocks in Yukon (Johnston *et al.*, 1996b; Wynne *et al.*, 1998; Enkin *et al.*, 2006), and in the southern Rocky Mountains (Enkin, 2006). In the case of the Carmacks Group, the Tintina fault is the only large transcurrent fault available to accommodate the anomalous paleomagnetic inclinations and, as discussed above, its post-Late Cretaceous displacement is well constrained at 400-430 km (Gabrielse *et al.*, 2006).

In an attempt to explain the anomalous paleomagnetic data from the Carmacks Group, it has been suggested that a large fault (with three times the displacement on the Tintina fault) must lie in miogeoclinal strata of Selwyn basin (Johnston, 2001) or even farther east in the Rocky Mountains (Enkin, 2006; Hildebrand, 2009); concepts that are difficult to reconcile with the well-established geological frameworks of Selwyn basin and the foreland fold-and-thrust belt. It is hard to conceive that a Late Cretaceous transcurrent fault with thousands of kilometres of displacement would be concealed in miogeoclinal strata when slightly younger faults, with only hundreds of kilometres of displacement, such as the Tintina-NRMT, correspond to well-defined physiographic trenches (Fig. A2) and have pronounced geophysical signatures (Fig. A4; Cook *et al.*, 2004; Snyder *et al.*, 2005; Nelson *et al.*, 2013). Butler *et al.* (2001) offer a moderate translation alternative (~1000 km), which is more in line with geological constraints, and account for the shallow paleomagnetic inclinations in part by tilting and compaction shallowing.

Tintina Fault

The town of Watson Lake (pop. 1500) is located near the eastern edge of the Liard Plain, a vast area (~7500 km^2) of few rock exposures at the junction of the Northern Rocky Mountain and Tintina trenches (Fig. A2). These two major topographic lineaments are underlain by one of the most prominent transcurrent fault systems in the Canadian Cordillera; the Tintina-Northern Rocky Mountain Trench (NRMT) fault (Figs. A1 and A6). This dextral strike-slip fault system has a well-constrained displacement of 400-430 km in Eocene time. An additional 60 km of Cretaceous dextral offset is postulated for the Tintina fault and additional earlier displacement is possible on the NRMT (Gabrielse *et al.*, 2006). In seismic reflection profiles, the Tintina fault appears as a 10-30 km-wide, structurally complex, crust-penetrating subvertical zone where gently-dipping reflectors are abruptly truncated (Fig. A4a; Cook *et al.*, 2004; Snyder *et al.*, 2005). The fault zone comprises at least four steeply-dipping fault panels (Snyder *et al.*, 2005), some of which are expressed at surface by grabens containing Upper Cretaceous to Eocene non-marine sedimentary strata, including coal, and minor Eocene volcanic and intrusive rocks (Jackson *et al.*, 1986). The profound change in the geochemistry of Quaternary volcanic rocks across the Tintina fault indicates different sub-lithospheric mantle sources on either side and suggests that the fault extends into the upper mantle (Abraham *et al.*, 2001).

A number of recent low-magnitude (5 or less, Richter scale) earthquakes have been recorded along the Tintina fault zone (Fig. A8). One of the most recent was a magnitude 4.6 earthquake with an epicentre near Faro, occurring in the aftermath of the magnitude 7.9 earthquake along the Denali fault, in east-central Alaska, in November, 2002. Only limited displacement has apparently occurred since Eocene time, as major rivers cross the Tintina Trench without significant deflection (Fig. A2). Earthquake statistics suggests that modern displacement along the Tintina fault is much less than 1 mm/yr (Hyndman *et al.*, 2005).

Neotectonics

Today, the northern Cordillera remains an active orogen with ongoing subduction along the Alaska trench (and corresponding arc volcanoes of the Aleutian chain) and right-lateral transform faulting along the Queen Charlotte-Fairweather fault system. Recent seismic activity is focused along the Denali fault and in the St. Elias and Chugach

Mountains, along the modern continental margin (Fig. A8), within the fold-and-thrust belt of the Mackenzie Mountains, and along strike-slip faults in the Richardson Mountains, some 600-800 km to the northeast (Hyndman *et al.*, 2005). Global Positioning System (GPS) measurements indicate that the northern Cordillera is currently moving northeasterly at a velocity of ~5 mm/yr relative to the North American craton (Mazzotti and Hyndman, 2002). Seismicity and GPS velocities are explained by oblique collision of the Yakutat terrane with the continental margin (Fig. A1) and far-field transfer of stress to the mountain front along a lower crustal detachment (Mazzotti and Hyndman, 2002; Hyndman *et al.*, 2005). The Yakutat collision and uplift of the St. Elias-Chugach Mountains probably began in mid-Miocene time and possibly as early as late Oligocene (Plafker *et al.*, 1994).

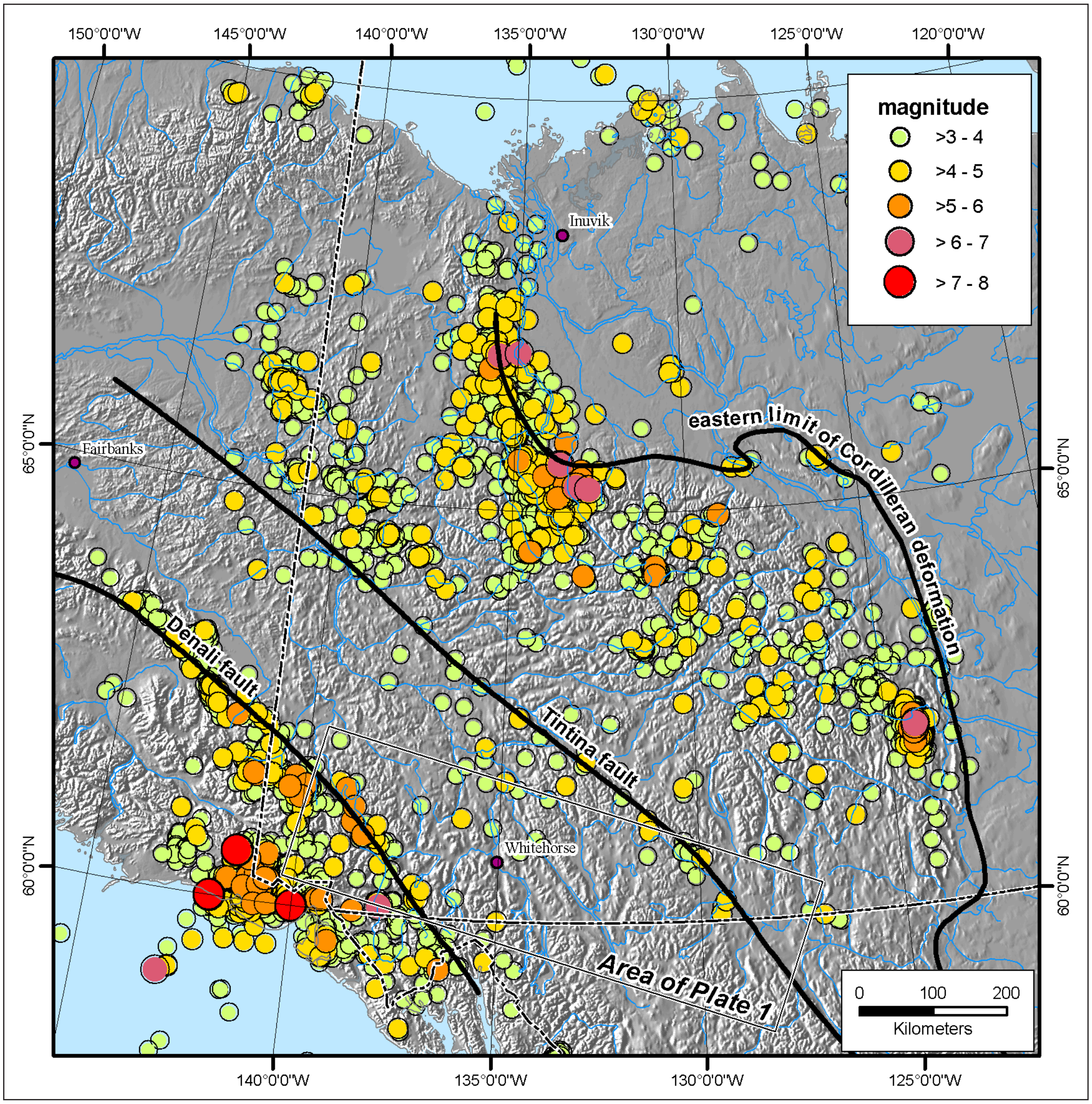


Figure A8. *Earthquake activity map, 1897 to 2006 (magnitude 3 and greater). Data from Natural Resources Canada's earthquake database (http://earthquakescanada.nrcan.gc.ca/stnsdata/nedb/index_e.php).*

The northern Cordillera is characterized by very high heat flow values of ~105 mW/m^2 north of 59°N, compared to ~73 mW/m^2 south of 59°N (Lewis *et al.*, 2003). This is reflected by widespread recent alkaline volcanism in the northern Canadian Cordillera (Edwards and Russell, 1999). Yukon examples include Rancheria basalts west of Watson Lake, the Selkirk Volcanics northwest of Carmacks (TQSv on Plate 1), and the Miles Canyon Basalt in Whitehorse (MPMC on Plate 1; Colpron *et al.*, 2016).

Miles Canyon

The Miles Canyon basalt is part of a large province of late Tertiary to recent alkaline olivine basalts which forms isolated occurrences in the northwestern Canadian Cordillera; the northern Cordilleran volcanic province (Edwards and Russell, 1999). Exposures at Miles Canyon are part of a series of north-trending flows with a surface area of approximately 30 km^2 (Hart and Villeneuve, 1999). Other good exposures are also found nearby, approximately 1 km up the road to Mount Sima ski area, south of the Alaska Highway (McCrae area). At Miles Canyon (UTM 8v, 498439E, 6725115N) the exposed succession consists of at least one ~20 m thick and two or three moderately thick (2–5 m) vesiculated flows that form the walls of the canyon constraining the Yukon River (Fig. A9). At the north end of the canyon the basal flows lie directly upon deeply weathered granite of the Whitehorse batholith. A sample of Miles Canyon basalt collected at the foot of the Whitehorse Dam yielded a whole rock $^{40}Ar/^{39}Ar$ date of 8.38 ± 0.12 Ma (Hart and Villeneuve, 1999).

Rocks at Miles Canyon once formed treacherous rapids which destroyed numerous boats and killed several stampeders who ventured on the Yukon River in crudely-built boats in an attempt to reach the Klondike gold fields in 1897 and 1898 (Fig. A9). These cataracts, Whitehorse Rapids and Miles Canyon, have since been tamed by the Whitehorse hydro-electric dam and the flooding of Schwatka Lake in 1954. During the Gold Rush era they prevented steam powered riverboats from ascending the Yukon River any farther, thus requiring transfer of supplies destined for Dawson City from trains of the White Pass & Yukon route to steamboats, such as the S.S. Klondike preserved in downtown Whitehorse. The city of Whitehorse originated from this Gold Rush transportation hub.

Field Trip Transect

Although the road trip begins in Whitehorse, Yukon, the actual start of this geological transect is east of Carmacks, in central Yukon; a two-hour drive from Whitehorse along the North Klondike and Robert Campbell highways (Fig. A10). The first day of this trip will focus mainly on development of the Jurassic Whitehorse trough by examining outcrops along the Robert Campbell and North Klondike highways. On the second day we will travel from Whitehorse to Kluane Lake along the historic Alaska Highway, built during World War II (see historical note below; Fig. A10 and Plate 1). Although we will technically be driving 'north' along the Alaska Highway, this portion of the highway

Figure A9. *Columnar-jointed basalt at Miles Canyon ca. 1900. Photograph from the Anton Vogee collection, Yukon Archives, #146.*

provides essentially an east-west transect from the Intermontane terranes, across the Coast Plutonic Complex and then following the Shakwak Trench and Denali fault at Kluane Lake. The trip ends at the foot of the majestic Kluane Ranges, where we will discuss the geology of the Insular terranes and the present-day tectonics of the northern Cordillera. The Kluane Ranges are the front ranges of the St. Elias Mountains, which include Mt. Logan (5959 m), Canada's highest peak and second only to Denali (Mt. McKinley) in North America.

As this field trip involves long distance travel (more than 820 km in three days), and because the North Klondike and Alaska Highway corridors offer limited access to the geology of some terranes, our choice of stops is necessarily selective. We hope that these selected outcrops and the northern Cordilleran landscape will provide an adequate backdrop for discussions of the regional geology and tectonics.

Several additional points of interests are also highlighted in the field trip log and are recommended for the leisurely traveller. Many of the relationships presented along this transect are extrapolated from relationships mapped in detail throughout southern Yukon and northern British Columbia. These detailed maps and reports are readily available from the Yukon Geological Survey (www.geology.gov.yk.ca) and the British Columbia Geological Survey (http://www.empr.gov.bc.ca/Mining/Geoscience/pages/default.aspx) websites.

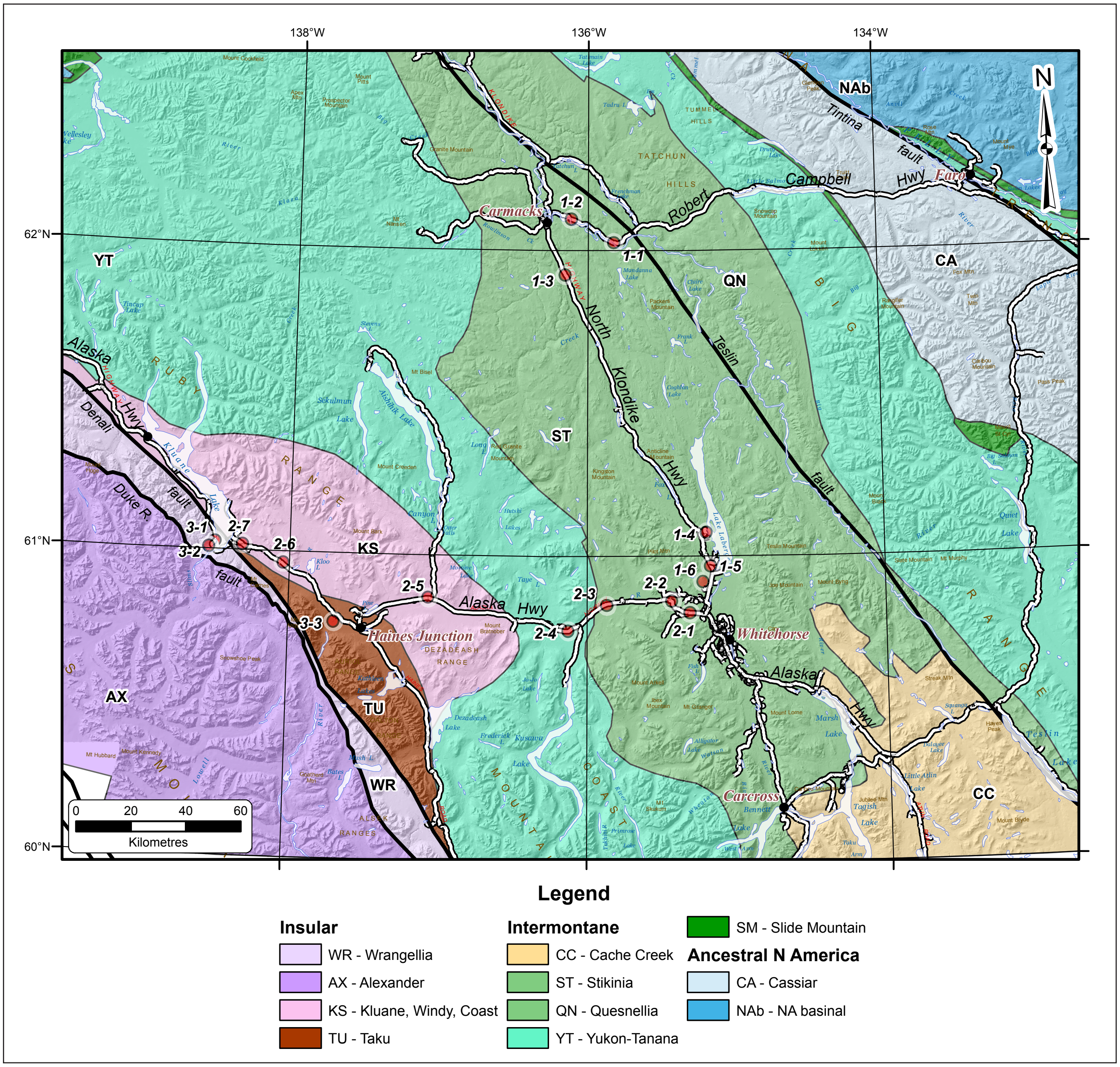


Figure A10. *Terranes along the field trip transect. Stops are indicated by red dots.*

The trip log is keyed to the green kilometre posts that are placed every 2 km along the north (or east) side of the major highways. Coordinates in Universal Transverse Mercator (UTM) NAD83 projection and decimal degrees are provided for the field trip stops (Table 1) and other notable features along the transect. All distances are in kilometres.

Table 1. *Stop locations.*

STOP	UTM zone	UTME	UTMN	Latitude	Longitude	Elev	KM	Road	Description
1-1	8	456959	6877113	62.02388	-135.82241	627	554.2	Robert Campbell	basal Laberge Gp - Eagles Nest Bluff
1-2	8	441715	6885880	62.10052	-136.11651	549	572.5	Robert Campbell	Tanglefoot fm
1-3	8	439316	6865680	61.91885	-136.15557	580	335.2	N. Klondike	Lone Pine Mtn - Tanglefoot delta?
1-4	8	489370	6771381	61.07701	-135.19702	635	225	N. Klondike (Deep Ck)	Richthofen
1-5	8	490661	6759010	60.96598	-135.17249	673	212.4	N. Klondike	Horse Creek conglomerate
1-6	8	487871	6753552	60.9169	-135.22367	1075	202.2	N. Klondike (Vista)	Nordenskiold
2-1	8	483090	6742250	60.81526	-135.31085	760	1443	Alaska	Mandanna
2-2	8	476497	6746461	60.85273	-135.43255	720	1452	Alaska	Laberge conglomerate
2-3	8	452869	6745060	60.83805	-135.86702	737	1476	Alaska	Takhini assemblage
2-4	8	438606	6736033	60.75507	-136.1265	711	1494	Alaska	Annie Ned pluton
2-5	8	387927	6748881	60.85932	-137.06325	650	1547	Alaska	Kluane Schist @ Otter Creek
2-6	7	660331	6762289	60.96299	-138.03837	981	1618	Alaska	Hayden Lake Suite @ road quarry
2-7	7	644934	6767722	61.01766	-138.31829	920	1634	Alaska	Denali fault - Kluane Lake overlook
3-1	7	634812	6768234	61.02584	-138.505	810	1651	Alaska	Wrangellia (Soldier's summit)
3-2	7	632830	6766101	61.00738	-138.54312	785	1648	Alaska (Slims River)	Slims River
3-3	8	353293	6740713	60.77478	-137.69396	605	1589	Alaska (Bear Creek)	Dezadeash @ Bear Creek

The Alaska Highway

The Alaska Highway (or Alcan Highway) was built in 8 months, between March and October, 1942, by the U.S. Army to provide an overland supply route to Alaska in the event of Japanese attacks on the west coast of North America during World War II. The 'highway' started seeing convoy traffic in 1943. Its historical length at completion time was 1523 miles (2451 km). The highway runs from Dawson Creek, BC to Delta Junction, Alaska, via Whitehorse, Yukon. Its original route was fairly tortuous with many abrupt curves and steep grades that were in part dictated by the mountainous landscape, but also designed as protection against potential air attacks on the convoys. The difficult land conditions in the north, particularly permafrost, required constant maintenance and upgrading of the road.

After the war, the U.S. government transferred control of the BC and Yukon portions of the highway to the Canadian government in April, 1946. After considerable reconstruction, the highway was opened to unrestricted traffic in 1947. Since then, the Alaska Highway has seen almost continuous rerouting and upgrading such that its current length is approximately 35 miles (55 km) shorter than its 1947 length. To take this shortening of the route into account, kilometre posts, placed at 2-km intervals along the highway (and used as markers in this guidebook), were recalibrated along the BC portion of the highway in 1990, and in Yukon, between the BC-Yukon border, near Watson Lake, and the east shore of Kluane Lake, at the end of this geological transect, in 2002 and 2005. Continued reconstruction along the Alaska Highway will likely bring future recalibrations of the kilometre posts and thus require adjustments to markers and distances in this guidebook.

Climate and other considerations

This trip can be done from May to early October most years, although variable snow cover on high peaks in spring and fall may limit the geological experience at some stops. Although the highways are drivable year-round, visiting these field trip stops between late October and May is not recommended as cold temperature, snow and/or mud are likely to limit access to some outcrops. Other secondary roads travelled along this trip may be subject to seasonal closures. During summer months, traffic along the Alaska and Klondike highways can be frequent and fast. Care should be taken to park vehicles well off the road and in a visible location. Watch for traffic before crossing the highway. Always approach outcrops with caution looking for potential falling rocks.

Wildlife is commonly sighted along the field trip route. Moose, elk, and caribou are common along much of the route. Dall sheep can be seen near Kluane Lake. Bison and 'wild' horses may be grazing along the Alaska Highway between Whitehorse and Haines Junction. Grizzly and black bears are present throughout the area, and are particularly active at lower elevations in spring and early summer.

DAY 1 - CARMACKS TO WHITEHORSE – WHITEHORSE TROUGH AND THE INTERMONTANE TERRANES

Day 1 of this excursion will focus on the Whitehorse trough between Carmacks and Whitehorse. The trip will begin at the northern end of the trough, east of Carmacks, necessitating a 2 hour drive to the first stop. Although we will not examine outcrops of the underlying Intermontane terranes (Stikinia, Quesnellia, Cache Creek, Yukon-Tanana) on Day 1, their geology will be discussed as their evolution bears on development of the Whitehorse trough during Jurassic terrane accretion. We will examine two exposures of Stikinia on Day 2 of this excursion.

The Intermontane terranes

Yukon-Tanana terrane

Although we will not examine outcrops of the Yukon-Tanana terrane on this trip, a brief review of its geology is warranted as it is inferred to make up the 'basement' to large part of the northern Intermontane terranes (cf. Colpron *et al.*, 2007b) and will therefore be mentioned during discussions on this trip. The Yukon-Tanana terrane is a vast terrane of peri-Laurentian affinity that extends from east-central Alaska across southern Yukon and into north-central British Columbia (Fig. A1). It lies outboard of parautochthonous distal ancestral North American strata and remnants of the oceanic Slide Mountain terrane, but generally inboard of arc and oceanic terranes that were accreted in Mesozoic time (Stikinia, Quesnellia and Cache Creek). Significant advances in understanding the Yukon-Tanana and related terranes were made during the Ancient Pacific Margin NATMAP project (1999-2003) and are summarized in the series of papers edited by Colpron and Nelson (2006).

The Yukon-Tanana terrane of Yukon and northern BC is a stratigraphic succession of four *tectonic assemblages* (Colpron *et al.*, 2006a, 2007b). The basal siliciclastic assemblage, the ***Snowcap assemblage*** (Piercey and Colpron, 2009), is overlain by up to three unconformity-bounded volcanic and volcaniclastic successions of predominantly continental arc character (Piercey *et al.*, 2006). These are the Upper Devonian to Lower Mississippian ***Finlayson assemblage***, the mid-Mississippian to Lower Permian ***Klinkit assemblage*** and the Middle to Upper Permian ***Klondike assemblage*** (Colpron *et al.*, 2006a). These Yukon-Tanana assemblages are coeval with the oceanic assemblage of chert, argillite and mafic volcanic rocks of the Slide Mountain terrane, which forms a discontinuous belt along the eastern edge of Yukon-Tanana terrane (Fig. A1). Immature, fine-grained clastic rocks and polymictic conglomerate of Permian to Triassic age overlie tectonic assemblages of Yukon-Tanana and Slide Mountain terranes, as well as miogeoclinal rocks of Selwyn basin and Cassiar terrane in Yukon and northern BC (Beranek, 2009; Beranek *et al.*, 2010).

The Snowcap assemblage is pre-Late Devonian in age and comprises varying amounts of quartzite, pelite, psammite, marble and calc-silicate, and minor mafic metavolcanic and meta-intrusive rocks (Colpron *et al.*, 2006a). Its lithological, geochemical and isotopic compositions, as well as its detrital zircon ages, suggest that the Snowcap complex represents a distal portion of the ancestral North American continental margin that was rifted off western Laurentia in mid-Paleozoic time (Nelson *et al.*, 2006; Piercey and Colpron, 2009) and subsequently formed the nucleus upon which magmatic arcs of the Finlayson, Klinkit and Klondike assemblages were deposited. Rocks of the Snowcap assemblage appear to have been deformed and metamorphosed prior to deposition of the overlying Upper Devonian to Permian strata.

Magmatism in the Yukon-Tanana terrane occurred in six distinct magmatic pulses, or cycles, that are punctuated (at least locally) by unconformities and/or deformational events (Nelson *et al.*, 2006; Piercey *et al.*, 2006). Syngenetic sulphide mineral deposits occur in Upper Devonian-Lower Mississippian back-arc facies rocks of the Finlayson Lake district, in southeast Yukon (*e.g.*, Kudz Ze Kayah, GP4F and Wolverine; Hunt, 2002; Piercey *et al.*, 2001, 2002, 2006; Murphy *et al.*, 2006).

Stikinia and Quesnellia

Stikinia and Quesnellia (also commonly referred to as the Quesnel and Stikine terranes) are two large terranes in which surface exposures consist primarily of Mesozoic volcanic and plutonic arc rocks (Fig. A1). Both terranes also include sporadically exposed Paleozoic arc 'basement' rocks. In Stikinia these correspond to the Stikine assemblage of northwestern British Columbia, a volcanic-sedimentary sequence of Devonian to Lower Permian age. It has Late Devonian to Early Mississippian calc-alkaline plutons intruding its base and limestone with McCloud faunal affinity at its top (Logan *et al.*, 2000; Gunning *et al.*, 2006). Correlative rocks in Yukon are the metamorphosed volcanic, volcaniclastic and minor carbonate rocks of the upper Paleozoic Takhini assemblage, exposed west of Whitehorse (see Stop 2-3; Hart, 1997; Fig. 1-1). In Quesnellia upper Paleozoic arc and back-arc assemblages are found in the Lay Range of central British Columbia (Ferri, 1997) and the Harper Ranch Group of southern British Columbia (Beatty *et al.*, 2006), which are correlated with the Klinkit assemblage of Yukon-Tanana terrane (Simard *et al.*, 2003) and the Huntergroup volcanics in the Sylvester allochthon (Nelson and Friedman, 2004). The Boswell assemblage of south-central Yukon is another upper Paleozoic volcanic-sedimentary sequence tentatively assigned to Quesnellia (M. Colpron, unpublished data; Fig. 1-1). It consists of basalt (MORB, EMORB) and limestone of the Upper Devonian to Lower Mississippian Moose formation and Upper Mississippian to Lower Permian arc volcanic, volcaniclastic and sedimentary rocks (including Pennsylvanian-Permian fossiliferous limestone) of the Boswell formation (Simard, 2003; Simard and Devine, 2003; M. Colpron, unpublished data). A Mississippian tonalite pluton intrudes rocks of the Moose formation at the northern end of the belt, north of the Jurassic Tatchun batholith (ca. 333 Ma; J.L. Crowley, pers. comm., 2015; PgK on Plate 1). These rocks are unconformably overlain by Upper Triassic volcanic and volcaniclastic strata of the Semenof formation (R.-L. Simard and M. Colpron, unpublished data). The Boswell assemblage and Semenof formation are

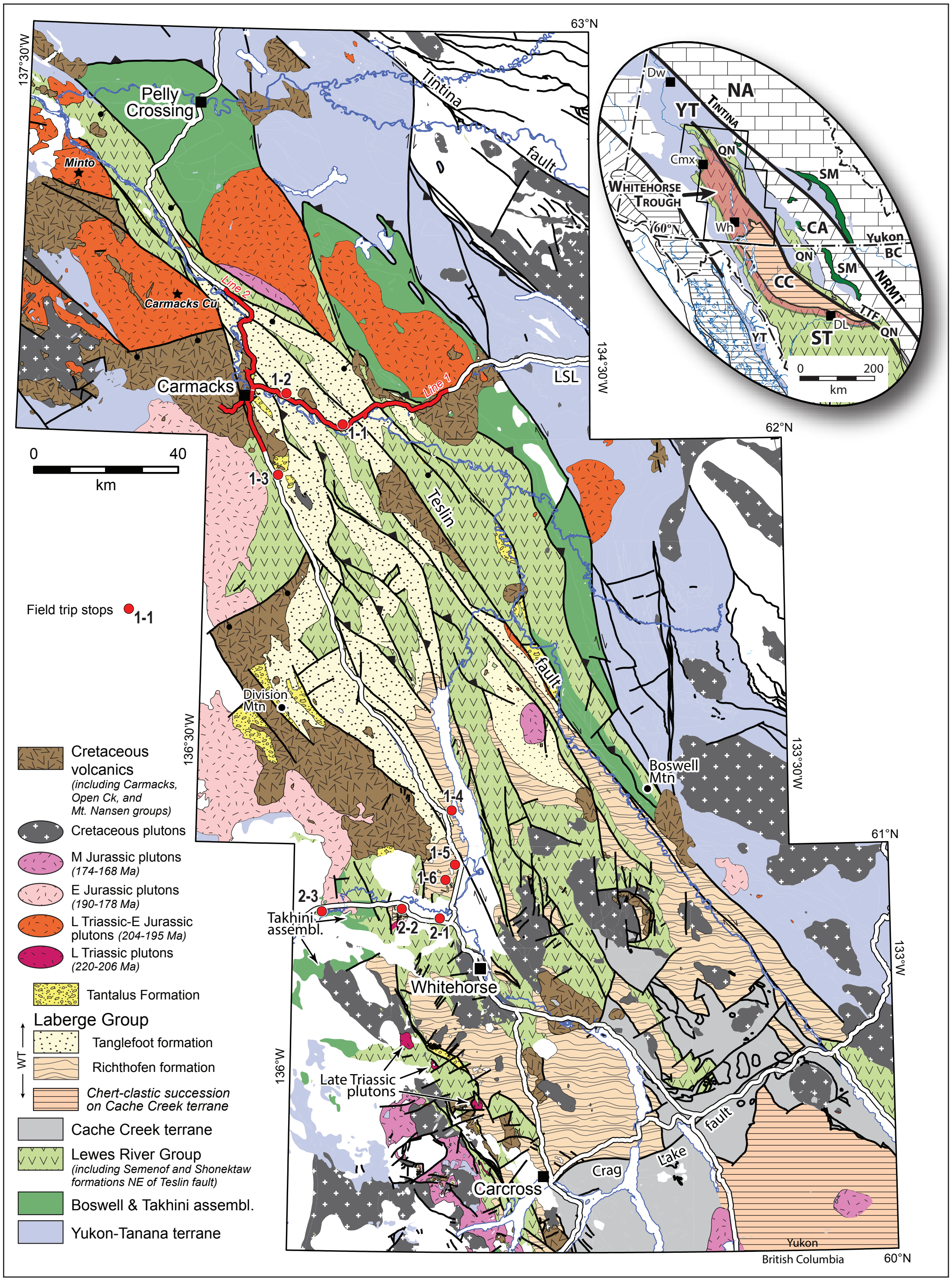


Figure 1-1. *Regional geology of the Whitehorse trough and surrounding region in south-central Yukon (after Colpron, 2011; Colpron* ***et al.****, 2015). Inset shows the location of the Whitehorse trough (red shading) with respect to terranes of the northern Cordillera (after Colpron and Nelson, 2011a). Field trip stops for Day 1 and the start of Day 2 are indicated by red dots. Parts of the Robert Campbell and North Klondike highways imaged by seismic reflection profiles shown in Figure 1-2 are indicated in red. The location of Early Jurassic copper-gold mineralization at Minto and Carmacks Copper is shown by black stars. Abbreviations: CA – Cassiar terrane (derived from ancestral North America); CC – Cache Creek terrane; Cmx – Carmacks; DL – Dease Lake; LSL – Little Salmon Lake; NA – rocks of ancestral North America; NRMT – Northern Rocky Mountain Trench fault; QN – Quesnellia; SM – Slide Mountain terrane; ST – Stikinia; TTF – Teslin-Thibert fault; Wh – Whitehorse; WT – Whitehorse trough; YT – Yukon-Tanana terrane.*

assigned to Quesnellia based on their age, composition and position east (in the hanging wall) of the Teslin fault (Plate 1; Figs. A4, A10, 1-1, 1-2; Cook *et al.*, 2004; White *et al.*, 2012). The relations between Boswell assemblage and other late Paleozoic sequences of Quesnellia and Yukon-Tanana terrane are uncertain. Pennsylvanian detrital zircons in a Triassic conglomerate overlying Yukon-Tanana terrane, and imbricated with Slide Mountain terrane, suggest proximity of the Boswell assemblage at that time (Colpron *et al.*, 2005).

The oldest Mesozoic volcanic and intrusive rocks in Quesnellia and Stikinia are Middle Triassic, but voluminous arc-related build-ups with coeval, cogenetic plutonism began in the Late Triassic (Anderson, 1991). In BC they include the Takla and Nicola groups northeast of the Cache Creek terrane and the Takla and Stuhini groups to the southwest (the oceanic, accretionary Cache Creek assemblage is used to demarcate between similar Mesozoic strata assigned to Quesnellia and Stikinia; see Wheeler *et al.*, 1991; Colpron and Nelson, 2011a). Upper Triassic, dominantly augite-(plagioclase-) phyric volcanogenic units on both sides of the Cache Creek assemblage are strongly similar in field characteristics, arc geochemistry and primitive isotopic signatures (Dostal *et al.*, 1999). The main Triassic volcanic accumulations of Quesnellia lie west of the belt of Paleozoic pericratonic exposures, which are onlapped by thinner, volcanic-poor siliciclastic units with continentally-influenced isotopic signatures (Unterschutz *et al.*, 2002) that also overlie Yukon-Tanana terrane and the western continental margin (Beranek, 2009; Beranek *et al.*, 2010; Beranek and Mortensen, 2011). Following the Permo-Triassic accretion of the innermost pericratonic terranes (Slide Mountain, Quesnellia and Yukon-Tanana), it is likely that the axis of the new west-facing arc migrated outboard from the collision zone. In Stikinia there is no evidence for a shift in the arc axis: the Stuhini and Takla groups are developed in a broad region on top of variably-deformed Paleozoic arc units.

In Yukon, Mesozoic Stikinia is represented by volcanic and sedimentary strata of the Middle Triassic Joe Mountain Formation and the Upper Triassic Lewes River Group (Fig. 1-3), which underlie large parts of the Whitehorse map area (Hart, 1997). The Joe Mountain Formation consists of a mafic-ultramafic intrusive complex, basalt and volcaniclastic rocks of Ladinian (Middle Triassic) age and of MORB to BABB geochemical affinity (Hart, 1997; Piercey, 2005). The Upper Triassic Lewes River Group includes a lower formation of Carnian augite-phyric basalt, basaltic andesite and volcaniclastic rocks (Povoas formation; informal nomenclature of Tempelman-Kluit, 1984, 2009) and an upper formation of Carnian to Rhaetian epiclastic, volcanogenic sedimentary rocks and limestone (Aksala formation; Fig. 1-3). Volcanic rocks of the Povoas formation have the general character of island arc tholeiite with minor MORB (S.J. Piercey, personal communication, 2005). The Aksala formation includes three mappable members (Fig. 1-3): 1) the Casca member, a Carnian-Norian heterogeneous sequence of lithic sandstone, argillite and conglomerate; 2) the Hancock member, a Norian-Rhaetian reef limestone, including Grey Mountain in Whitehorse and Lime Peak near Lake Laberge; and 3) the Mandanna member, a Rhaetian maroon lithic sandstone, siltstone, mudstone and minor conglomerate of fluvial origin (Long, 2005; see Stop 2-1). These rocks record the waning stage of the Lewes River arc.

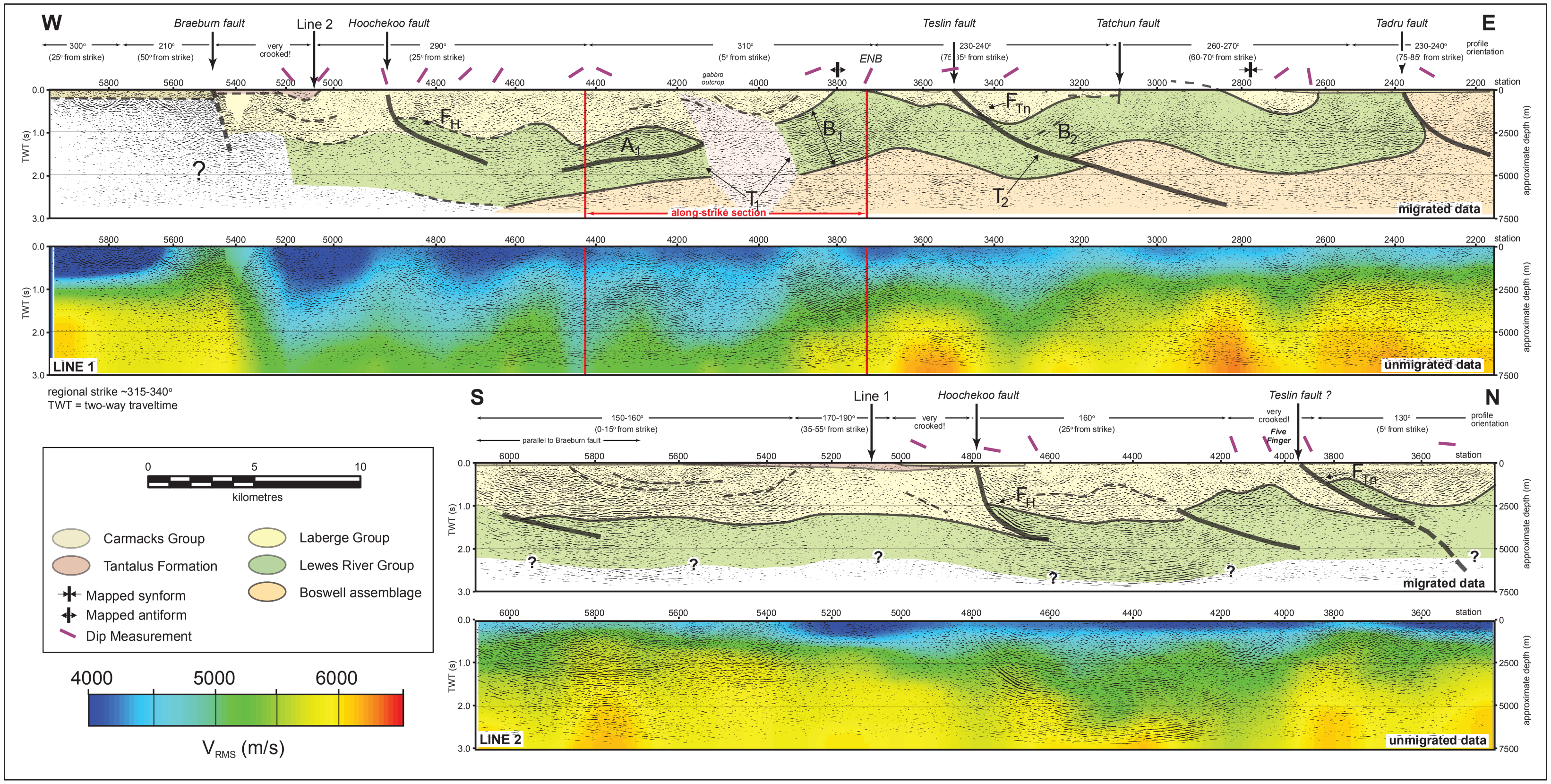


Figure 1-2. *Migrated seismic reflection profiles shown with overlays of schematic interpretations (above) and smoothed stacking velocities (below) for seismic lines 1 and 2 (indicated by red portions of Robert Campbell and North Klondike highways in Figure 1-1; after White et al., 2012). Indicated along the top of the interpretations are: 1) apparent dip of bedding measured on outcrops near the profile (solid purple bars); 2) orientation of the seismic line with respect to regional strike of structures in Whitehorse trough (~315°N); 3) surface location of major faults; 4) surface projection of an anticline-syncline pair mapped north of the profile (Tempelman-Kluit, 1984); and 5) location of Eagle's Nest Bluff (ENB), where Upper Triassic limestone of the Lewes River Group is exposed. Note that the depth of the bottom of the Lewes River Group along Line 2 is uncertain although it is shown continuing to 7500 m depth. The approximate depth scale indicated on the right vertical axis assumes a mean subsurface seismic velocity of 5000 m/s. TWT = two-way traveltime (in seconds).*

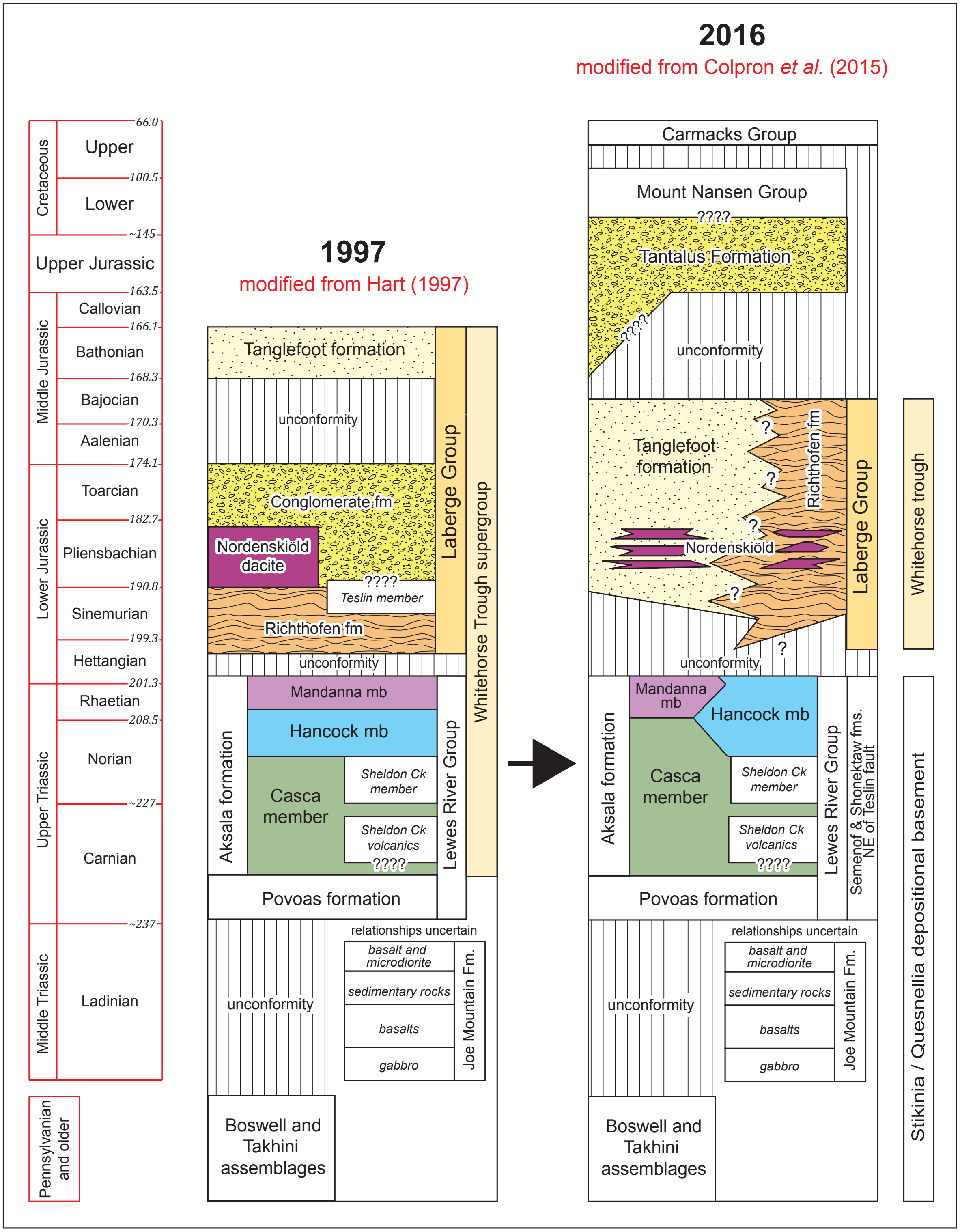


Figure 1-3. Stikinia and Whitehorse trough stratigraphic nomenclature and age revisions (timescale from Cohen et al., 2013).

Lime Peak north of Whitehorse is the site of the thickest and best-developed Upper Triassic reef complex in the North American Cordillera (see Stop 1-6). Norian in age, it contains corals, sponges, brachiopods, bivalves, disjectoporids, and spongiomorphs, including a number of coral species that are also found in central Quesnellia, the Wallowa terrane of Oregon, and the Antimonio terrane of western Mexico, as well as in the parautochthonous Luning Formation of Nevada (Yarnell *et al.*, 1999). Similar reef faunas occur in the western part of the Tethyan seaway, an equatorial belt that extended along the southern margin of Pangea, from Asia through southern Europe. The similarity of Triassic Cordilleran and European species lends support to the early opening stages of the "Hispanic corridor", a shallow, westward continuation of the Tethyan seaway that was fully established by Early Jurassic time (Stanley, 1994). The more northerly terranes Quesnellia and Stikinia contain equatorial faunas, hence they may have undergone considerable northward displacement since the Late Triassic.

Basinal Triassic sedimentary rocks, which have been modelled as back-arc basins to the Triassic arc of Quesnellia, show evidence of pre-Triassic ties to the northern part of the continental margin (Colpron *et al.*, 2006a; Beranek *et al.*, 2010). None of these contain Tethyan coralline faunas. This contrast may argue for considerable tectonic lateral mobility of the frontal arcs with respect to their back-arc regions in early Mesozoic time.

Mesozoic volcanogenic exposures of Quesnellia in Yukon are restricted to a narrow and discontinuous belt northeast of Teslin fault (Gordey and Stevens, 1994; Simard, 2003; Simard and Devine, 2003; Colpron *et al.*, 2016). These rocks have been variously assigned to the Shonektaw Formation in Teslin area (Gordey and Stevens, 1994), the Semenof formation in Laberge area (Tempelman-Kluit, 1984, 2009; Simard, 2003; Simard and Devine, 2003) and the Lewes River Group (Povoas formation) in Glenlyon (Colpron *et al.*, 2002).

By the latest Triassic-Early Jurassic newly-configured arcs were superimposed on the Triassic architecture on both sides of the Cache Creek terrane. Contact relationships range regionally from disconformable to deeply unconformable on folded and thrust-faulted older strata. In Quesnellia and Yukon-Tanana terrane, the Early Jurassic magmatic zone migrated eastwards towards the continent, as shown by abundant 200-185 Ma plutons in the Yukon-Tanana terrane. These are equivalent to the volcanic strata of the Lower Jurassic Rossland Group, which lie well east of the Triassic Nicola Group in southern BC (Wheeler and McFeely, 1991). In Stikinia, Lower Jurassic volcanogenic strata of the Hazelton Group are widespread and voluminous. The preferred tectonic model for this terrane in Early Jurassic time is a microplate with subduction under both east and west sides (present coordinates), which generated two arcs separated by a marine trough (Marsden and Thorkelson, 1992).

In northern BC and southern Yukon the Early Jurassic plutonic suite of Quesnellia and Stikinia intrudes pericratonic basement rocks of Yukon-Tanana terrane in a horseshoe-shaped belt around the northern end of Whitehorse trough (Fig. 1-4), which is an Early to Middle Jurassic synorogenic basin (see below). The Early Jurassic suite was emplaced during rapid exhumation of the metamorphic host rocks of the Yukon-Tanana terrane. Early phases are variably foliated (locally mylonitic), epidote-bearing granodiorite; younger phases are undeformed granite and pegmatite, locally with miarolitic cavities (Johnston and Erdmer, 1995; Johnston *et al.*, 1996a; Colpron *et al.*, 2003). Mica cooling

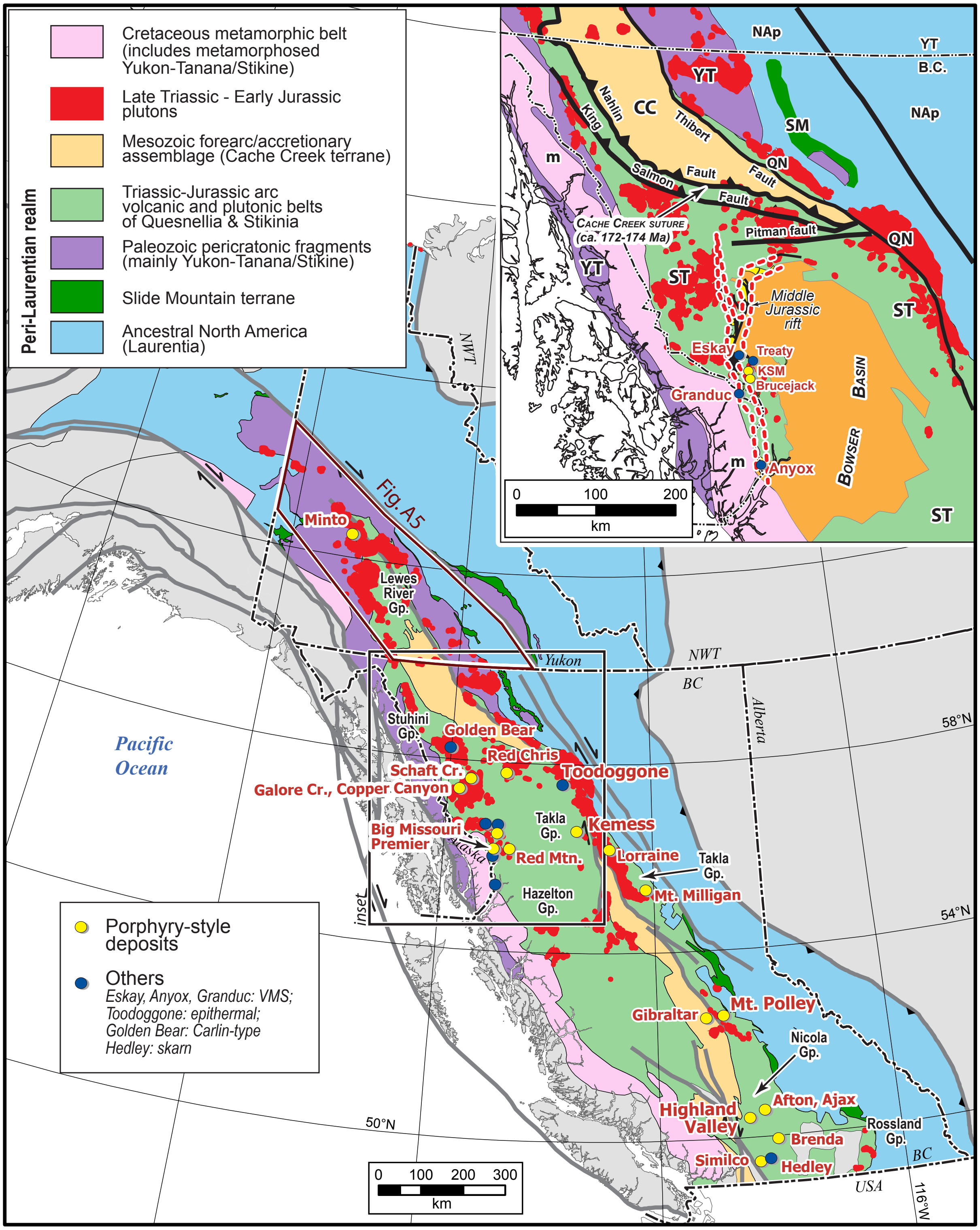


Figure 1-4. Triassic to Middle Jurassic magmatic belts and associated deposits of the peri-Laurentian terranes (after Nelson et al., 2013). Deposit locations are from McMillan et al. (1995). Bowser basin is the Middle Jurassic to Early Cretaceous foreland basin to the Cache Creek accretionary complex. Area of Figure A5 in Yukon is shown by brown outline. Inset shows details of the mid-Jurassic Eskay rift and associated VMS deposits (from Alldrick et al., 2005; note that Granduc is Late Triassic but lies within the later rift zone). Terrane abbreviations: CC – Cache Creek; m – Coast plutonic complex; NAp – Ancestral North America; QN – Quesnellia; SM – Slide Mountain; ST – Stikinia; YT – Yukon-Tanana.

ages from the Yukon-Tanana terrane indicate that most of it had cooled below ~300°C by late Early Jurassic time (Fig. A5; Colpron *et al.*, 2015). The Late Triassic to Early Jurassic plutonic suite of Quesnellia and Stikinia is famous for its Cu-Au and Cu-Mo porphyry deposits, including the Highland Valley, Gibraltar, Kemess, and Mt. Polley mines in British Columbia (to name a few), and the Minto mine in Yukon (Fig. 1-4; Nelson and Colpron, 2007; Nelson *et al.*, 2013). At Minto, the high grade Cu-Au ore is hosted in strongly deformed early phases of the Minto suite (Tafti, 2005; Hood, 2012; Colpron *et al.*, 2016).

Cache Creek terrane

The Cache Creek terrane consists predominantly of oceanic rocks (basalt, chert, argillite, gabbro and ultramafic rocks) of Early Mississippian to Middle Jurassic age, and upper Paleozoic limestone with exotic Tethyan faunas (Monger and Ross, 1971; Monger, 1975; Gabrielse, 1998; Mihalynuk, 1999). Also present locally are abundant Upper Permian to Lower Triassic arc volcanic rocks (Kutcho assemblage; English and Johnston, 2005; Schiarizza, 2012; Bickerton, 2014). The highly disrupted nature of the Cache Creek terrane and occurrences of Triassic and Middle Jurassic blueschist indicate that it represents an accretionary complex, possibly recording more than 6000 km of subduction of Panthalassa lithosphere beneath the Quesnellia-Stikinia arcs (Monger, 1969; Cordey *et al.*, 1991; Struik *et al.*, 2001). Early Permian faunas of the Cache Creek terrane are more closely related to Eurasia than North America (Ross and Ross, 1983; Stevens, 2007). The position of the Cache Creek terrane between the peri-Laurentian Quesnel and Stikine terranes is best explained by oroclinal entrapment during the Jurassic amalgamation of the Intermontane terranes (Mihalynuk *et al.*, 1994; Fig. 1-5). By the Middle Jurassic, the Cache Creek complex was rapidly exhumed and thrust westward onto Lower to Middle Jurassic strata of the Laberge Group (Whitehorse trough; see below) along the Nahlin fault (Mihalynuk *et al.*, 2004; English and Johnston, 2005). Middle Jurassic plutons (ca. 174 Ma) in northern BC and southern Yukon postdate terrane imbrications. Major units of the Cache Creek terrane (Cache Creek Group) in northern BC and southern Yukon include the Mississippian to Pennsylvanian Nakina Formation (basalt, minor chert), the Pennsylvanian-Permian Horsefeed Formation (limestone), and the Permian-Jurassic Kedahda Formation (chert, clastic rocks; Gabrielse, 1998; Mihalynuk, 1999).

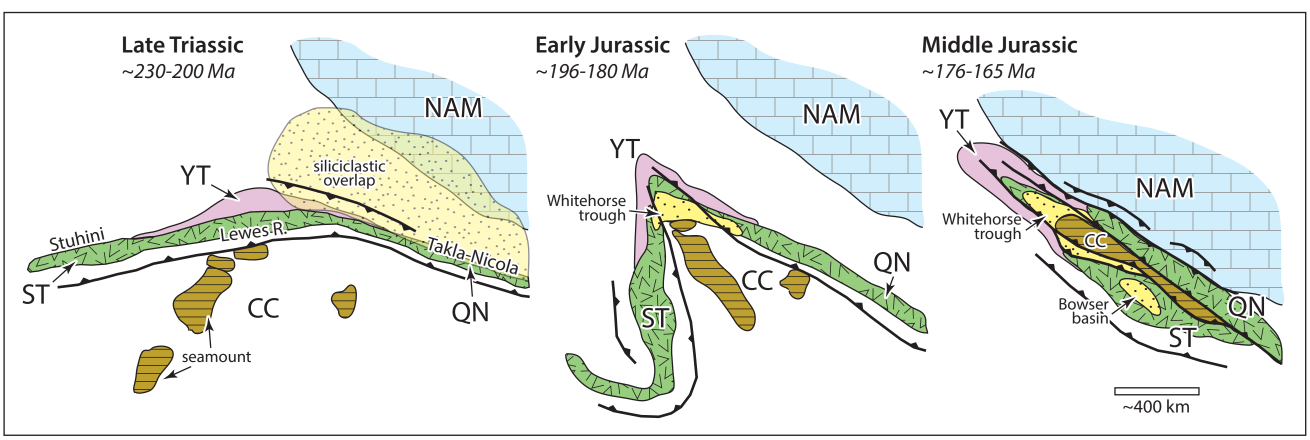


Figure 1-5. *Tectonic setting of the Intermontane terranes and Whitehorse trough according to the oroclinal enclosure model of the Cache Creek terrane (after White et al., 2012; modified after Mihalynuk et al., 1994, 2004). CC – Cache Creek terrane; NAM – ancestral North American margin; QN – Quesnellia; ST – Stikinia; YT – Yukon-Tanana terrane.*

Whitehorse trough

Whitehorse trough is an Early to Middle Jurassic marine sedimentary basin that overlaps the Intermontane terranes (Stikinia, Quesnellia and Cache Creek) in the northern Cordillera (Fig. 1-1). The basin was originally interpreted as a forearc basin that formed during convergence of Stikinia with North America after subduction of the Anvil Ocean (now known as the Slide Mountain terrane; Tempelman-Kluit, 1979). Subsequent mapping in the area highlighted that the middle Paleozoic to early Mesozoic Yukon-Tanana and Quesnellia arc terranes separated the trough from the Slide Mountain terrane, which is now known to have closed during the Permo-Triassic (Mortensen, 1992; Nelson *et al.*, 2006; Beranek and Mortensen, 2011).

Current tectonic models interpret the Whitehorse trough as a forearc basin that progressively evolved to become a synorogenic piggy-back basin during development of the Cache Creek accretionary complex and subduction of part of the Panthalassa ocean beneath the contiguous arc terranes of Stikinia and Quesnellia sometime after the end of the Pliensbachian (Fig. 1-5; Mihalynuk *et al.*, 1994; English and Johnston, 2005; Nelson *et al.*, 2013; Colpron *et al.*, 2015). In 2004, two 2D seismic lines were acquired in the northern part of the basin which provided approximate stratigraphic thicknesses and subsurface visualization of the southwest-verging fold-and-thrust belt that shortened the basin (Fig. 1-2; White *et al.*, 2012). A recent 3D geologically constrained inversion of magnetic and gravity data has provided higher-resolution evidence for dome structures and 'crested anticlines' in the northern trough around Carmacks, together with modelling the base of the trough as shallower than previously estimated (Mira Geoscience, 2014).

The elongate, northwest-southeast trending basin straddles the Yukon-British Columbia border, where it tapers 650 km from Dease Lake in the south to its northernmost tip in the Carmacks area (Fig. 1-1 inset). Its geology is characterized by an approximately 3 km thick deformed Lower-Middle Jurassic (late Hettangian-Bajocian) sedimentary succession (the Laberge Group), which is underlain by a depositional basement of Triassic Stikinia (the Lewes River Group) and capped by Upper Jurassic to Lower Cretaceous fluvio-lacustrine and coal deposits of the Tantalus Formation (Long, 2005, 2015), and Cretaceous to Neogene volcanic rocks (Fig. 1-3). Laberge Group sandstone detrital zircons all display a major Late Triassic-Early Jurassic peak (220-180 Ma) and a minor peak in the middle Paleozoic (340-330 Ma) that correspond exactly with known igneous ages from areas surrounding the trough (Fig. 1-6; Colpron *et al.*, 2015). Source regions typically have Early Jurassic (ca. 200-180 Ma) mica cooling ages (Fig. A5) and the petrology of metamorphic rocks and Early Jurassic granitoid plutons flanking the trough suggests rapid exhumation during emplacement that was coeval with the onset of orogenic activity in the southern Canadian Cordilleran hinterland.

Subsidence and Early Jurassic coarse clastic sedimentation in the trough occurred concurrently with rapid exhumation of the basin shoulders (Colpron *et al.*, 2015). Conceptually, deposition was dominated by transport from the rift shoulders in a high shelf-basin relief (SBR) margin basin with a high accommodation/sediment supply (A/S) ratio (Fig. 1-7). Hettangian and younger, shelf-detached submarine fan-delta

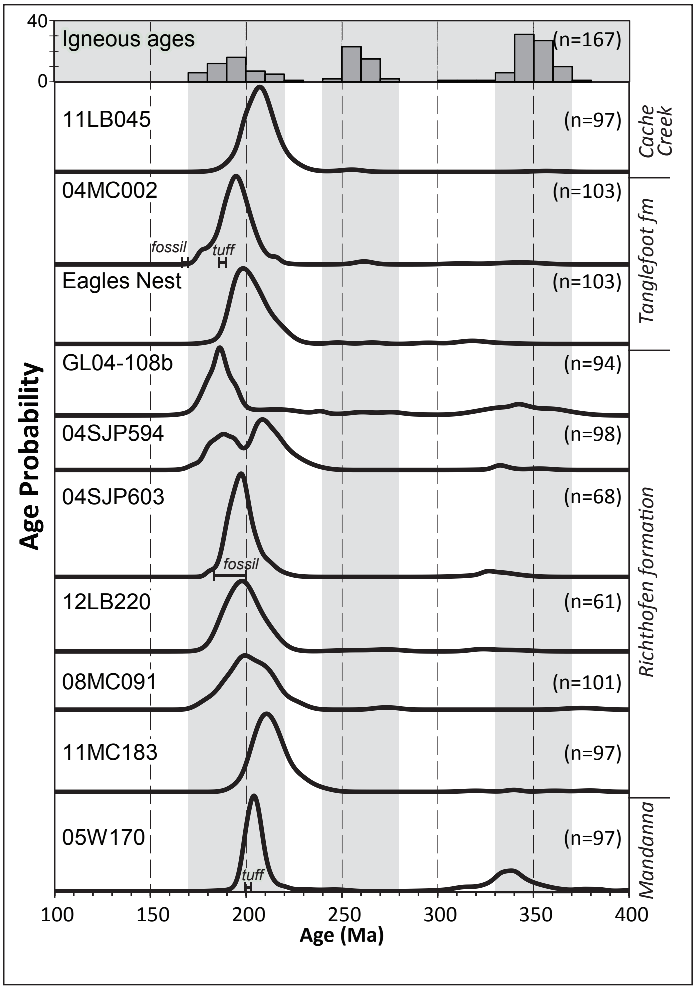


Figure 1-6. *Normalized age probability plots for detrital zircons from the Mandanna member, Laberge Group (Richthofen and Tanglefoot formations), and greywacke overlapping the Cache Creek terrane (from Colpron et al., 2015). Histogram for 167 U-Pb zircon igneous ages from pre-Cretaceous (>145 Ma) rocks of volcanic or plutonic parentage in the Intermontane terranes is shown at the top for comparison. Sample Eagles Nest was collected at Stop 1-1, 04MC002 near Stop 1-2, 05SJP603 at Stop 1-4, and 05SJP594 at Stop 2-2.*

conglomerates and deep-water turbidites (historically assigned to the Richthofen formation) characterize Laberge Group deposition in the Whitehorse area and southern trough at this time. During later shoaling and oroclinal closure of the Cache Creek ocean, Laberge Group deposition became progressively dominated by axial, southeasterly-directed transport as the margin's SBR and A/S ratios decreased and the basin filled (M.P. Hutchison, unpublished, 2015). Coastal morphology, paleogeography and wind direction modelling (Fig. 1-8) suggests that proximal Laberge Group sandstones were deposited primarily by tidal-dominated and fluvially-influenced coastal processes (M.P. Hutchison, unpublished, 2015). These Sinemurian and younger sediments, historically assigned to the Tanglefoot formation in the northern part of the trough, comprise shallow marine, deltaic, fluvial and coal deposits. Richthofen and Tanglefoot strata are coeval in part (Lowey, 2008), and intercalated Nordenskiold unit dacitic tuffs dated to ca. 188-184 Ma (Colpron and Friedman, 2008) have been recognized at several distinct horizons within both formations (see Fig. 1-3).

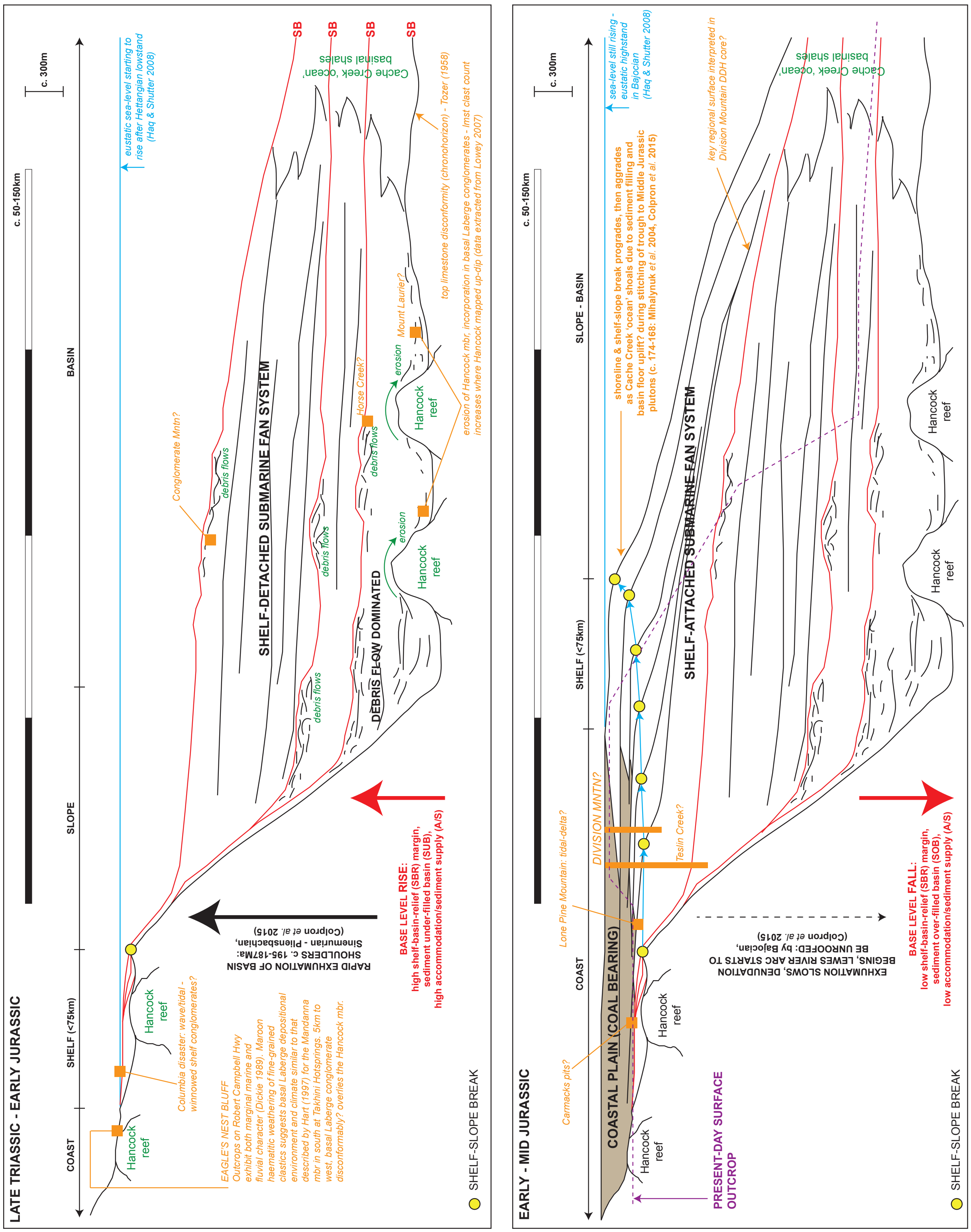


Figure 1-7. *Laberge Group depositional control conceptual model (modified from Hutchison, unpublished, 2015; after Hadler-Jacobsen et al., 2005).*

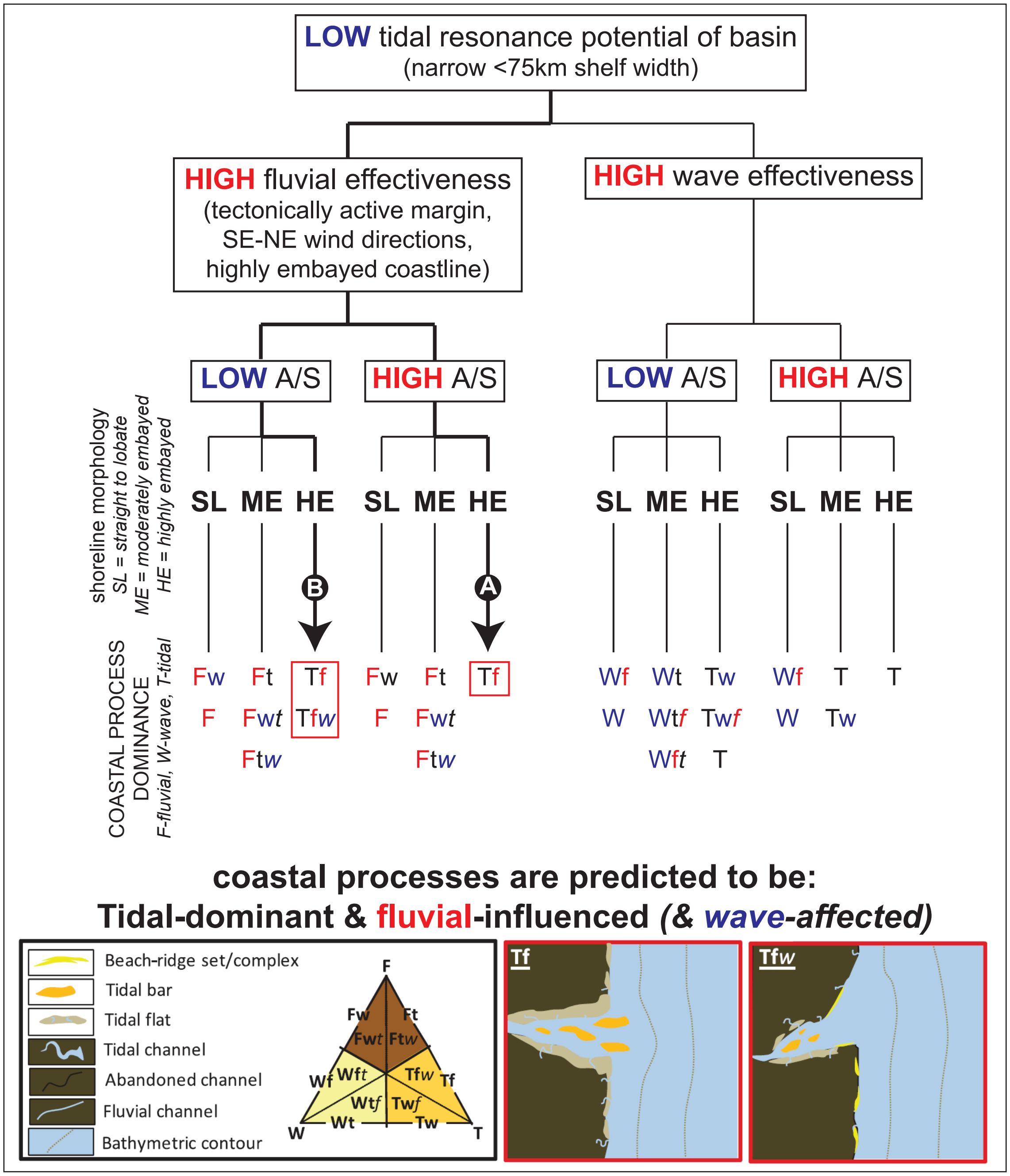


Figure 1-8. Prediction of Laberge Group depositional processes (coastal morphology matrix from Ainsworth et al., 2011; paleogeography from Colpron et al., 2015; wind directions from Moore et al., 1992).

The basin is prospective for both conventional and unconventional hydrocarbons, predominantly gas (Hayes, 2012; Hayes and Archibald, 2012), but lacks systematic petroleum studies (except source rock potential; Lowey *et al.*, 2009) due to an absence of industry activity and limited survey fieldwork. Current conventional resource assessments estimate mean, risked in-place volumes of 17.48 MMbls oil and 379.3 Bcf gas for the basin (Hayes, 2012). The Whitehorse trough outline and spatial distribution of its resource have evolved over the years, and the conventional resource assessment by Hayes (2012) listed five conceptual plays, only two of which can now be considered as Whitehorse trough basin-fill strata and which have chances of geological success greater than 10%. Recent work to redefine both the basin outline and its plays (Fig. 1-9) has resulted in prospectivity polygons that are a more accurate representation of resource distribution (Hutchison, unpublished, 2015). The Tanglefoot proximal sandstone play in the northern trough is the most prospective, although typically immature at surface, with conventional hydrocarbons expected to occur in both structural and stratigraphic traps (Hayes, 2012). New field permeability data for these sandstones, however, typically falls within 'tight gas play' parameters (<0.1mD), with corresponding porosities averaging just 4% (Fig. 1-10).

From 1904 to 1922 small tonnages of coal were mined from the Tantalus mine at Carmacks and used to fuel riverboats plying the Yukon River between Whitehorse and Dawson, and for domestic heating in Dawson. Coal extracted between 1923 and 1938 from a new mine at Tantalus Butte also supplied domestic heating coal fuel to Dawson. From 1947 to 1968 coal was mined for use in the mines at Elsa and Cassiar, and from 1972 to 1981 up to 25 000 tonnes/year of coal was mined by Cyprus Anvil Mining Corp. for plant heating and drying of concentrate at the now abandoned Faro SEDEX Pb-Zn mine. Speculative unconventional targets in the trough include coal bed methane in both Tanglefoot and Tantalus coal deposits, and tight/shale gas in the distal Richthofen shales (Hayes, 2012). A qualitative assessment of unconventional prospectivity in the trough suggests that evidence for shale gas is compelling (Hayes and Archibald, 2012), however recent play redefinition now considers shale potential to be restricted to only the very southeast of the basin (Hutchison, unpublished, 2015). No systematic unconventional petroleum studies have been undertaken in the Whitehorse trough to date.

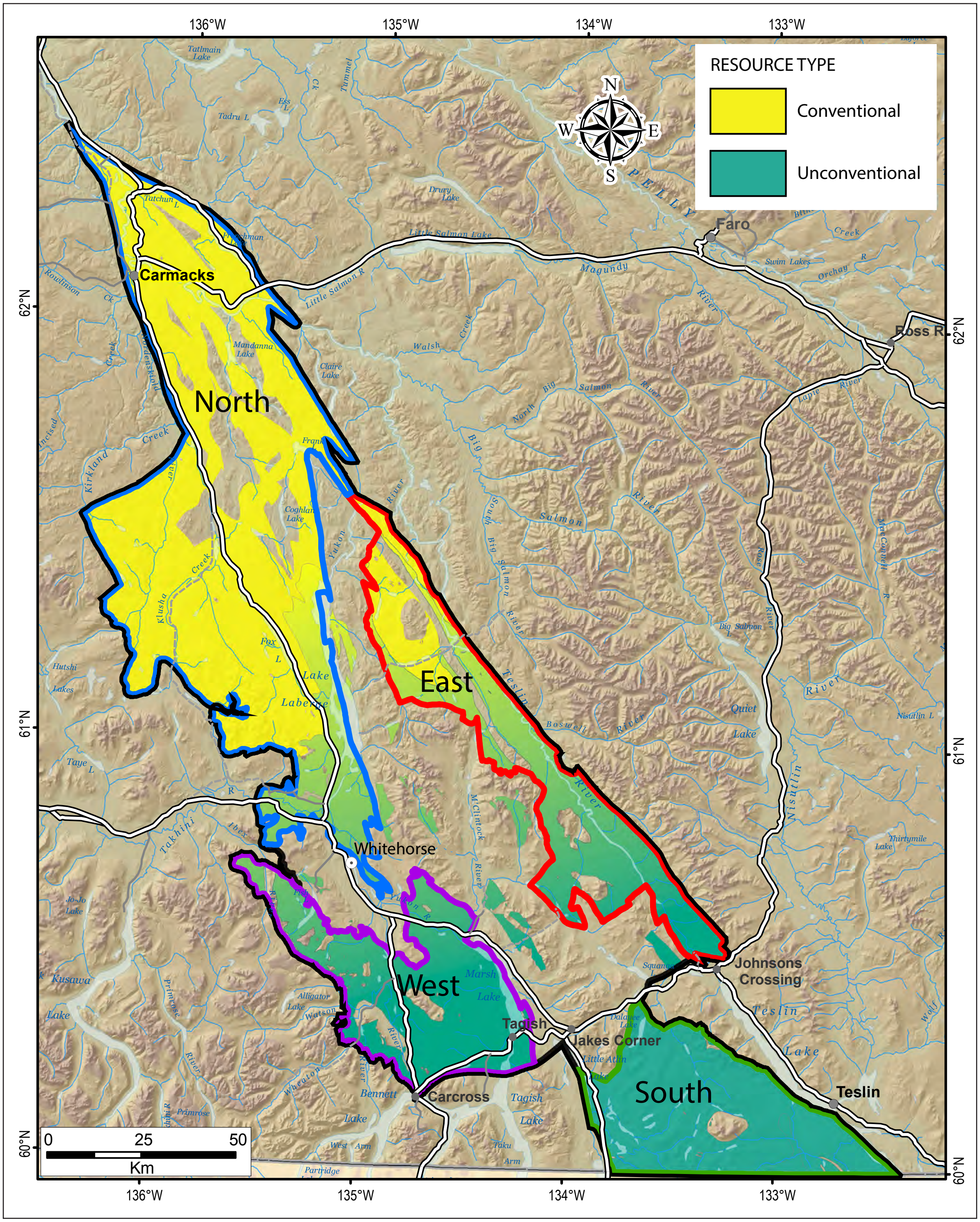


Figure 1-9. Resource exploration and petroleum research areas for the Whitehorse trough (from Hutchison, unpublished, 2015).

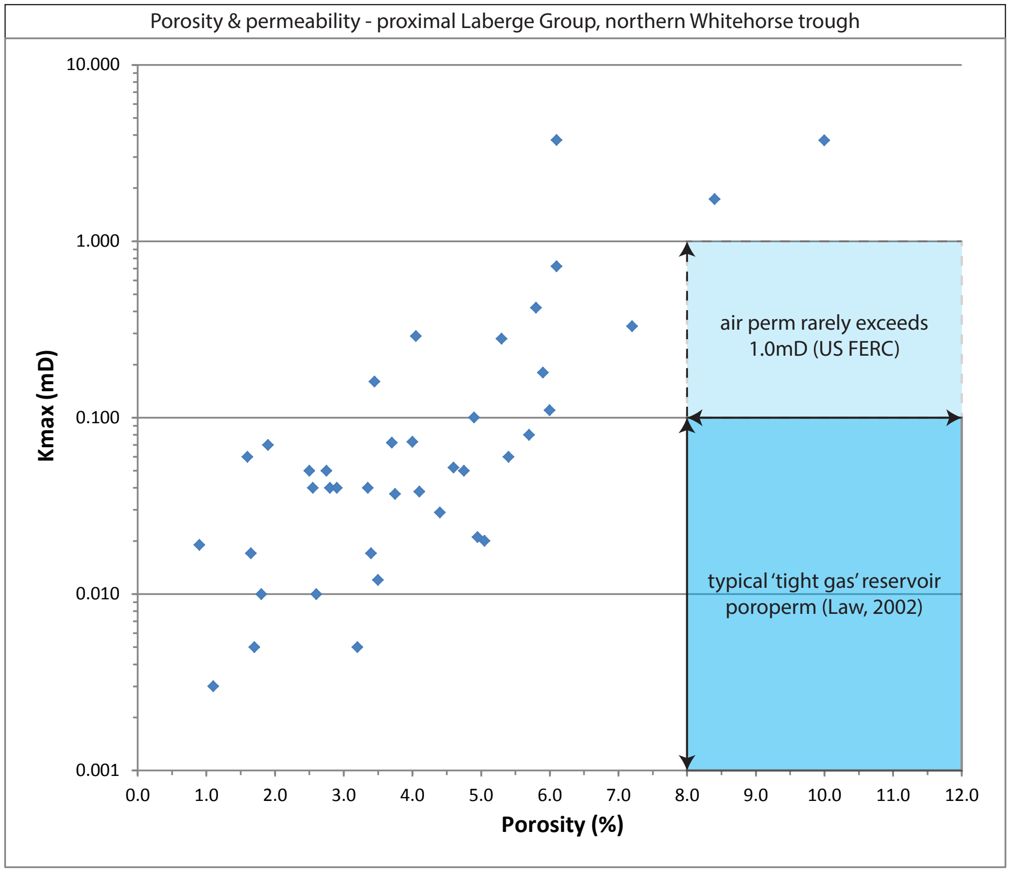


Figure 1-10. *Poroperm data from the proximal Laberge Group outcrops along the Robert Campbell and North Klondike highways and shallow DDH core from Division Mountain.*

DAY 1 - TRIP LOG

From Whitehorse we will be traveling approximately 195 km to the first outcrop east of Carmacks. We will first travel west (north) on the Alaska Highway to the junction with Mayo Road (North Klondike Highway), then north along the Klondike Highway to the junction with the Robert Campbell Highway, and then east to the first outcrop (Stop 1-1; Fig. 1-1; Plate 1). The following trip log starts at Stop 1-1 on the Robert Campbell Highway, and traces our journey back south to Whitehorse over the day. Distances recorded in the log are those along each of the principal highways, although a separate odometer log is also given in parentheses with instructions as to when to start and reset. The first three stops will examine rocks of the proximal Laberge Group in Whitehorse trough. We will then drive south to visit three time-equivalent outcrops of distal Laberge Group between Lake Laberge and Vista Road on the North Klondike Highway.

ROBERT CAMPBELL HIGHWAY (EAST – WEST)

Stop 1-1 – proximal Laberge Group (Tanglefoot formation)

km 554.2 (start 0.0 km) east of Eagles Nest Bluff, Robert Campbell highway (UTM 8v, 456959E, 6877113N, elev 627 m).

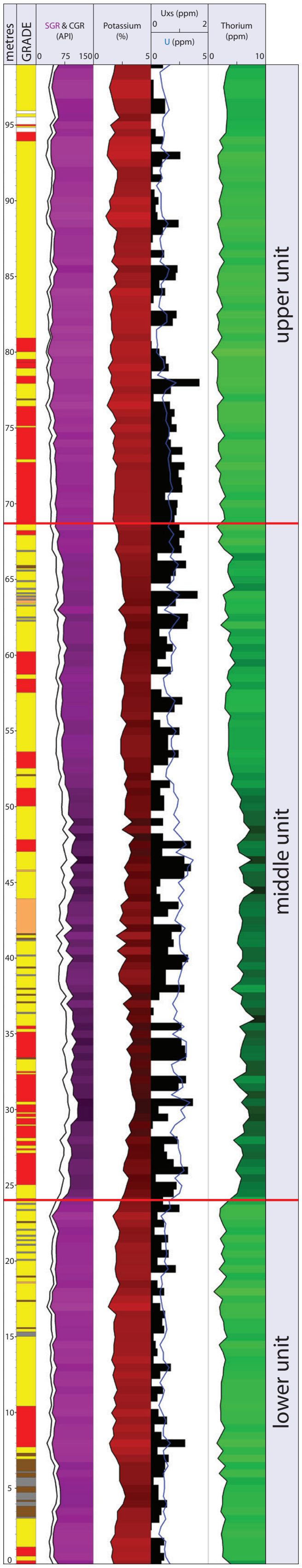
The maroon-weathering, medium to coarse grained sandstones and poorly sorted conglomerates exposed at Eagles Nest Bluff are the oldest Laberge Group rocks known in the Whitehorse trough (Fig. 1-11). Clasts of the conglomerate are dominated by volcanic and sub-volcanic rocks, but also include lesser limestone, red mudstone and, rarely, eclogite lithologies. Long (2005) interpreted these strata as deposits of a gravel-bed meandering fluvial system, with channel-fill sequences dominated by lateral accretion surfaces and interbedded mudstones representing overbank deposits. Red mudstone interbeds (<10 cm) locally display sand-filled desiccation crack casts (Fig. 1-12). Sandstone grain composition and sorting appears similar to the arkosic, maroon-weathering Rhaetian (Upper Triassic) Mandanna member sandstones of the Lewes River Group (see Fig. 1-3) farther south in the trough (Stop 2-1; Fig. 1-1; Plate 1), and in view of this outcrop's structural and stratigraphical position above Hancock member exposures immediately to the west, Long (2005) assigned these rocks to the Mandanna. Recently, however, detrital zircon analysis of a single coarse-grained sandstone sample yielded a weighted mean age for a cluster of young zircons of 193.8 ± 1.8 Ma (Fig. 1-6; Colpron *et al.*, 2015), suggesting a Sinemurian depositional age and re-assignment of this section to the base of the Laberge Group (Tanglefoot formation).

Figure 1-11. *Outcrop of Tanglefoot formation (proximal Laberge Group) immediately east of Eagles Nest Bluff on the Robert Campbell highway. Vehicle parking is on the graveled area opposite.*

Figure 1-12. *Sand-filled desiccation crack casts in the lower maroon fine-grained unit.*

The section can be broadly divided into upper and lower maroon, fine-grained facies that encase a middle section of grey/red weathered, poorly sorted conglomerates and sandstones. Gamma spectrometer and whole rock geochemical data highlight that the upper and lower strata are significantly depleted in potassium (average 1.30%) relative to the coarser-grained middle unit (Fig. 1-13), the entire section at stop 1-2 or Tanglefoot formation strata analyzed from Division Mountain to the south (average of 2.81%). They appear, however, to be very similar to those of older the Mandanna member around Whitehorse (averaging 1.52%). The maroon hematitic weathering and desiccation of fine-grained clastics in the Lower Jurassic basal Laberge Group and Upper Triassic Mandanna member (c.f. Hart, 1997; Long, 2005) suggest the prevalence of Late Triassic depositional processes and semi-arid climate across the Hettangian-Pliensbachian sub-Laberge unconformity (Colpron *et al.*, 2015) in this area (see Fig. 1-7). Geochemical results also hint at the potential to detect subtle provenance shifts in these older, proximal Laberge Group rocks that may facilitate future chemostratigraphic correlation.

14-MH-013 (Eagles Nest Bluff)



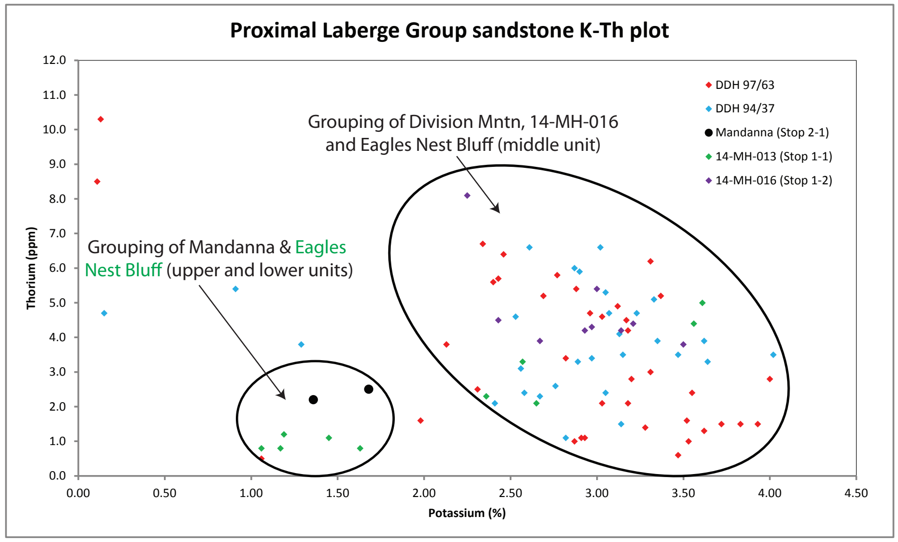


Figure 1-13. *Spectral gamma ray log for the Eagles Nest Bluff outcrop and Tanglefoot sandstone K/Th crossplot (from whole rock geochemistry). Note the depletion of potassium especially in the upper and lower unit logs relative to central unit, and the stronger geochemical relationship of these units with the Mandanna member than with other Tanglefoot outcrop rocks in the trough.*

In addition to stratigraphic assignment, way-up direction has also been of debate at this outcrop. Long (2005) interpreted scoured fluvial channel-fill deposits with an east to west way-up (Fig. 1-14). However, desiccation crack casts in both the lower and upper fine-grained facies at this outcrop indicate a west to east way-up direction. In addition to the absence of any structural fabric to indicate such a tight fold in the section, the latter direction is supported by the presence of Hancock member limestones unconformably capped by Laberge Group conglomerates 500 m west of this section. This will therefore require a re-interpretation of depositional environments here, and is planned as future work in the trough.

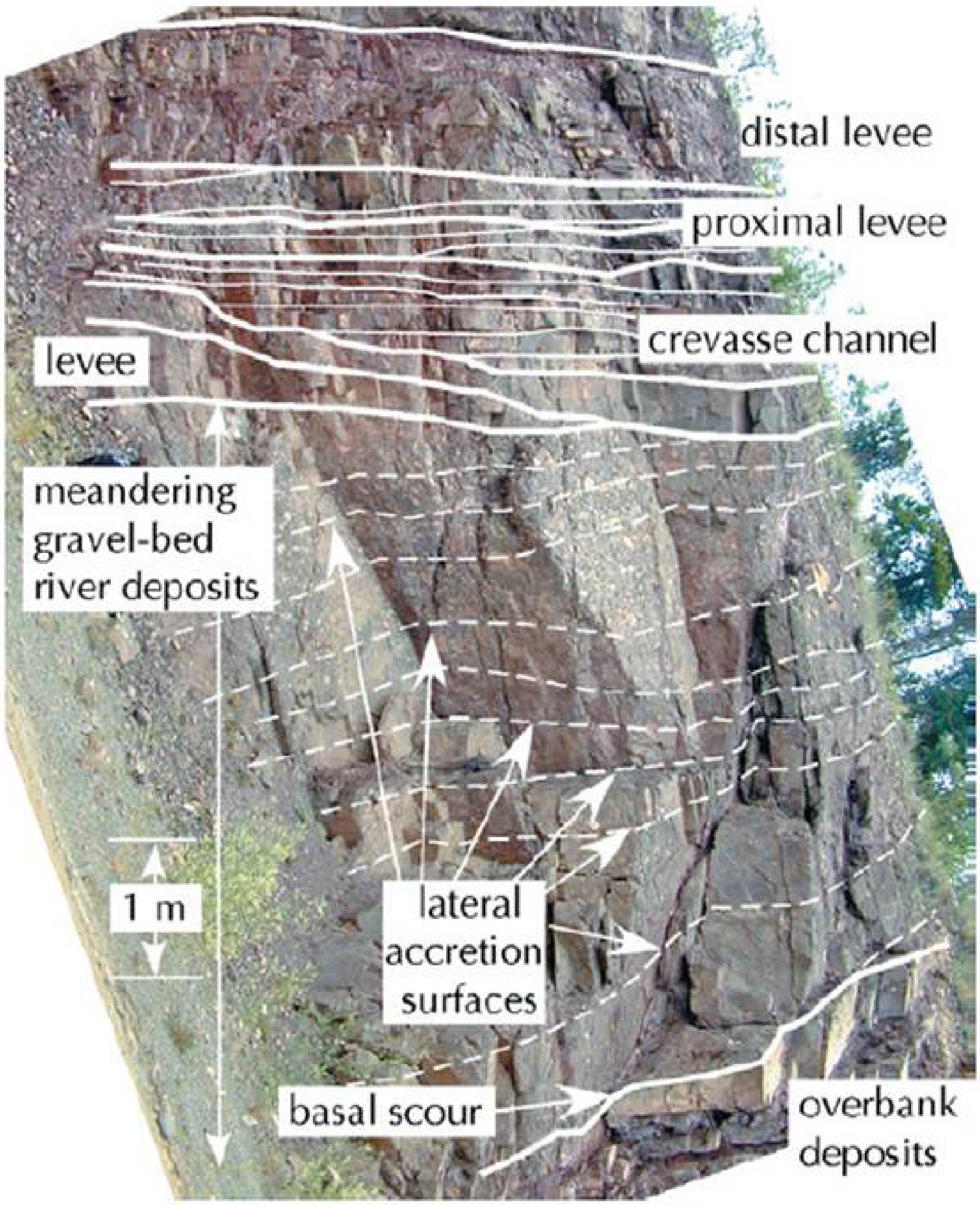


Figure 1-14. *Meandering gravel-bed river channel interpretation from Long (2005) inferring a younging direction to the west.*

km 554.7 (0.5 km) Track heading south up to exposures of Hancock member (Lewes River Group) on Eagles Nest Bluff. The basal Laberge Group unconformity can be viewed in the undergrowth before the track emerges onto the bluff overlooking the Yukon River.

km 555.2 (1.0 km) Outcrop of proximal Laberge Group (Tanglefoot formation) on north side of highway.

km 555.6 (1.4 km) The Columbian disaster rest area and viewpoint. The Columbian, one of the fleet of sternwheelers that plied the Yukon River early last century, exploded and sank at this point on September 25, 1906 killing six men. There is also an intriguing outcrop of Tanglefoot formation on the way down to the river – interbedded coarse sandstones and pebbly conglomerates that may represent a winnowed beach deposit?

km 561.0 (6.8 km) Volcanics of the Upper Cretaceous Carmacks Group outcrop on the hillside to the north of the highway. Exposures end at km 562.8 (8.6 km).

km 567.2 (13.0 km) The White River Ash is visible on the north side of the highway at this location. Much of the roadside between here and Whitehorse is draped with a fine white tuff known as the White River Ash. The ash is derived from an eruption of Mount Churchill in Alaska approximately 1,200 years ago which was one of the largest volcanic events in North American history. Strong westerly winds blew the ash over an area of approximately 500 000 km^2 – as far east as Great Slave Lake in the NWT. Look out for it as the day progresses!

Stop 1-2 – proximal Laberge Group (Tanglefoot formation)

km 572.5 (18.3 km) Proximal Laberge Group (Tanglefoot formation), Robert Campbell highway (UTM 8v, 441715E, 6885880N, 549 m).

Outcrops of proximal Laberge Group (Tanglefoot formation) along the Robert Campbell highway east of Carmacks comprise interbedded sandstone and mudstone, conglomerate, pebbly sandstone, tuff beds and coal. Outcrops of this formation continue intermittently along the highway until km 573.1 (18.9 km). A detrital zircon date from a sandstone just west of this section round the corner yielded a weighted mean age of 181.9 ± 3.0 Ma (Fig. 1-6, 04MC002; Colpron *et al.*, 2015). Benthic macrofossils include pelecypods, brachiopods, corals, gastropods and crinoids indicative of shoreline to marginal marine environments (*e.g.*, Poulton, 1979), and fossilized plant and wood fragments are abundant (Lowey, 2004). Fossil assemblages indicate a Sinemurian to Bajocian age for the formation (Lowey, 2004). Spore and pollen assemblages suggest a well-drained (semi-arid) alluvial and coastal plain environment (Sweet, 2007). Coral wackestone, floatstone and oyster rudstone in the formation suggest either bioclastic bar development in a shallow marine setting or supratidal storm deposits (Lowey, 2008). This section is much younger than that of Stop 1-1: U-Pb detrital zircon analysis of a sandstone sample from equivalent strata just to the west of this section yielded a weighted mean age of 181.9 ± 3.0 Ma (early Toarcian; Colpron *et al.*, 2015; Fig. 1-6, sample 04MC002).

This outcrop of proximal Laberge Group consists of thick to very thickly-bedded coarse sandstones and granule to pebble conglomerates intercalated with finer-grained heterolithic intervals (Fig. 1-15a). Thick bedded sandstone intervals are typically internally structureless, but are often interbedded with thin mudstone beds that become reworked as angular rip-up clasts in bed bases (Fig. 1-15b). A rare cluster of sub-vertical, sparsely branched unlined burrows (*Psilonichnus*; E. Nesbitt, pers. comm.) was observed in the central coarse-grained interval (Fig. 1-15c), suggesting an estuarine or tidal delta bar depositional environment for these sandstones. Sandstone intervals typically fine up-section from a conglomeratic base, but exhibit a corresponding 'boxcar' gamma ray signature (Fig. 1-16). Gamma ray profiles of these proximal Laberge Group sections (Stops 1-1, 1-2 and 1-3) highlight a potential provenance and mineralogical control

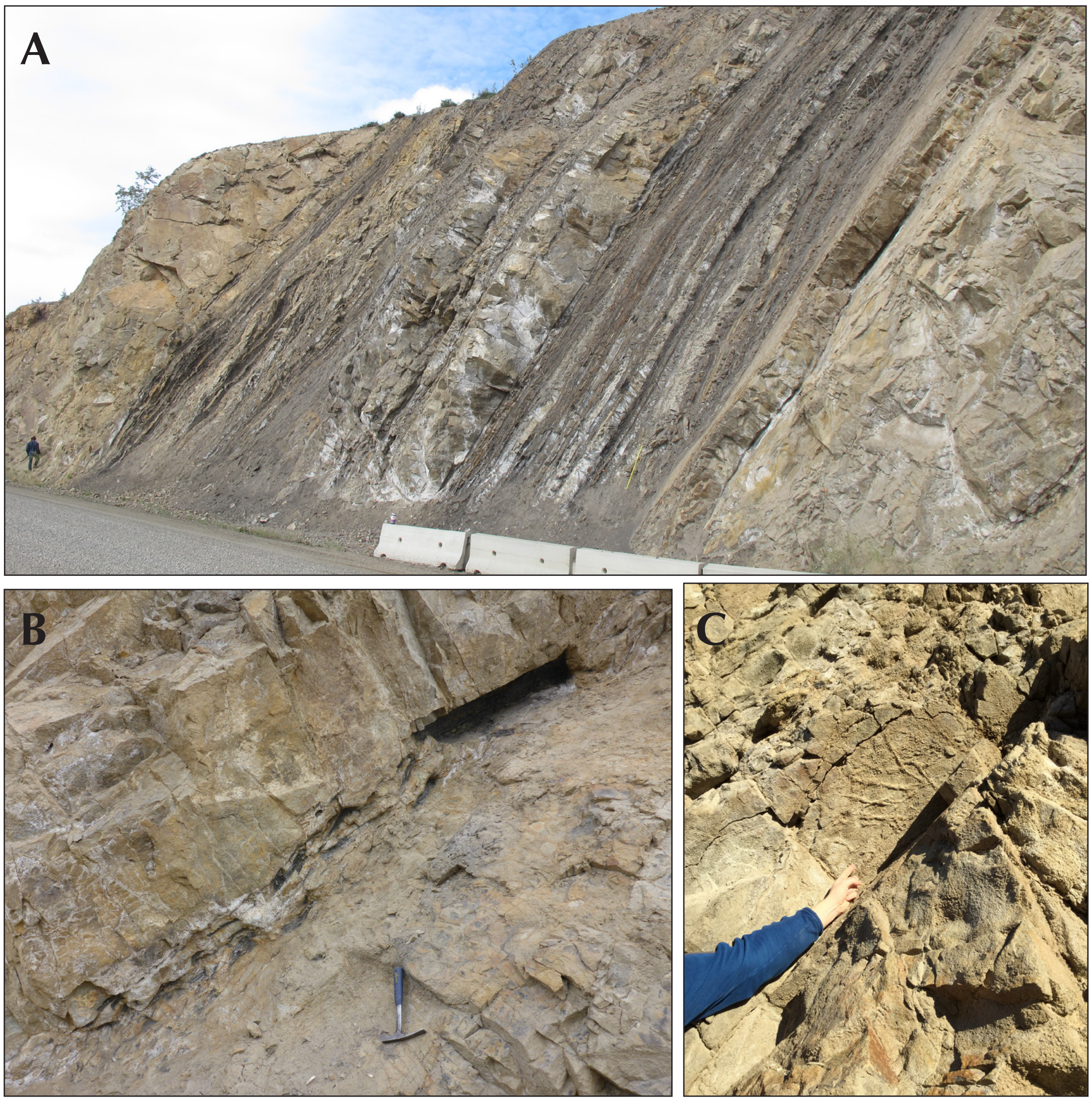


Figure 1-15. *A) Intercalated coarse sandstone to pebble conglomerates and heterolithic sediments on the Robert Campbell highway east of Carmacks. B) Mudstone rip-up clasts – the large angular 'raft' to the top right of the photo may represent the in situ remnants of an interbedded mudstone unit that has then been eroded and reworked as rip-up clasts further down dip (centre and bottom left). C) Sub-vertical, sparsely branched, unlined burrows in the central coarse-grained sandstone interval. These are interpreted as Psilonichnus.*

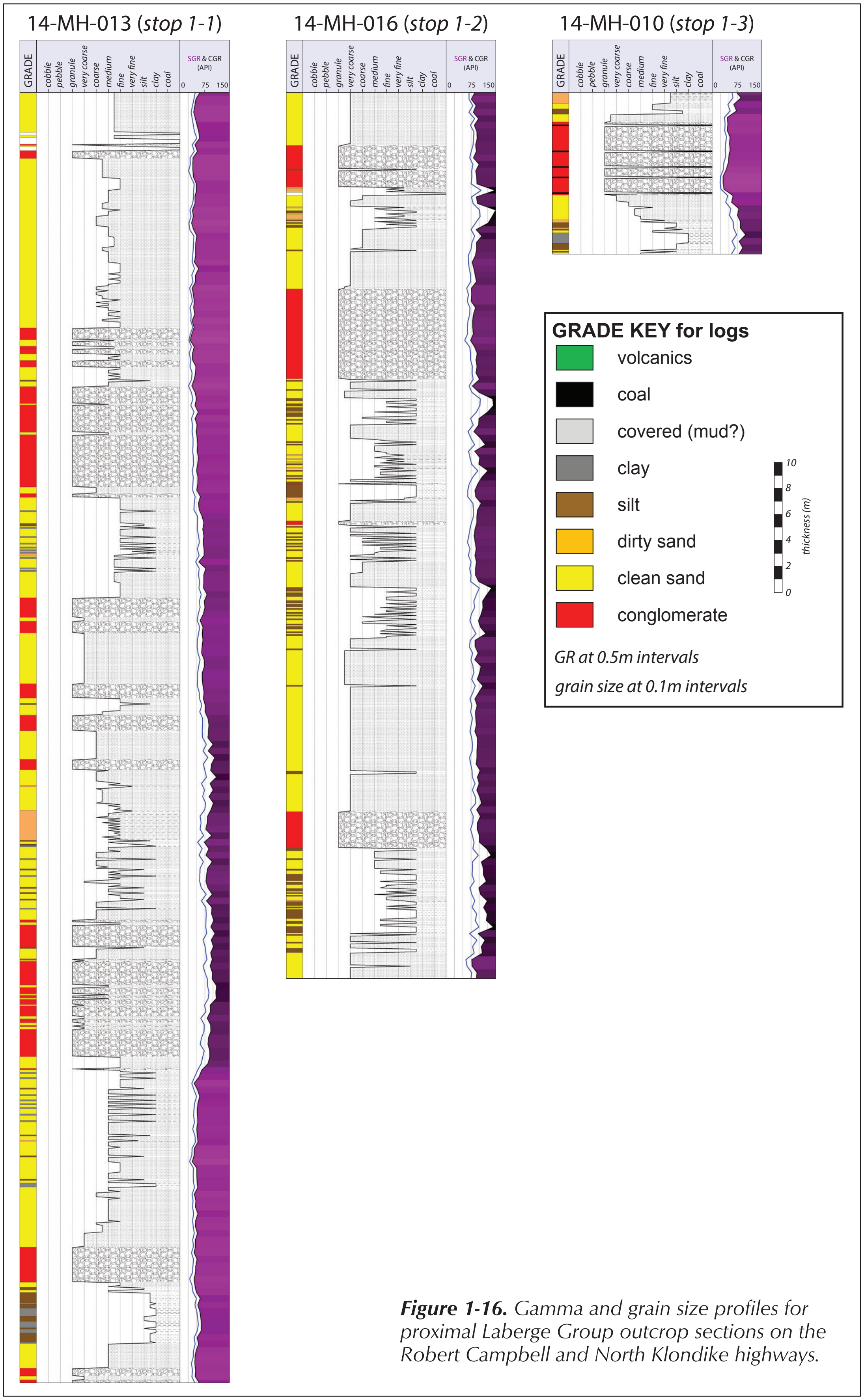


Figure 1-16. *Gamma and grain size profiles for proximal Laberge Group outcrop sections on the Robert Campbell and North Klondike highways.*

on gamma radioactivity rather than simple grain size difference. Conglomerates and very coarse sandstones throughout this entire section have a high radioactivity that is comparable to the middle portion of the Stop 1-1 section just visited (see Fig. 1-16), but which is much higher than strata of equivalent grain size in both the lower and upper intervals of Stop 1-1 and the upper interval of Stop 1-3 (next locality).

Heterolithic interval sandstone beds are finer grained (but still medium to coarse), internally structureless and occasionally exhibit wave-rippled bed tops. Circular patches of red-brown mottling in these sandstones are tentatively interpreted as burrows (Fig. 1-17a). Mudstones are also mottled, but heavily fractured and weathered. Further detailed sedimentological work is planned at this outcrop to better understand its depositional environment. The outcrop also displays evidence of the trough's compressional history, with shortening accommodated primarily within the mudstones of the heterolithic, fine-grained facies (Fig. 1-17b). Intense sigmoidal folding occurs within the more competent thin sandstone beds.

km 573.5 (19.3 km) **Lunch stop.**

Pull-off on the south side of the highway to a terraced area overlooking the Yukon River.

km 577.6 (23.4km) Carmacks airport road.

km 578.8 (24.6 km) Outcrop of Tanglefoot formation on north side of highway.

Figure 1-17. *A) Mottling interpreted as potential burrows within medium to coarse-grained sandstones in the heterolithic interval. B) Compressional deformation accommodated by sigmoidal folding in competent sandstones and plastic flow in mudstones of the heterolithic intervals.*

km 580.6 (26.4km) This point marks the start of 400 m of visible exposures of Middle Jurassic to Lower Cretaceous Tantalus formation on the hills to the north of the highway. This is Tantalus Butte, which was mined for coal both in open pits and underground until 1981. Steeply dipping interbedded shale and sandstone comprise the lower stratigraphic section in the mine area, and this is underlain by a 1 m thick continuous coal seam. Fossil leaf and plant material are abundant in exposures in the open pit. The upper stratigraphy is dominated by characteristic fluvial chert pebble conglomerate. A forest fire in the 1950s ignited a small secondary coal seam at the old underground mine, and smoke is still observed from cracks in the ground around the old workings today.

km 582.3 (28.0 km) Junction with the North Klondike Highway. Look north to Tantalus Butte. We will now head south on the North Klondike Highway, stopping at the Carmacks General Store en route.

RESET ODOMETER

NORTH KLONDIKE HIGHWAY (North – South)

km 359.1 (0.0 km) Junction with Robert Campbell Highway (km 582.3). Head south.

km 357.3 (1.8 km) Yukon River bridge.

km 357.0 (2.1 km) Just after the Yukon River bridge is a roadside turnoff on the left. Here there is a sign marking the beginning of the trail to Coal Mine Lake, site of the underground Tantalus coal mine, and an information board conveying some of the mine's operational history in the early 1900s. Cliff exposure above this turnoff are of Tantalus Formation chert pebble conglomerate.

km 356.3 (2.8 km) Carmacks General Store and 'downtown' Carmacks.

km 354.6 (4.5 km) Carmacks visitor information center and rest stop.

km 343.3 (15.8 km) Plume agate gem and mineral trailhead, east side of highway. Up the trail there is an exposure of green weathering chalcedony conglomerate. Farther away from the highway, the agates within the conglomerates occur in vein-like structures. At the top of the hill is the unconformity between the Tantalus formation and the capping Carmacks Group basalts.

km 341.6 (17.5 km) Outcrop of Carmacks Group volcanics on the east side of the highway.

km 337.5 (21.6 km) Start of 1.2 km of sporadic exposures of Tantalus formation chert pebble conglomerate on the eastern edge of the highway.

Stop 1-3 – proximal Laberge Group (Tanglefoot formation)

km 335.2 (23.9 km) Lone Pine Mountain, North Klondike highway (UTM 8v, 439316E, 6865680N, 580 m). Park on the western side of the highway on the verge. Take care when crossing the highway to the outcrop.

This outcrop of proximal Laberge Group on the east side of the North Klondike highway forms a key link between good exposure of Tanglefoot gravels and sandstones (that we have just looked at) in the north and the tightly-drilled, mud-prone coal deposits to the south at Division Mountain (Plate 2). The abrupt transition between interbedded grey-brown sandstones and mudstones to coarse-grained, white sandstones up-section is also recognized in core from Division Mountain, where it was used to locally divide the Tanglefoot formation into a 'lower' and 'upper' member (Allen, 2000). It is a key regional surface, although likely diachronous, and shows evidence of loading along its lateral extent in outcrop (Fig. 1-18a). Coal deposits only occur above this horizon in the Tanglefoot formation.

A pronounced coarsening-up signature is recorded in both grain size and gamma ray logs in the lower 5 m of this section. Sandstone beds are typically internally structureless, although there are hints of storm-wave processes and thin, current-rippled beds. Thicker, planar beds towards the top of this interval exhibit sharp, erosive bases (Fig. 1-18b). Interbedded mudstones are generally too weathered and fractured to reveal structure, however their bed thickness and frequency decreases up-section. A marine environment is indicated by local Trigoniid and coral recoveries from outcrops at Division Mountain (Allen, 2000) and by glauconite observed in sandstone thin sections. The lack of bioturbation at this location suggests a more stressed environment than to the south in Division Mountain, with repeated sediment/freshwater? influx combined with possible storm activity in a prograding offshore to lower shoreface transition.

The coarse-grained sequence that forms the bulk of the outcrop exhibits abundant current-generated structures draped by mudstone and carbonized plant material (Fig. 1-18c). Cross-stratification is shallowly inclined, with occasional preservation of topsets and common muddy toesets (Fig. 1-18d). Reactivation surfaces, carbon/mud-rich flasers and current ripple-lamination are also observed. This section is tentatively interpreted as a sequence of stacked tidal bars of estuarine or tidal-delta origin. Its presence is consistent with the progradational character of the shoreface deposits below, and the sharp contact at its base is evidence for abrupt (regional) base level fall (see Fig. 1-7) resulting in the reworking of older swamps and low-lying coastal plains further up depositional dip. Low-sulphur contents of the coals in the upper Tanglefoot formation suggest a depositional environment outside of the influence of marine water (Allen, 2002), such as plains landward of the bayline, and vitrinite varieties of this unit from Division Mountain indicate an environment dominated by reeds of a low-lying wetland flora (Beaton *et al.*, 1992).

km 332.3 (26.8 km) Outcrop of Lower Jurassic Nordenskiold (Laberge Group) volcanics.

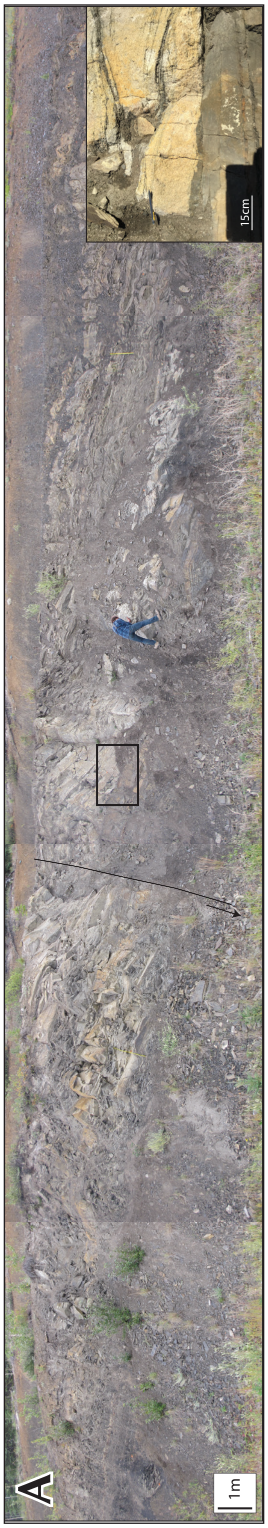


Figure 1-18. *A) Lone Pine Mountain outcrop photopanel and inset detail of the abrupt transition between the lower and upper sequences in this section. B) Orange-weathered, erosive-based planar sandstone beds at the top of the section's lower sequence. C) Abundant current-generated structures draped by mudstone and carbonized plant material in tidal deposits of the upper sequence. Note possible preservation of herringbone cross-stratification? in upper-centre of photo. D) Muddy toesets and foreset drapes in a thin, cross-stratified sandstone bed in the section's upper sequence.*

km 325.1 (34.0 km) Start of 2.1 km of Carmacks Group volcanics on the eastern side of the highway.

km 322.6 (36.5 km) Montague Roadhouse and rest stop. View to east is of Montague Mountain, with thick-layered Nordenskiold (Laberge Group) tuffs exposed on the open slopes.

km 320.8 (38.3 km) White River Ash. Much of the roadside from Minto Mine (between Carmacks and Pelly Crossing) south to Twin Lakes is draped with the White River Ash.

km 308.5 (50.6 km) Twin Lakes campground. An interpretative sign showing the glacial history of the area can be found in the campground area next to the cooking shelter and water pump.

km 298.7 (60.4 km) Conglomerate Mountain and rest stop. Views to the south of this mountain start from km 301.6 (57.5 km) on the highway. Boulders of distinctive Laberge Group (Tanglefoot formation) conglomerate line the borders of this rest stop beneath Conglomerate Mountain (once the type locality for the now-abandoned Conglomerate formation – see Fig. 1-3). The conglomerates are polymict, containing pebble to cobble-sized rounded clasts of sedimentary rocks, basic volcanic and related igneous (granitic) rocks mainly derived from the underlying Lewes River Group and Early Jurassic plutons flanking the trough. There is an old interpretative sign here that explains the evolution of the Whitehorse trough.

km 288.5 (70.6 km) Outcrop of Hancock member (Aksala formation, Lewes River Group) on the east side of the highway. Limestone exposures in this area were subject of exploration as a source of lime in recent past.

km 281.9 (77.2 km) Access road to Division Mountain and Braeburn Lake on the west side of the highway. The Division Mountain property is an aerially extensive coal lease that was explored relatively continuously between the early 1970s and the mid-2000s. There is very little exposure of the coal seams at surface in the area, and exploration was conducted mainly by shallow diamond drilling and trenching. Holes reach measured depths of ≥300 m into the Tanglefoot formation, and the cores (stacked at camp) would have provided an excellent sedimentological record of Early Jurassic coastal plain deposition had they not been abandoned and left to weather for over a decade. One core, DDH 72/05, has been stored at the core library in Whitehorse and detailed work on this material is planned for summer 2016.

km 281.7 (77.4 km) Braeburn Lodge, airstrip and rest stop. Views to the north are of low mountains of Hancock member limestone. The Lodge produces world famous cinnamon buns renowned for their size.

km 272.8 (86.3 km) Fox Lake 1998 burn pull-off and rest stop. The boulders here are glacial erratics of Tanglefoot formation. The trail overlooks glacial meltwater channels and gives a view over Braeburn Lake to the north. Approximately 45 000 ha were swept by the fire.

km 268.7 (90.4 km) Outcrop of distal Laberge Group (Richthofen formation) in highway cuts. Look carefully to see submarine fan channel-fill sandstones and interbedded mudstone-sandstone turbidites. We will see similar rocks exposed at Stop 1-4.

km 248.8 (110.3 km) Fox Lake campground.

km 234.2 (124.9 km) Tantalus Highway stop. The outcrop is composed of black fissile shale interbedded with massive, fine-grained arkosic sandstone of the distal Laberge Group (Richthofen formation). Beds are almost vertical, and leaf fossils can be found at the southern end of the outcrop on sandstone bedding planes.

km 226.0 (135.0 km) Deep Creek Road – turn left here and head east on the gravel track towards Lake Laberge campground. Just before the campground on the left is Fossil Point Road (136.0 km), which eventually leads to a shoreline outcrop of Richthofen formation productive for ammonite fossils. Continue to the campground (136.3 km) and park near the boat launch. Outcrops of distal Laberge Group (Richthofen formation) on the shoreline of Lake Laberge comprise Stop 1-4.

Stop 1-4 – distal Laberge Group (Richthofen formation)

Lake Laberge campground and shoreline (UTM 8v, 489370E, 6771381N, 635 m).

Distal Laberge Group (Richthofen formation) exposures along the shoreline of Lake Laberge near the boat launch consist of thin-bedded (<10 cm) siltstone-sandstone and mudstone couplets. The sediments retain characteristics of deposition from turbidity currents (*e.g.*, Bouma Tcde subdivisions, normal grading and asymmetric ripple cross-lamination; Lowey, 2004, 2005), however they also show evidence of significant post-depositional modification by storm wave processes and biological activity.

Sandstone bed bases range from sharp and erosive to loaded with occasional flame structures (Fig. 1-19a), suggesting that mud substrate conditions varied between being continually waterlogged during rapid, repeated flood events or having time to dewater and indurate. Sandstones display pinch-and-swell lenticular bedding (suggesting tractive, oscillatory transport and deposition above storm wave-base), and bed tops exhibit long wavelength, low amplitude swales (Fig. 1-19b) together with isolated, preserved mudstone laminae. Sandstones are also occasionally abundantly bioturbated with unlined, mudstone filled horizontal to sub-horizontal burrows (Fig. 1-19c) interpreted as *Cruziana* ichnofacies (Lowey, 2005), indicating bottom waters were oxygenated. Stacked thicknesses of unbioturbated, normally graded mudstone-sandstone couplets (Fig. 1-19d) suggest a storm and river-influenced shelf environment where repeated sediment influx and storm-wave reworking prevented post-depositional colonization by bottom-dwellers.

Exposures to the south, between the campground and Deep Creek (~250 m) are of thick-bedded (<1 m) lithic sandstone. These sandstones are immature and poorly-sorted, and are typically composed of medium grained, angular to sub-rounded feldspar and quartz, lithic clasts of volcanic (and plutonic?) origin, and grains of augite and epidote. Graded siltstone-sandstone beds up to 10 cm thick occur between the thick sandstones, and mudstone rip-up clasts up to 10 cm in length form sandstone bed basal lags (Fig. 1-20). Lenses of reworked crystal-lithic tuff similar to the Nordenskiold occur on top of the southernmost exposure.

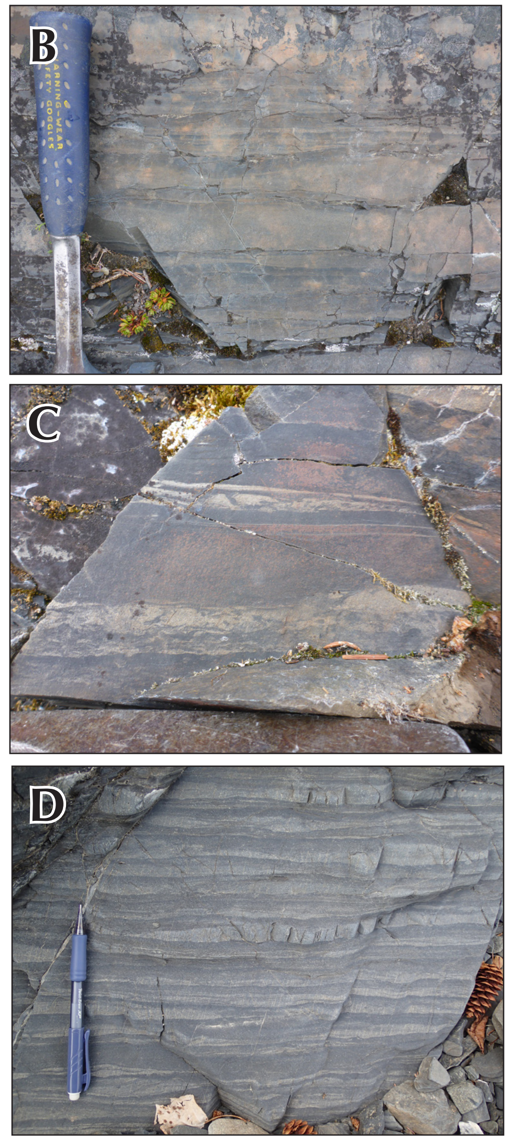


Figure 1-19. *A) Localized loading and flame structures at the base of sandstone beds in the Richthofen formation near the boat launch. B) Pinch-and-swell bedding in normally-graded sandstone beds. Note the preservation of asymmetric ripple cross-lamination in very thin sandstone beds towards the top of the section. C) Abundant sub-horizontal bioturbation in Richthofen turbidite sandstone beds. Note in the lower left of the photo, the sandstone bed structure is almost completely disrupted by burrowing. In this section, the much greater mud:sand ratio suggests less frequent high energy flood events that allowed substrate colonization by bottom dwellers. D) Stacked, unbioturbated sandstone-mudstone couplets displaying wavy, lenticular bedding and starved sand ripples with internal asymmetric cross-lamination. This depositional environment was stressed by rapid, repeated sediment (and possible freshwater) influx.*

Overall, distal Laberge Group strata at this locality represent the products of a variety of primary and secondary depositional processes acting in an oxygenated, neritic shelf environment. Thin-bedded, storm wave-reworked turbidites were deposited in the distal outer or mid-fan lobes of a submarine fan, with the thicker-bedded, erosive sandstones closer to Deep Creek representing more proximal, channeled mid-fan or inner-fan channel-fill deposits. Variability in bioturbation abundance and substrate induration suggests fluctuations in sediment influx (flood events) over time, and this may have ultimately been controlled by staccato rift shoulder uplift and/or high-frequency climatic cycles.

A sample of lithic sandstone from this locality was analyzed for detrital zircons (Fig. 1-6, sample 04SJP603; Colpron *et al.*, 2015). The majority of zircon grains yielded ages between 180-220 Ma, with a peak in the age distribution at ca. 197 Ma, and a subordinate population of Mississippian grains with ages between 320 and 350 Ma (Fig. 1-6). Colpron *et al.* (2015) estimated a maximum depositional age between 197-190 Ma (Sinemurian to Pliensbachian) for this sample. The Late Triassic to Early Jurassic ages compare well to those of plutons intruding Stikinia, Quesnellia and Yukon-Tanana terranes around the Whitehorse trough (Breitsprecher and Mortensen, 2004; Joyce *et al.*, 2016). These plutons likely represent the roots of the arc contributing sediments that filled the basin, and Mississippian sources are also known from these terranes (Takhini and Boswell assemblages in Stikinia/Quesnellia, see Fig. 1-3; and Simpson Range and Tatlmain plutonic suites in Yukon-Tanana terrane; Colpron *et al.*, 2006a; Piercey *et al.*, 2006). This detrital zircon signature clearly indicates a local derivation for the distal Laberge Group sandstones, and ages are similar to those interpreted from Whitehorse trough fossil evidence (Hettangian to Toarcian; Lowey, 2004) and to the correlative Inklin Formation in northern British Columbia (Sinemurian to Toarcian; Mihalynuk, 1999).

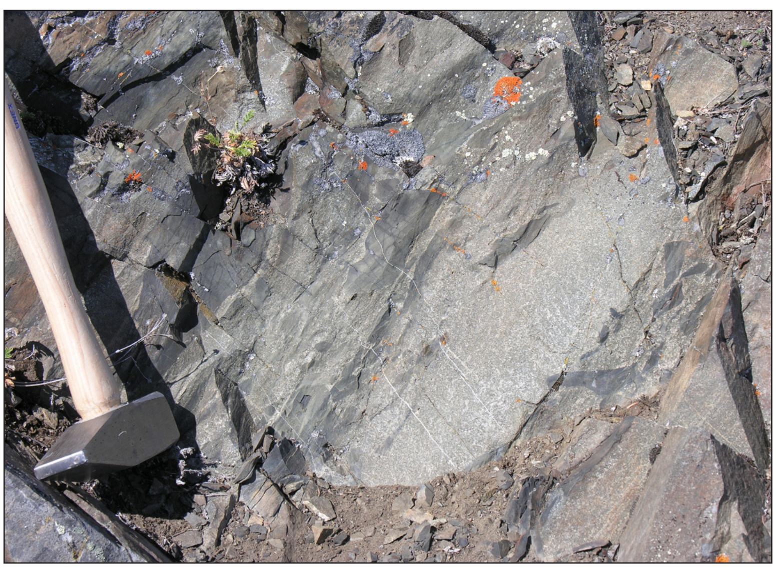


Figure 1-20. *Mudstone intraclast at the base of a sandstone bed, Richthofen formation.*

Vista

Looking east from the boat launch, the eastern shoreline of Lake Laberge is composed of Upper Triassic volcanic and sedimentary rocks of the Aksala formation (Lewes River Group). Exposed, grey-weathered outcrops are upper Norian limestone of the Hancock member, whilst the more subdued vegetated topography is underlain by Carnian-Norian volcaniclastic rocks of the Casca member. On the southeast skyline there is a clear view of Lime Peak to the north (underlain by Hancock member limestone) and Mt. Laurier to the south (underlain by conglomerate of the Laberge Group). This area is currently being remapped by the Yukon Geological Survey to better understand the Triassic stratigraphy of the Lewes River Group and its relationship to the overlying Jurassic Whitehorse trough basin-fill succession (see Bordet, 2016). Richthofen Island lies 1.6 km offshore to the northeast of the campground.

Return to North Klondike highway junction.

RESET ODOMETER

km 219.5 (6.5 km) Cliffs to the west of the highway are of Richthofen formation polymict conglomerates

Stop 1-5 – distal Laberge Group (Richthofen formation)

km 212.4 (13.6 km) Sharp turn off right onto the dirt track to Horse Creek and Stop 1-5. Drive south along the side of the highway for 300 m to a V-junction and take the right hand turn. Follow this more rutted track for 1 km and park in the clearing at the foot of the hill. The track to the Richthofen conglomerate cliffs heads west through the alder stands (UTM 8v, 490661E, 6759010N, 673m).

Laberge Group exposure in the far southwest of the northern exploration area of the Whitehorse trough (see Fig. 1-9) is dominated by polymictic cobble and boulder conglomerates, together with lesser sandstone-mudstone lithologies similar to those observed at Lake Laberge campground. The Horse Creek section was originally interpreted to contain the contact between the lower fine-grained Richthofen formation and the massive pebble conglomerates of the Conglomerate formation (see Fig. 1-3; Hart, 1997; Dickie, 1989; Dickie and Hein, 1995), however more recent work by Lowey (2004, 2005) resulted in the abandonment of the Conglomerate formation, and incorporation of the Horse Creek conglomerates into the Richthofen formation.

The finer grained facies at the base of the section are dominated by interbedded thin to medium-bedded sandstones and massive to laminated mudstones (Fig. 1-21a). Sandstone beds have scoured bases, are normally graded and exhibit planar lamination characteristic of high-energy, upper flow regime Bouma Tab turbidite deposits (Fig. 1-21b). Massive to laminated mudstones were deposited during waning flow from low density turbidity currents. Sandstone beds are laterally continuous, and appear stacked in parasequences defined by sets of increasing bed thickness up-section (see Fig. 1-21a).

Ammonite assemblages from these facies yielded fossils that confirm a Sinemurian age, and which locally are as young as lowermost Pliensbachian (Hart, 1997).

Sharply overlying these facies are 300 m (Dickie, 1989) of massive, cliff-forming conglomerates consisting of both matrix-supported boulder conglomerates with mudstone rafts and clast-supported cobble conglomerates with heavily oxidized granitic clasts (Fig. 1-21c). Mudstone rafts, up to 3 m in length, are a feature of some of the basal conglomerates in this area (Hart, 1997). The very large average clast size, and exceptionally large individual clasts, required an extreme topographic gradient typical of an uplifted source terrain. Common unidirectional paleocurrent structures indicate easterly, transverse mass-flow transport of debris from the trough's western shoulder (Hart, 1997; Dickie, 1989) onto submarine fan-deltas prograding into an under-filled basin (see Fig. 1-7). The abrupt shift in facies and energy conditions at this locality further suggests a rapid, tectonically-controlled reorganization of the western trough's drainage system.

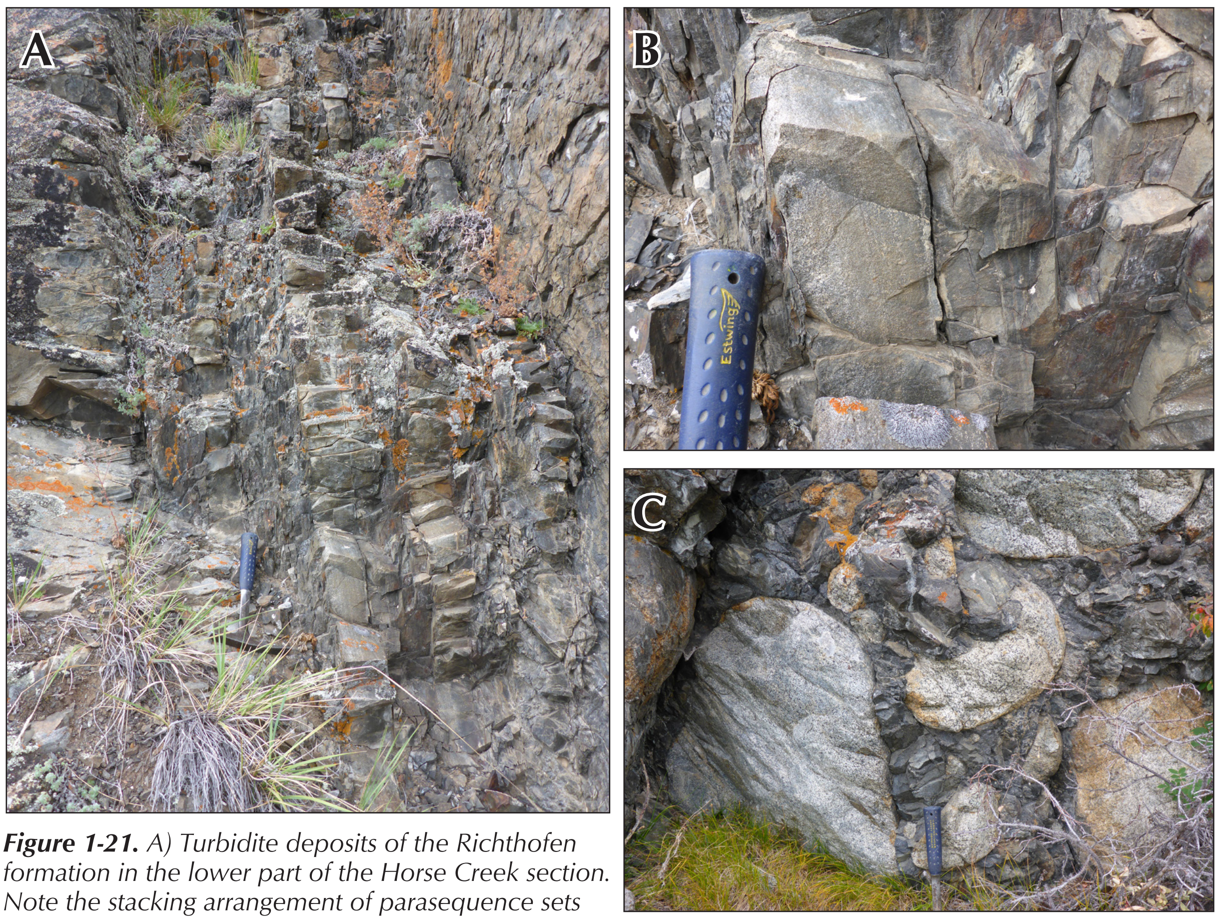


Figure 1-21. *A) Turbidite deposits of the Richthofen formation in the lower part of the Horse Creek section. Note the stacking arrangement of parasequence sets defined by increasing bed thickness up-section (left to right in the photo). B) Close-up of a graded, planar-laminated turbidite bed in the lower Richthofen deposits at Horse Creek. C) Mass-flow, clast-supported conglomerates of the Richthofen formation in the upper part of the Horse Creek section.*

Sinemurian-age conglomerates in the Whitehorse trough typically have a high proportion of sedimentary and volcanic clasts, with limestone characteristically representing up to 10-20% of the clast mode (Dickie and Hein, 1995; Johannson *et al.*, 1997; Shirmohammad *et al.*, 2011). By early Pliensbachian, volcanic clasts were dominant, suggesting the progressive exhumation of the arc terranes (Upper Triassic Povoas formation volcanics and Mandanna and Hancock member sediments; see Fig. 1-7) that flanked the trough (*e.g.*, Colpron *et al.*, 2015). The story of the Laberge Group conglomerates and their age will be expounded upon at Stop 2-2 tomorrow.

After looking at the rocks, head back to the highway junction.

RESET ODOMETER and turn right back onto the highway.

Stop 1-6 – Nordenskiold 'dacite' (Laberge Group)

km 203.8 (8.6 km) Left turn onto Vista Road (on north side of highway). Drive approximately 3 km to the end of the road at the receiver tower and park. Walk back down the track to see the outcrops of Nordenskiold 'dacite' (UTM 8v, 487871E, 6753552N, 1075 m).

Exposures at the base of the communication tower and along its access track are of the Nordenskiold 'dacite', a crystal-lithic tuff unit of dacitic composition that is interbedded with the clastic sediments of the Laberge Group (Fig. 1-22, also see Fig. 1-3). At this locality, the Nordenskiold is dark blue-grey in colour, resistant and generally massive, and weathers a mottled grey. Finer grained tuff horizons have a rusty weathered appearance. The Nordenskiold consists of a high density of medium to coarse-grained (up to 2 mm) plagioclase and quartz crystals, with finer and fewer hornblende and biotite crystals (Fig. 1-23a) and locally abundant angular to subangular mudstone clasts up to 10 cm in length (Hart, 1997; Fillmore, 2006). Bedding orientation is locally defined by faint laminations in the tuff. To the south, and across the access track, rusty weathering, fine to medium-grained crystal-lithic tuff is interbedded with mudstones and lithic sandstones of the distal Laberge Group (Richthofen formation). Patches of pebble conglomerate, consisting of granitic clasts (<2 cm) in a recessive matrix (Fig. 1-23b) are either lenses within the reworked tuff or large lithic boulders. The Nordenskiold was likely emplaced as a series of subaqueous pyroclastic flows which were subsequently reworked (Fillmore, 2006).

A sample of crystal-lithic tuff collected near this locality yielded a U-Pb zircon date of 184.1 ± 4.2 Ma (Hart, 1997), similar to ages of ca. 186-188 Ma reported from other occurrences of "Nordenskiold tuff" in Yukon and northern British Columbia (Fig. 1-24; Johannson *et al.*, 1997; Colpron and Friedman, 2008). Ammonite collections from both stratigraphically above and below the U-Pb sampled horizon also indicate an upper Pliensbachian (Lower Jurassic) age for this section (Hart, 1997). A comparative geochemical study of the Nordenskiold 'dacite' and the nearby Early Jurassic Aishihik batholith (ca. 190-180, Long Lake suite; Johnston *et al.*, 1996a; Joyce *et al.*, 2016) to the west suggests that granodiorite of the Aishihik batholith is the most likely magmatic parent of the tuffaceous rocks in the Laberge Group (Fillmore, 2006).

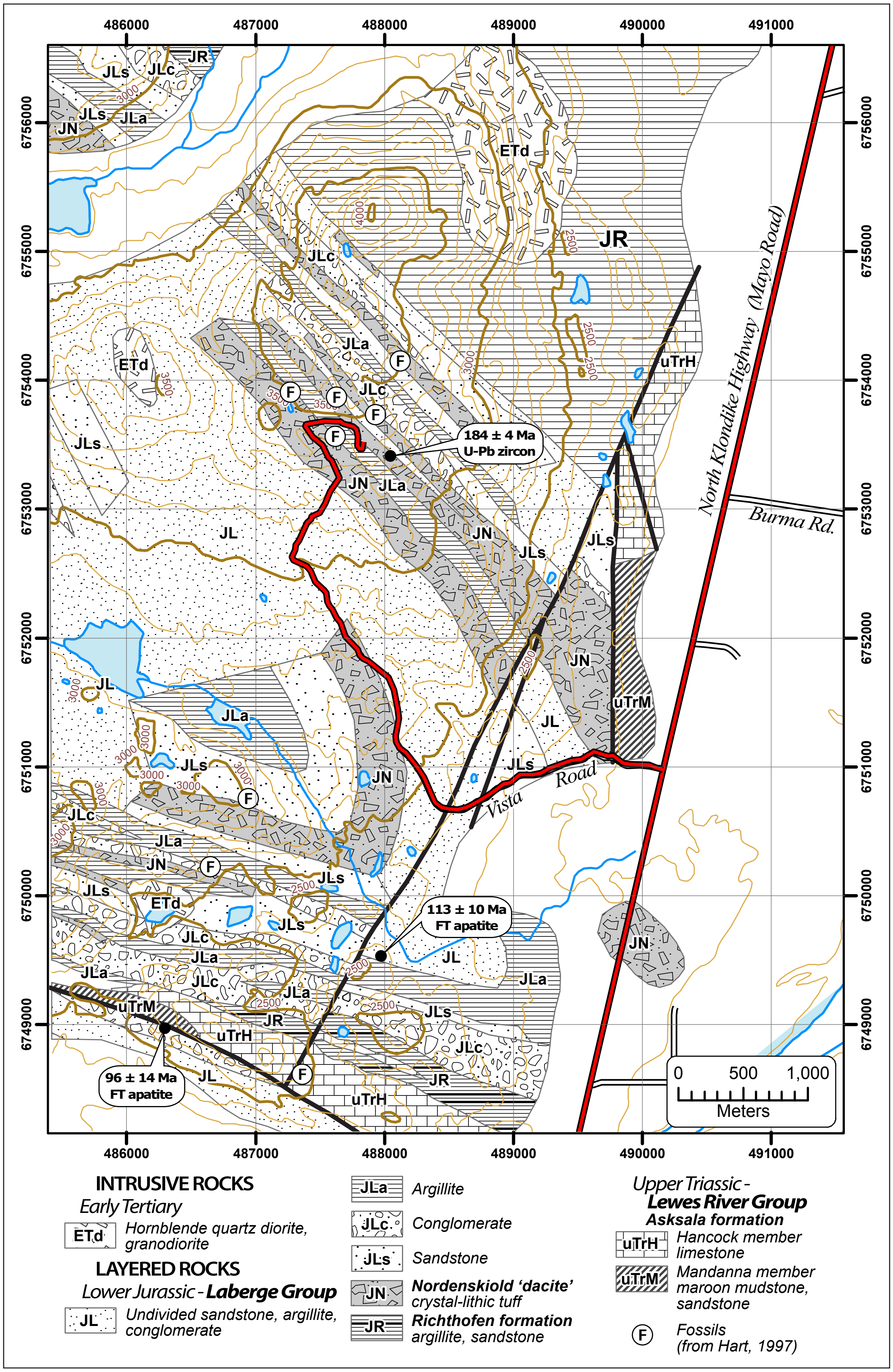


Figure 1-22. *Detailed geological map of the Vista Road area (after Hart, 1997). Coordinates are UTM (NAD83), zone 8v.*

Figrue 1-23. *A) Fresh hand sample of crystal-lithic tuff of the Nordenskiold 'dacite'. B) Pebble conglomerate lense (or weathered boulder?) in reworked tuff of the Nordenskiold.*

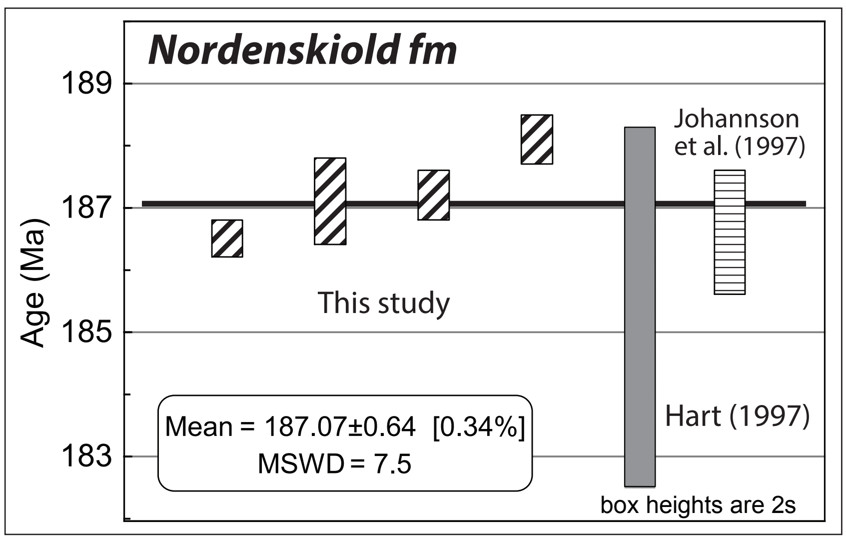


Figure 1-24. *Weighted-average age plot for all dated volcaniclastic rock units in the Laberge Group in Yukon and British Columbia (after Colpron and Friedman, 2008).*

Vistas

Ridges to the east and northeast, across the Yukon River valley and Lake Laberge are underlain primarily by volcanic and sedimentary rocks of the Upper Triassic Lewes River Group. Lime Peak and Mt. Laurier are also visible from the communication tower outlook. The high ridge to the west of the tower is the Miners Range which is underlain by Eocene granite of the Flat Creek pluton. Looking southeast from the access track outcrops, Whitehorse can be seen in the distance nestled in the Yukon River valley. The east-west trending lowland in the foreground is the Takhini River valley, and this will be our starting point for Day 2 of this transect. Haeckel Hill, Mount Williams and Mount Sumanik are visible to the south of the Takhini River, and they are underlain by Mandanna and Casca member rocks of the Lewes River Group and Eocene granites.

When driving back down the hillside to the highway junction look out for exposures of Richthofen turbidites on the roadside.

Turn right (south) on the North Klondike Highway in direction of Whitehorse.

RESET ODOMETER

km 202.4 (1.4 km) Outcrop of Lewes River Group on the east side of the highway.

km 199.6 (4.2 km) Takhini gas station and Hot Springs Road.

km 199.1 (4.7 km) Research forest.

km 197.4 (6.4 km) Takhini River bridge and Takhini-Yukon river confluence (just to the east of the bridge). Thick sections of unconsolidated clay were deposited as glacial lake bottom sediments. As you continue south on the highway you can see undulating sand surfaces along both sides of the road. These represent the lake margin aeolian dunes of ancient Lake Champagne – cross-bedding is evident if you look carefully.

km 191.6 (10.2 km) Junction with Alaska Highway (km 1437.1). Turn left to head south to Whitehorse.

DAY 2 – WHITEHORSE TO KLUANE LAKE

The second day of this geological transect of the northern Canadian Cordillera will take us from the rolling hills of the Intermontane terranes near Whitehorse, through progressively more rugged mountains underlain by the Coast Plutonic complex, and finally to the foot of the majestic Kluane Ranges, underlain by the Insular terranes, between Haines Junction and Kluane Lake. We will be travelling along the famous Alaska Highway and will overnight at the Kluane Lake Research Station, a facility of the Arctic Institute of North America.

Coast Plutonic Complex

The Coast Plutonic complex is a long, narrow and continuous zone of plutonic and lesser metamorphic rocks that extends the length of the Canadian Cordillera, from southern BC to Yukon (Woodsworth *et al.*, 1991). It straddles the boundary between the peri-Laurentian and Arctic realms (Figs. A1 and A3), although most plutons lie near the western edge of the Intermontane terranes. The calc-alkaline batholiths of the Coast Plutonic complex vary in ages from Middle Jurassic to Eocene, with predominance of older plutons in southern BC and progressively younger ones in the northern Cordillera (Wheeler and McFeely, 1991; Gehrels *et al.*, 2009). These rocks apparently become younger eastward across the belt from southeast Alaska to southern British Columbia, and may represent migration of the magmatic arc from west to east (van der Heyden, 1992).

The development of the Coast Plutonic complex is attributed to accretion of the Insular terranes to the western margin of the Intermontane terranes, beginning in Middle Jurassic (or before) and continuing for at least 150 m.y. (Monger *et al.*, 1982; McClelland *et al.*, 1992; van der Heyden, 1992; Gehrels, 2001; Gehrels *et al.*, 2009). Protracted deformation accompanied intrusion of the plutonic rocks, and several phases of deformation linked to orogen development have been tied to crustal thickening, transpression, extension and exhumation of middle and lower crustal rocks (Andronicos *et al.*, 1999; Crawford *et al.*, 1999; Rusmore *et al.*, 2005; Hollister and Andronicos, 2006; Israel *et al.*, 2013). The exposed metamorphic rocks within the Coast Plutonic complex are generally metasedimentary and are assigned to the Yukon-Tanana terrane (Nisling terrane of Wheeler *et al.*, 1991; likely equivalent to the Snowcap assemblage of Colpron *et al.*, 2006a, 2016; Plate 1), as well as metamorphosed equivalents of rocks belonging to both the flanking Insular and Intermontane terranes.

When viewed along its length, the Coast Plutonic complex has a geometry that shows an apparent doubling of the Jurassic and Early Cretaceous portions of the magmatic arc. This geometry is interpreted to reflect orogen parallel sinistral faulting of up to 800 km that occurred during the latest Jurassic to Early Cretaceous (Monger *et al.*, 1994; Israel *et al.*, 2006a; Gehrels *et al.*, 2009). Evidence for sinistral faulting within the Coast Plutonic complex and along its flanks can be found along the length of the magmatic arc and attributed to the development of several Jura-Cretaceous basins located between the Insular and Intermontane terranes (McClelland *et al.*, 1992; Monger *et al.*, 1994; Umhoefer *et al.*, 2000; Israel *et al.*, 2006a; Gehrels *et al.*, 2009; Israel *et al.*, 2013; Angen *et al.*, 2014).

In Yukon, along its eastern edge, Eocene and older granitic plutons of the Coast Plutonic complex intrude the upper Paleozoic Takhini assemblage of Stikinia (see Stop 2-3; Hart, 1997). To the west, magmatic rocks of the complex intrudes the Kluane Schist, a belt of predominantly biotite-quartz schist of Cretaceous age (*e.g.*, Eisbacher, 1976; Mezger *et al.*, 2001a; Israel *et al.*, 2010; see Stop 2-5), and the terranes of southwestern Yukon, comprising elements of the Yukon-Tanana, Slide Mountain (Seventymile), Chulitna and possibly parts of McKinley, Aurora Peak and Pingstone terranes of Alaska (Murphy, 2007), as well as parautochthonous continental margin rocks (Colpron *et al.*, 2016).

In southern Yukon, the large granitic batholiths east of Denali fault are mainly PaleocenIe-Eocene in age (Ruby Range suite, including the Ruby Range and Annie Ned batholiths; as well as the Eocene Hayden Lake suite; Plate 1; Colpron *et al.*, 2016). They form a nearly continuous belt that passes eastwards into smaller and older plutons, including the mid-Cretaceous Whitehorse plutonic suite.

Kluane Schist

The Kluane schist is an informally named package of highly deformed and metamorphosed sedimentary rocks mainly characterized by biotite-quartz schist and slightly carbonaceous muscovite-quartz schist (Fig. 2-1). The northern boundary of the schist is defined mostly by a fault that places the oldest portion of the Ruby Range batholith over top of the schist. This contact is characterized by strongly deformed quartz-diorite and diorite juxtaposed with migmatitic biotite-quartz schist (Fig. 2-2). The southern boundary of the Kluane schist is not exposed but is at least in part cut-off by the Denali fault (Plate 1). Thin, discontinuous lenses of ultramafic and gabbroic rock are found sporadically structurally interleaved throughout the schist. The largest of these are assigned to the Doghead assemblage and have been interpreted as being portions of the lower crustal roots of a Late Triassic (ca. 204 Ma) intra-oceanic magmatic arc (Escayola *et al.*, 2012).

Figure 2-1. *Biotite-quartz schist typical of the Cretaceous Kluane schist.*

Figure 2-2. *Strongly foliated quartz diorite of the Paleocene Ruby Range suite near the contact with structurally underlying Kluane schist.*

The age of the Kluane schist is not well constrained. However, detrital zircon analyses from two samples of Kluane schist indicate a probable mid-Cretaceous maximum depositional age based on a 94 Ma date for the youngest zircons (Israel *et al.*, 2011; Fig. 2-3). The detrital zircon analyses indicate the schist was sourced from rocks to the northeast (present day coordinates) including the Yukon-Tanana terrane, and Jurassic and Early Cretaceous plutons intruding the Intermontane terranes (Plate 1). Israel *et al.* (2011) interpret the schist as a forearc basin developed adjacent to an Early Cretaceous arc built on the outboard margin of the Yukon-Tanana terrane. These forearc deposits were eventually overridden by the Yukon-Tanana terrane during latest Cretaceous compressional faulting that accompanied a renewal in arc development (Ruby Range suite). Overgrowths on detrital zircons in one sample of the Kluane schist (08DM126, Fig. 2-3) suggest a metamorphic event occurred at ~82 Ma, which is interpreted to reflect the timing of burial by overthrusting of the Yukon-Tanana terrane (Israel *et al.*, 2010). This event was either ongoing, or the boundary was reactivated in the latest Cretaceous to earliest Paleocene as indicated by syn-deformation characteristics of the earliest phases of the Ruby Range suite (ca. 64 Ma), at the contact with the Kluane schist (Murphy *et al.*, 2009; Israel *et al.*, 2011). This contact is intruded by massive, ca. 58 Ma undeformed granodiorite and quartz diorite of the Ruby Range suite indicating deformation had ceased by this time. The schist and the contact with the Ruby Range had cooled below the biotite closure temperature (~300°C) as indicated by 57-55 Ma $^{40}Ar/^{39}Ar$ dates from the schist (Mezger, 2001; Israel, unpublished data). This coincided with the eruption of Paleocene volcanic centres that are preserved at the northern boundary of the Ruby Range batholith (Rhyolite Creek; Plate 1). This relationship is part of an overall section from mid to upper crustal levels (Fig. 2-4).

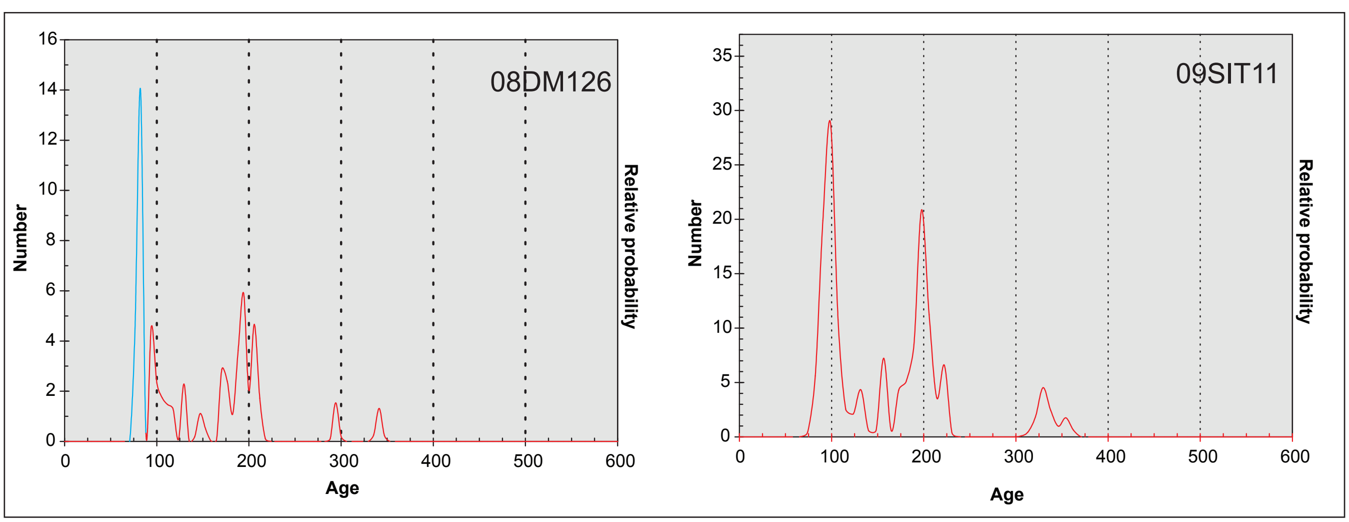


Figure 2-3. *Normalized age probability plots for detrital zircons from two samples of Kluane schist. Blue peak in sample 08DM126 is the age of metamorphic overgrowths on detrital grains (from Israel et al., 2011).*

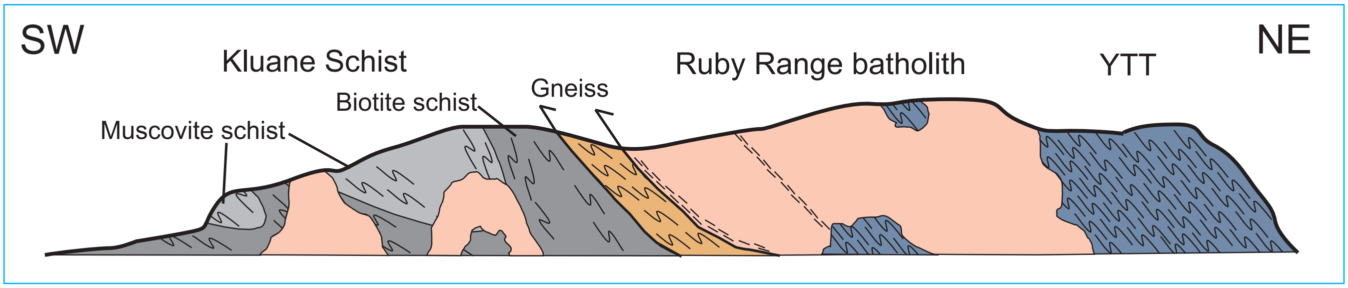


Figure 2-4. *Schematic cross-section through parts of southwest Yukon showing structural and igneous relationships between the Yukon-Tanana terrane, the Kluane schist and the Ruby Range suite (from Israel et al., 2011).*

Day 2 – Trip Log

From Whitehorse we will be traveling west (north) along the Alaska Highway, retracing part of the previous day travel to the junction with Mayo road (North Klondike Highway). The following trip log starts at the junction of Two Mile Hill and the Alaska Highway. Distances are measured along the Alaska Highway. The first three stops will further examine rocks of Stikinia and Whitehorse trough. We will then visit outcrops of the Coast Plutonic complex, and end in the Insular terranes to the west.

km 1425.3 Junction with Two-Mile Hill, north access to downtown Whitehorse. The large complex to the west of the Alaska Highway is the Canada Game Centre, the largest recreational facility in Whitehorse. The orange building on the east side of the highway, approximately 400 m north of the Two Mile Hill junction is the H.S. Bostock Core Library, home of the Bedrock Geology unit of the Yukon Geological Survey. Outcrops between this point and the Kopper King commercial complex (km 1426.8) are hornblende granodiorite of the mid-Cretaceous Whitehorse batholith. The contact between the batholith and Upper Triassic carbonates of the Lewes River Group is crossed at McIntyre Creek (km 1428.0). Copper and gold-bearing skarn deposits of the Whitehorse Copper Belt occur along this contact. The first discovery of these deposits was made 500 m west of this crossing by Jack McIntyre in 1898 while he was out hunting. The Kopper King deposit is accessible by a short road south of McIntyre Creek. The Fish Lake road leads to the subalpine Fish Lake, and easy access to alpine country above Whitehorse.

km 1428.2 Junction with Fish Lake road, leading to the Whitehorse Copper Belt and the first hydro-electric operations in the Whitehorse area. Electricity is still generated from two locations on this creek.

km 1429.0 Entering Rabbitsfoot Canyon. Exposures on either side of this natural canyon are of well-bedded carbonate of the Upper Triassic Lewes River Group (Hancock member of the Aksala formation). Rocks at the south end of the canyon are marble developed in the contact aureole of the Whitehorse batholith. Malachite staining is present in these rocks to the left (south) as we enter the canyon. The strata form a northwest-striking, moderately to steeply northeast-dipping sequence with some complex tight folds and southwest-verging thrust faults. Although generally northwest-trending, most Whitehorse trough strata typically form low amplitude open folds. Here the well-bedded carbonate likely acted as a detachment horizon.

km 1434.4 Outcrops from here to the North Klondike Highway junction are maroon and green lithic sandstone of the upper Lewes River Group (Aksala formation, Casca and Mandanna members). These rocks occur both above and below the carbonate unit (Hancock member). Strata along this section are dipping gently to the north.

km 1437.1 Junction with North Klondike Highway (Mayo road).

km 1441.0 Outcrop of upper Lewes River Group lithic sandstone (Aksala formation, Casca member).

Stop 2-1 – Mandanna member – Takhini Fire Hall

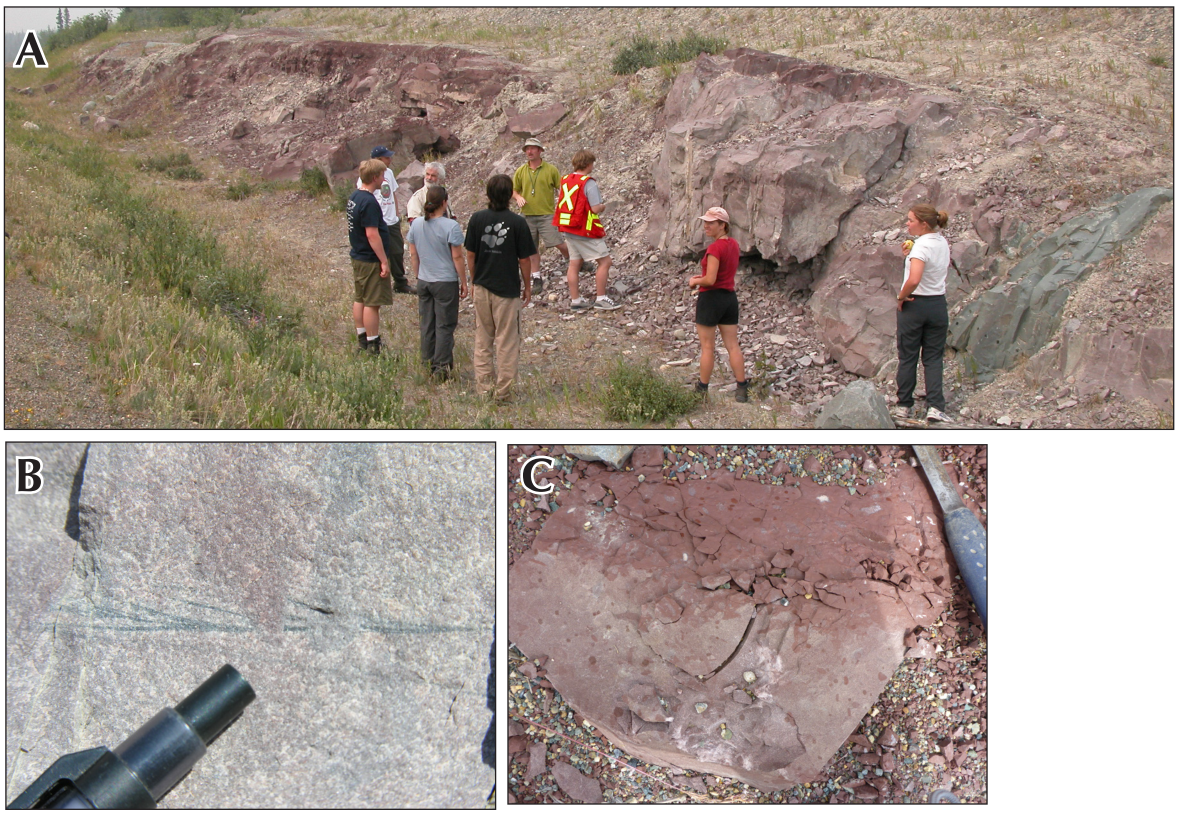
km 1443.0 Park on the shoulder to the right in front of outcrop and across from firehall (UTM 8v, 483090E, 6742250N, elev 760 m); alternatively, continue another 200 m to large pullout area beside mailboxes and walk back to the outcrop.

These distinctive maroon outcrops are characteristic of the Upper Triassic Mandanna member (Aksala formation) of the Lewes River Group. They, like other outcrops in the local area, comprise bioturbated red to maroon mudstone, siltstone and arkosic sandstone (Fig. 2-5a). Sandstones are fine to coarse grained and composed of angular plagioclase, hornblende, volcanic lithic grains and quartz. Maroon, pebble to cobble-sized siltstone rip-up clasts are locally abundant (Colpron *et al.*, 2015). Sandstone beds are typically normally graded, exhibit planar and cross-lamination (rarely with heavy-mineral lined fore and toesets - Fig. 2-5b), and are locally massive. Scoured bed bases and mud draped bed tops are common, and beds exhibit lensoid geometries in the upper part of the outcrop that were interpreted by Long (2005) to characterize a broad, stepped bank channel-fill succession (Fig. 2-5c). Detrital zircons from a nearby outcrop have a bimodal distribution, with peaks at ca. 338 and 205 Ma (Fig. 1-6). The latter peak and the weighted mean age of 201.5 ± 1.5 Ma (Colpron *et al.*, 2015) are consistent with the 201.5 ± 0.6 Ma date from a tuff near the top of the Mandanna member ~15 km to the south (Mortensen *in* Lowey, 2008; Colpron *et al.*, 2015) and suggest a Rhaetian maximum depositional age for the Mandanna.

Bioturbation, although abundant in this section, is of very low diversity and interpreted here as *Planolites*. Burrows are sub-vertical cylindrical tubes that are unlined and un-branched. They are filled with a darker red, slightly finer-grained matrix (Fig. 2-5d), or occasionally by coarse-grained sandstone; in both cases indicating downwards transport of fill-material from above. Burrow abundance decreases vertically towards the bed base; again suggesting downwards burrowing towards higher moisture content substrate and that sediment influx was too rapid to allow for syn-depositional colonization. *Planolites* represents active backfilling of sediment in an ephemeral burrow constructed by a mobile deposit feeder (*e.g.*, Pemberton and Frey, 1982), but contrary to Long's (2005) interpretation for this outcrop, the ichnogenus cannot be used to specifically infer an intertidal environment. Local observations of caliche and desiccation cracks in this member (Dickie and Hein, 1995) also support ephemerality and a semi-arid to arid climate. Rapid deposition resulting in massive sandstone beds, scoured to welded bed bases and mud rip-up lags also support an ephemeral, flood-dominated alluvial system interpretation. Proximity to coastline or a marine (tidal?) influence has yet to be demonstrated at this outcrop.

Two green intermediate dikes (Eocene?) crosscut the Mandanna strata at this outcrop (see Fig. 2-5a). In some places, malachite can be seen on fracture surfaces. The many drill holes at the top of the outcrop (also seen yesterday at Stop 1-1) are paleomagnetic sites that were sampled for the study of Wynne *et al.* (1998), which documented a regional Late Cretaceous remagnetization event. This stone is popular as decorative crush gravel around Whitehorse.

Resume westward travel along the Alaska Highway.



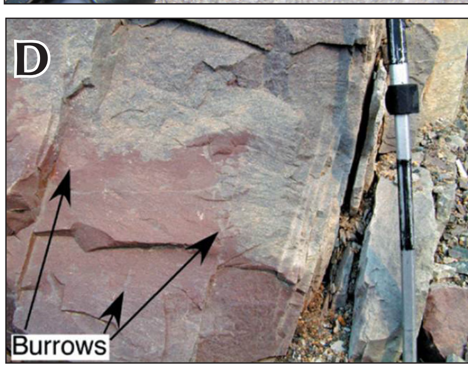


Figure 2-5. *A) Outcrop of Mandana member, Aksala formation, near Takhini fire hall; B) Heavy mineral cross-bedded laminations in the Mandana member. C) Stepped channel margin in the upper part of the outcrop (from Long, 2005). D) Planolites burrows showing increasing density towards the top of the sandstone bed (dark red splotches are raindrops!).*

Stop 2-2 – Laberge Group conglomerate

km 1452.0 Spectacular outcrops of polymictic, clast-supported, boulder and cobble conglomerate of the lower and middle Laberge Group are present in the curve to the left (UTM 8v, 476497E, 6746461N, elev 720 m). Park after you pass the curve, on the wide shoulder at the start of a straight stretch of highway. Additional exposures of this conglomerate can also be accessed via a short road on the left, another 400 m down the highway (private property).

The Laberge Group conglomerate in this exposure comprises a wide variety of clast types that are predominantly very well rounded and very large (Fig. 2-6). They include a variety of granitoids and hypabyssal rocks, typical of Laberge conglomerates, but also shale, limestone, lithic sandstone, augite-phyric basalt, and feldspar-phyric andesite (the latter being most apparent on top of the outcrop). Boulders are up to 1.3 m-wide, but most clasts are typically in the 30-40 cm range. The Laberge Group conglomerates in this region are interpreted as mass-flow deposits in a submarine fan environment (Dickie and Hein, 1995; Johannson *et al.*, 1997). The conglomerate was originally given formation status in the Laberge Group (Tempelman-Kluit, 1984; Hart, 1997), but recent studies of the Whitehorse trough show that it occurs at various stratigraphic levels within the Richthofen and Tanglefoot formations (Fig. 1-3; Lowey, 2004, 2005).

Figure 2-6. *Boulder conglomerate of the Laberge Group near Takhini Crossing (Stop 2-2).*

Granitic cobbles from this outcrop (and another one nearby) have yielded U-Pb zircon ages between 205 and 215 Ma (Hart *et al.*, 1995). They are likely sourced from the plutonic root of the Lewes River arc. A sample of the lithic sandstone matrix from this outcrop was collected for detrital zircon analysis (04SJP594, Fig. 1-20; Colpron *et al.*, 2015). As with other Laberge Group sandstones (see Fig. 1-6; Colpron *et al.*, 2015), the majority of zircons yielded ages between 180 and 230 Ma, with peaks in age probability at 189 and 209 Ma, and a small population of Mississippian grains. Colpron *et al.* (2015) suggested a Pliensbachian-Toarcian maximum depositional age for this conglomerate, and apparent younging of the sub-Laberge unconformity to the west. Again, these ages match well the local source terranes surrounding the Whitehorse trough (Fig. 1-6).

km 1469.3 Takhini River bridge.

km 1474.2 Vista to southwest – this location marks the approximate boundary between the Intermontane and the Coast physiographic belts. So far the topography has been marked by rounded hills, large broad valleys and composed of sedimentary and altered volcanic rocks. Looking towards the southwest, the mountains are composed dominantly of granite with erosional remnants of metamorphic rocks.

Outcrops to the right are part of the Annie Ned batholith. This granite, part of the Ruby Range suite, is a high-level, quartz-rich, miarolitic, coarse-grained biotite granite, with distinctive dipyramidal, smokey grey quartz-eyes. Locally this suite contains accessory fluorite. This suite forms huge batholiths in the Coast Plutonic complex but only small, circular plutons and subaerial volcanic complexes in the Intermontane terranes to the east. The Annie Ned batholith is dated at 58 Ma.

Stop 2-3 – Takhini assemblage

km 1476.2 Turn left onto decommissioned gravel road. Park alongside the road, near the gravel berm. Walk down the road to the far end of the gravel pit, approximately 400 m (UTM 8v, 452869E, 6745060N, elev 737 m).

These outcrops of metavolcanic rocks are part of the Takhini assemblage, the oldest unit of Stikinia in this region. The Takhini assemblage occurs within a northwest-trending belt (up to 12 km wide) of discontinuous exposures west of Whitehorse (Plate 1). These rocks were originally considered to be deformed equivalents to volcanic and volcano-sedimentary rocks of the Upper Triassic Lewes River Group (Povoas formation) because of their compositional similarities. However a U-Pb zircon date from felsic metavolcanic rocks within the Takhini assemblage yielded a concordant age of 322.9 ± 1.2 Ma, indicating an Upper Mississippian age for the unit (Hart, 1997). These rocks form the westernmost exposures of Stikinia adjacent to the Coast Plutonic complex. For the most part, they occur as xenoliths within the Coast Plutonic complex. To the east, the contact between the Takhini assemblage and the Lewes River Group is poorly defined but corresponds to a sharp decrease in the intensity of the deformation fabrics. Hart (1997) speculated an unconformity beneath the Upper Triassic strata.

Here the rock is predominantly strongly foliated, dark green chlorite-biotite schist, which is intruded by two sets of felsic dikes (Fig. 2-7). Locally, near the contact with surrounding intrusive rocks (western end of the outcrop), the Takhini assemblage is amphibolite with felsic layers (‘sweats’) along the dominant foliation (likely related to Jurassic intrusion?). Garnet occurs in the schist, in the woods on the upper part of the outcrop. The chlorite-biotite schist commonly contains metamorphic segregations and epidote veins that are typically aligned along the dominant foliation. The dominant foliation dips moderately to the south, and contains a mineral-elongation lineation (smears of chlorite and biotite) which plunges shallowly to moderately to the southwest. The dominant foliation is folded by a series of tight, northwest-trending and shallow-plunging folds that are similar in style to folds affecting Jurassic strata in the Whitehorse trough to the east (Hart, 1997). Left-lateral shear bands are locally developed within the foliation.

Figure 2-7. *Two phases of granitic dikes intrude chloritic schist of the Takhini assemblage (Stop 2-3).*

The Takhini assemblage is intruded by two sets of felsic dikes, both of which cut across the dominant foliation. The older dikes are likely related to the Early Jurassic (186 Ma) Aishihik batholith (Long Lake suite; Joyce *et al.*, 2016). They are weakly foliated and folded by the northwest-trending folds. The younger set of dikes is quartz-feldspar porphyry and cut across all ductile structures. They are probably related to the late Paleocene (58 Ma) Annie Ned pluton. A series of brittle faults postdate these dikes and locally result in offsets in the order of a few centimetres.

Greenstone of the Takhini assemblage have the geochemical characteristics of island arc tholeiites, and Nd and Hf isotopic compositions are indicative of derivation from juvenile, depleted mantle sources within an arc system (S.J. Piercey, pers. comm., 2006). Based on their age and stratigraphic position, rocks of the Takhini assemblage are likely correlative with the Stikine assemblage of northwestern BC, a sequence of Devonian to Permian volcanic and carbonate rocks and related calc-alkaline intrusions (Logan *et al.*, 2000; Gunning *et al.*, 2006). These Paleozoic arc volcanic and sedimentary rocks are coeval, but of uncertain correlation, with similar rocks in Quesnellia and Yukon-Tanana terranes.

Vista to the southeast is of the Ibex Valley.

Resume westward travel along Alaska Highway.

km 1482.9 Turnoff to rock quarry in Annie Ned granite (UTM 8v, 447283E, 6742475N, elev 714 m). The quarry at the end of the short access road (200 m; note that access from the highway is very steep) displays characteristic outcrops of the 58 Ma Annie Ned granite batholith, part of the Coast Plutonic Complex. Here it is intruded by a north-trending mafic dike regionally dated at 52 Ma.

km 1487.5 Lookout – Glacial Lake Champagne.

km 1490 Road to Kusawa Lake.

Stop 2-4 – Coast Plutonic Complex

km 1493.6 Outcrop over the next ~4 km display multiple intrusive phases of the Coast Plutonic complex. Pull over on shoulder after the curve, near the end of this outcrop (UTM 8v, 438606E, 6736033N, elev 711 m). The following description is mainly from Johnston *et al.* (1993).

This outcrop displays the relationships of one pluton intruding into another. The host rock is a medium-grained, mesocratic, slightly foliated, brown and black biotite-rich quartz diorite to diorite orthogneiss. This unit is crudely gneissic, with some very mafic phases and a northwest-striking fabric. The country rock is intruded by a medium to coarse-grained, leucocratic, biotite and hornblende granite with local, small pegmatitic dikes of white K-feldspar, brown biotite and grey to lavender quartz. This granite is a deeper phase of the late Paleocene (58 Ma) Annie Ned batholith. There are two phases of leucocratic granite in this outcrop: an older phase hosts the xenoliths, the younger one cuts across both xenoliths and their host. Angular xenoliths average 20 cm in size, but are locally up to 1.5 m wide (Fig. 2-8). All phases are cut by north-trending, shallowly west-dipping, mafic dikes that are probably related to 52 Ma dikes dated farther to the east.

Resume westward travel along Alaska Highway.

Figure 2-8. *Xenolithic granite of the Paleocene Annie Ned pluton (Stop 2-4).*

Stop 2-5 – Kluane Schist at Otter Falls

km 1547.4 Turn into Otter Falls rest area adjacent to the restored Canyon Creek bridge (UTM 8v, 387927E, 6748881N, elev 650 m).

Outcrops on the west side of the bridge and in the canyon of the Aishihik River are monotonous, brown-weathering, medium-grained, quartz-plagioclase-muscovite-biotite schist assigned to the Kluane Schist (Muller, 1967; Israel *et al.*, 2011; or Kluane metamorphic assemblage, Erdmer, 1991; Mezger *et al.*, 2001b). Regionally, the Kluane Schist consists of biotite, quartz schist, muscovite, quartz, carbonaceous schist and garnetiferous, migmatitic paragneiss, with minor orthogneiss and isolated serpentinite bodies (Mezger *et al.*, 2001b). The migmatitic part of the Kluane schist occurs at the contact with the Ruby Range suite, where partial melt and injection of igneous material occurred (Fig. 2-9).

In this outcrop, discontinuous lenses of quartz are common and locally define tight to isoclinal intrafolial folds. A penetrative, steeply southeast-dipping foliation is well-developed. A quartz-rodding lineation along the foliation plane is parallel to isoclinal fold hinges.

Regionally, metamorphic mineral assemblages from the Kluane Schist record an early, syntectonic Late Cretaceous medium pressure-temperature event (*ca.* 7 kbar, 500°C) followed by a lower pressure event related to emplacement of the Eocene Ruby Range batholith (Mezger *et al.*, 2001a). The schist is intruded by micaceous pegmatite and leucocratic two-mica granite.

Continue westward travel along the Alaska Highway.

km 1578.5 Haines Junction – turn right and continue driving west along the Alaska Highway. The Kluane Ranges, on the left, from Haines Junction to Kluane Lake are primarily underlain by sedimentary strata of the Jura-Cretaceous Dezadeash Formation, which overlaps Wrangellia and Alexander terrane.

Figure 2-9. *Migmatitic paragneiss of the Kluane schist located near the contact with the overlying Ruby Range suite.*

Stop 2-6 – Mineralized pluton of the Eocene Hayden Lake suite, roadside quarry

km 1617.6 Pull off highway near the large outcrop of quartz-diorite to granodiorite of the Haden Lake suite (UTM 7v, 660331E, 6762289N, elev 981 m). The mineralized portion of the pluton can be found by walking along the decommissioned road leading into the quarry. At the end wall, sheeted quartz veins host abundant molybdenum mineralization and are characterized by highly altered vein selvages (Fig. 2-10). A U-Pb zircon date from this location returned an age of 45.8 Ma, interpreted to be the crystallization age of the pluton.

The Hayden Lake suite includes several plutons that intrude the Kluane Schist (Plate 1). The suite is several million years younger than the Ruby Range suite and its tectonic setting is not well characterized. Locally some of these plutons contain abundant garnet and muscovite suggesting a possible crustal melt source.

The Denali fault is located in the valley to the southwest of this outcrop (Plate 1).

From this stop, continue travel northwest along the Alaska Highway.

Figure 2-10. *Sheeted veins with strong alteration selvages developed in Eocene granodiorite of the Hayden Lake suite.*

Stop 2-7 – Kluane Lake overlook

km 1634.4 Turn into parking lot near overlook platform with view of Kluane Lake.

This location provides a unique vantage point to see the main geological features of the Insular terranes. Kluane Lake and this observation point are located just north of the trace of the Denali fault (Plate 1). Post-Early Cretaceous movement on the Denali fault is estimated at 350-400 km of right lateral offset (Plafker *et al.*, 1989b; Lowey, 1998). The Denali fault is presently active with recent slip rates on the Alaska portion of the fault measured at between 8.4-9.4 mm/yr (Matmon *et al.*, 2006).

To the north, the Ruby Ranges are underlain by rocks of the Kluane Schist and Paleocene to Eocene intrusions of the Ruby Range and Hayden Lake suites. Looking west, the frontal Kluane Ranges are underlain by rocks of Wrangellia. The lower slopes consist primarily of northeast-dipping basaltic strata of the Upper Triassic Nikolai formation underlain by Paleozoic sedimentary and volcanic rocks of the Skolai Group (Fig. 2-11). The prominent valley that intersects the Slims River (large valley at the south end of Kluane Lake) is underlain by the Duke River fault, which separates Wrangellia from carbonates and siliciclastic rocks of the Alexander terrane. The deformation history of this fault is long and protracted and includes at least two main thrusting events, mid-Cretaceous and Pliocene (Cobbett *et al.*, submitted, 2016). The compressional events appear to be oblique with at least some sinistral strike-slip component to the movement (Cobbett *et al.*, submitted, 2016). This fault is still active today with dozens of small earthquakes occurring every year. It continues into Alaska where it becomes the Totschunda fault, an active splay of the main Denali structure.

The obvious orange-weathering strip of rock on the north side of Sheep Mountain is the trace of the Bocks Creek fault, a Denali-parallel structure internal to Wrangellia.

Resume travel westward from the Kluane Lake Overlook to the road leading to the Arctic Institute of North America's Kluane Lake Research Station at **km 1639**. We will overnight here. Take care and watch for air traffic before crossing the airfield at the end of the access road.

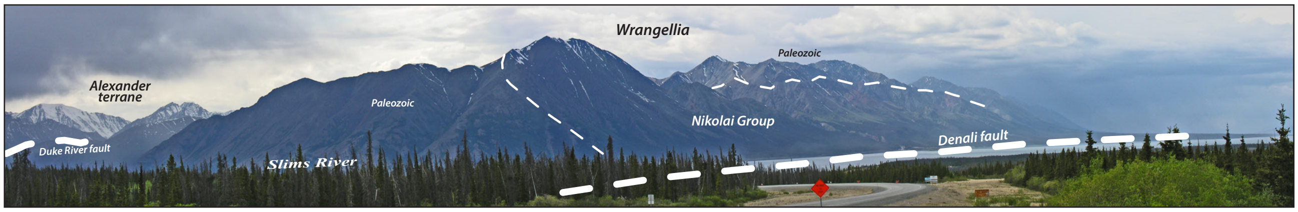


Figure 2-11. *Looking west at the Kluane Ranges from the Kluane Lake overlook (Stop 2-7). Slopes in the foreground are underlain by Triassic basalt of the Nikolai Group (Stop 3-1), which rest unconformably on Paleozoic strata of Wrangellia. Distant peaks to the left are underlain by the Alexander Terrane.*

DAY 3 – THE INSULAR TERRANES AND JURA-CRETACEOUS DEZADEASH FORMATION

Day 3 of this excursion will include two short hikes that focus on the Insular terranes, Wrangellia and Alexander, as well as the Dezadeash Formation and the tectonically and stratigraphically enigmatic Bear Creek assemblage. We will be venturing into the Kluane Mountains, the front range of the St. Elias Mountains which encompasses some of the highest mountains in Canada including Mount Logan at 5959 m.

The Insular terranes – Wrangellia, Alexander

The Insular terranes include Wrangellia and Alexander terrane in the Canadian Cordillera, and the Peninsular terrane of Alaska (Fig. A1). Parts of Wrangellia and Alexander share history back to the mid-Paleozoic (Israel *et al.*, 2014) and a suite of Pennsylvanian plutons intrude both Wrangellia and Alexander terrane in Alaska and Yukon (Gardner *et al.*, 1988; Beranek *et al.*, 2014). However, the current understanding of their Mesozoic histories, particularly in Late Triassic, is not well constrained and there are some differences. Accretion of the Insular terranes to the Intermontane terranes likely began in Early to Middle Jurassic (McClelland *et al.*, 1992; van der Heyden, 1992; Gehrels, 2001).

Wrangellia

Wrangellia is one of the most extensive terranes in the northern Cordillera (Fig. A1). It extends from the northwest United States to Alaska and includes middle Paleozoic to middle Mesozoic sedimentary and volcanic rocks.

The Paleozoic basement to Wrangellia comprises a complex of Late Devonian to Permian volcanic and sedimentary succession (Fig. 3-1; Smith and MacKevett, 1970, Read and Monger, 1976; Israel *et al.*, 2014; Ruks, 2015). The stratigraphic complexity and lack of age constraints has lead some workers to suggest that the Paleozoic basement to Wrangellia comprises a number of different terranes brought together some time before the Late Triassic. More recent, detailed work show stratigraphic and age similarities between the northern (Alaska/Yukon) and southern (Vancouver Island) parts of Wrangellia (Israel *et al.*, 2014; Ruks, 2015).

The hallmark of Wrangellia is a thick sequence of Upper Triassic flood basalts that unconformably overlies Paleozoic to Middle Triassic volcanic and sedimentary rocks. On Vancouver Island these basalts are referred to as the Karmutsen Formation and in Yukon and Alaska as the Nikolai formation (Smith and MacKevett, 1971; Reid and Monger, 1976; Carlisle and Suzuki, 1974; Nixon and Orr, 2006; Greene *et al.*, 2008; Greene *et al.*, 2009). Current models for the flood basalts are that they are related to a Late Triassic mantle plume.

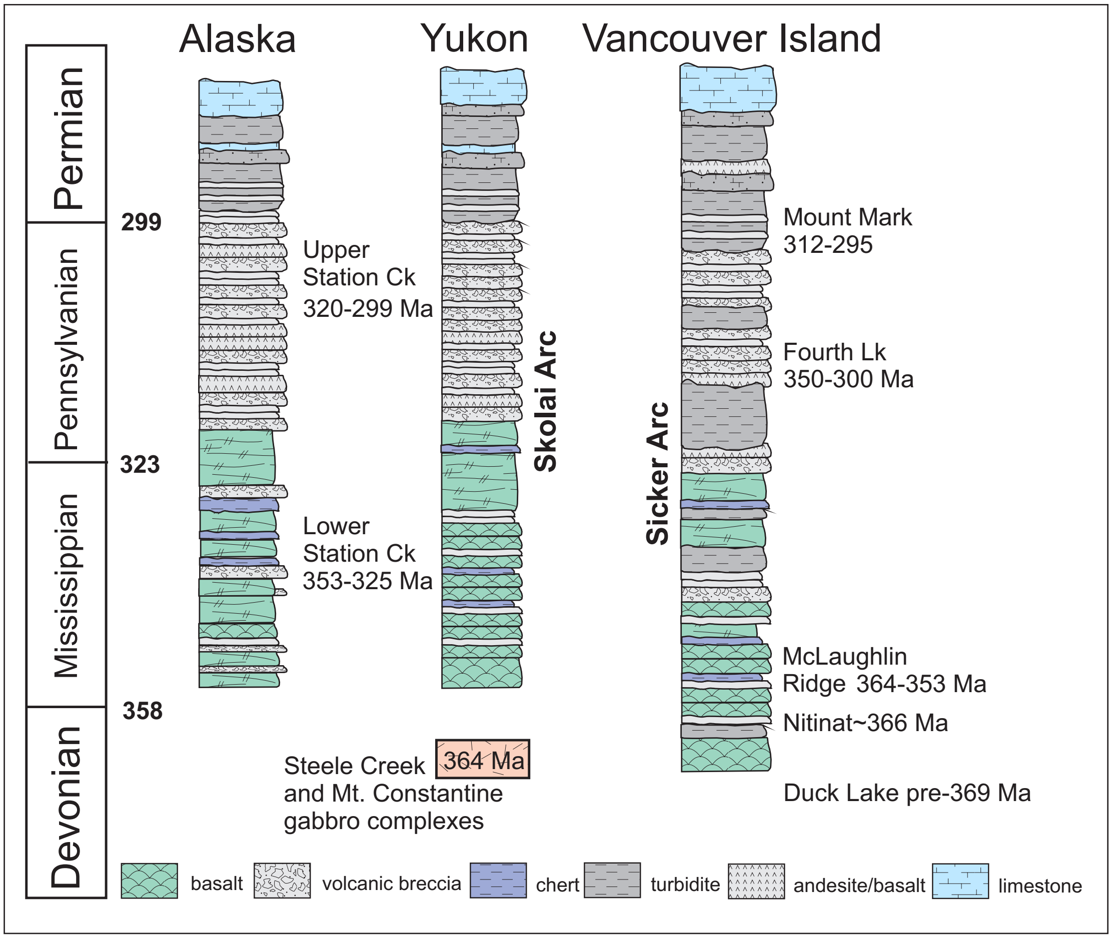


Figure 3-1. *Schematic stratigraphic sections for Wrangellia from Vancouver Island, eastern Alaska and southwest Yukon (after Smith and MacKevett, 1970; Israel et al., 2014; Ruks, 2015).*

In Yukon and Alaska, rocks of the Station Creek Formation form the oldest part of the Skolai Group. These are earliest Mississippian basalts that have non-arc geochemical signatures that pass upwards into Pennsylvanian arc volcanic and associated sedimentary rocks (Fig. 3-2; Smith and MacKevett, 1970; Read and Monger, 1976; Israel *et al.*, 2014; Fig. 3-1). The Station Creek Formation is gradationally overlain by more sediment-rich and carbonate-dominated Permian rocks of the Hasen Creek Formation. Locally, a thin sequence of Middle Triassic mudstone, identified by *Daonella*-rich beds, unconformably overlies the Paleozoic rocks. The Upper Triassic Nikolai formation unconformably overlies the Paleozoic rocks, and the Middle Triassic rocks where preserved. The Nikolai consists of highly vesicular and amygdaloidal, maroon and olive green basalts (Fig. 3-3). The Nikolai basalts have been interpreted as dominantly subaerial based on the ubiquitous presence of amygdules, the amount of vesicles and the oxidized nature of much of the formation (Read and Monger, 1976; Hulbert, 1997).

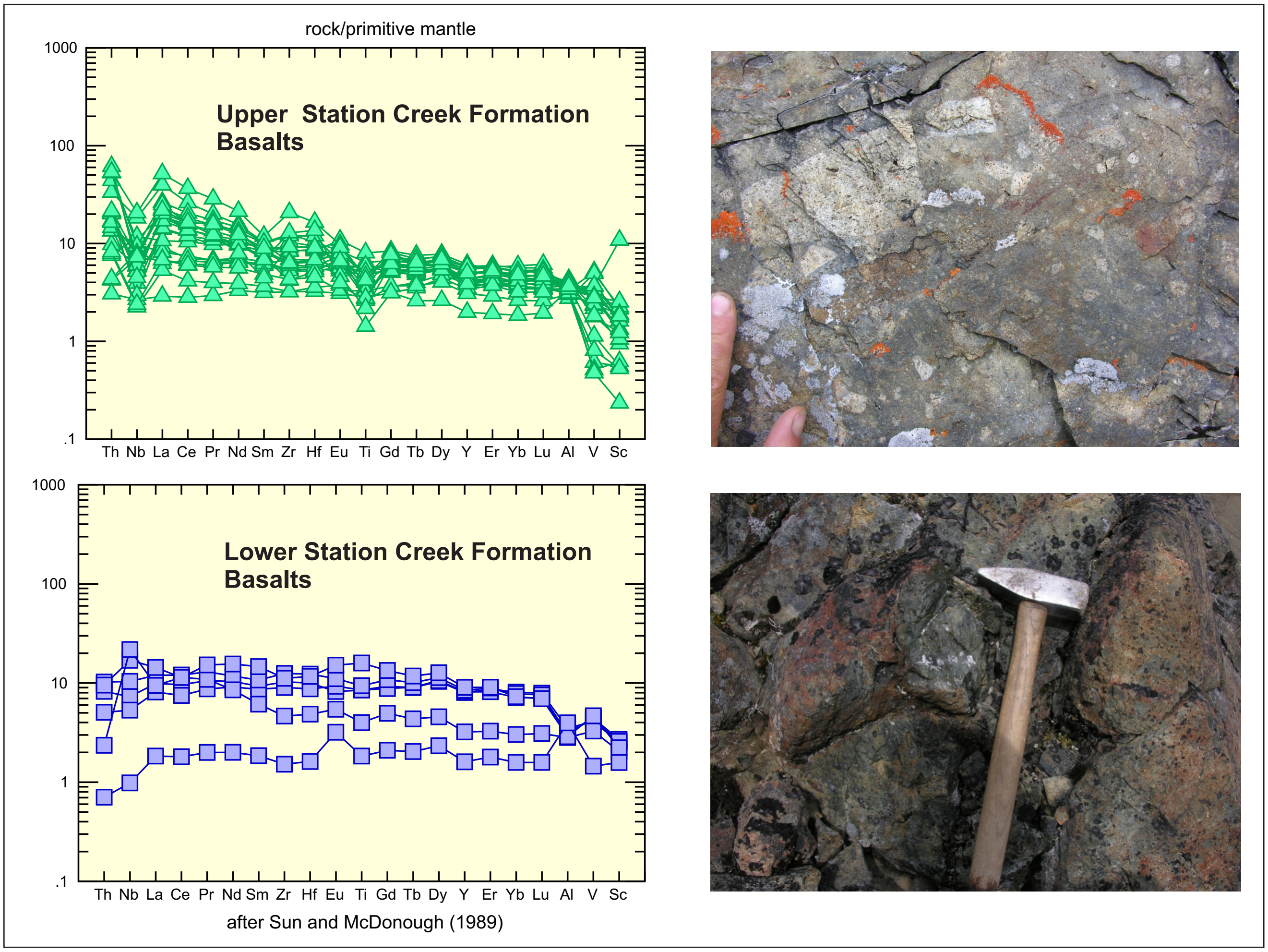


Figure 3-2. *Primitive mantle normalized spider plots for Mississippian (purple) and Pennsylvanian (green) Station Creek volcanic rocks and photos of typical outcrops of each unit.*

Figure 3-3. *Typical maroon to olive green, amygdaloidal basalt of the Nikolai formation, the Late Triassic flood basalt package seen as the hallmark of Wrangellia.*

Rare pillows and pillow breccia near the base of the Nikolai suggests that at least part of the volcanic sequence was erupted in a subaqueous environment. Thin carbonate layers at the top of the volcanic sequence have yielded upper Norian conodonts. Up to several hundred metres of carbonate with Norian microfossils, the Chitistone Limestone, overlie the Nikolai formation. The McCarthy Formation, a sequence of alternating calcareous and carbonaceous mudstones and siltstones, also of Norian age, rests conformably above the Chitistone Limestone. These siliciclastic rocks probably grade into overlying Jura-Cretaceous sedimentary rocks of the Tatamagouche succession and the Dezadeash Formation (Israel *et al.*, 2006b).

In southern Yukon, large bodies of gabbro and ultramafic rocks intrude the Paleozoic section of Wrangellia. Collectively these intrusions have been included in the Kluane mafic-ultramafic suite and consist of gabbro, peridotite, dunite and pyroxenite characteristically forming semi-zoned bodies with sill-like geometry, but also locally cross-cutting units at high angles (Fig. 3-4). A U-Pb zircon age of 232±1 Ma from the Maple Creek gabbro, one of the Kluane intrusions, constrains the upper limit of the suite (Mortensen and Hulbert, 1991). Phlogopite from a peridotite body yielded a cooling age of *ca.* 228 Ma (Greene *et al.*, 2009). Hulbert (1997) interpreted intrusions of the Kluane mafic-ultramafic suite as feeders to the extensive Nikolai flood basalt. Ni-Cu-PGE mineralization, including the Wellgreen deposit (43 Mt grading 0.36% Ni, 0.35% Cu, 0.51g/t Pt and 0.34 g/t Pd), is associated with these mafic-ultramafic intrusions. In southern Alaska, intrusion of a Cretaceous pluton in the Nikolai formation and Chitistone Limestone produced the Kennecott copper replacement deposit, one of the richest ever mined.

Figure 3-4. *Triassic ultramafic (mainly peridotite) sill of the Kluane mafic/ultramafic suite. Here the ultramafic rocks are surrounded by associated gabbro. These intrusions are thought to be part of the feeder system to the voluminous flood basalts of the Nikolai formation. They are also associated with large Ni-Cu-PGE deposits in Yukon and Alaska.*

Alexander Terrane

The Alexander terrane is a large crustal fragment that is a composite terrane composed of two main tectonic elements, the Craig and Admiralty subterranes (Fig. 3-5; Berg *et al.*, 1978; Gehrels and Saleeby, 1987; Monger and Berg, 1987). The Craig subterrane makes up ~90% of the Alexander terrane including the St. Elias Mountains of eastern and southeast Alaska, southwest Yukon and northwest British Columbia (Beranek *et al.*, 2014). The Admiralty subterrane is found exclusively in southeast Alaska underlying the Admiralty Island area. The two subterranes are thought to have amalgamated during Permian tectonism (Karl *et al.*, 2010; Nelson *et al.*, 2013; Beranek *et al.*, 2014).

In southeastern Alaska, Neoproterozoic to early Paleozoic volcanic arc rocks of the Alexander terrane have no obvious continental underpinnings, and continentally derived sedimentary strata that contain Precambrian detrital zircon populations with peaks at 1.0-1.2 (dominant), 1.35-1.39, 1.48-1.53, 1.62-1.68, 1.73-1.77, 1.8-2.0, and 2.5-3.0 Ga, a pattern very unlike northwestern Laurentia, but showing strong Grenvillian influence and a possible connection with Baltica (Bazard *et al.*, 1995; Gehrels *et al.*, 1996; compare with dominant 1.8-2.0 Ga northwestern Laurentian peaks in Gehrels *et al.*, 1995 and Gehrels and Ross, 1998; see Colpron and Nelson, 2009, 2011b, for further discussion; Fig. 3-6). In far northwestern BC, southern Yukon and far eastern Alaska, the Alexander terrane comprises mainly Cambrian through to Triassic volcanic, carbonate and siliciclastic rocks. The Paleozoic portion of the terrane is broadly divided into three assemblages: the Donjek, Goatherd Mountain and Icefield assemblages (Fig. 3-7; Dodds and Campbell, 1992; Beranek *et al.*, 2012). A thick Devonian carbonate horizon, the Bullion Creek limestone, is also found throughout southwest Yukon and northwest British Columbia (Dodds and Campbell, 1992). New data from Yukon and British Columbia indicates a Baltican association for lower Paleozoic and older rocks of the Alexander terrane (Beranek *et al.*, 2012) and subsequent Devonian to Permian rifting and translation of the terrane (Gehrels and Saleeby, 1987; Colpron and Nelson, 2009, 2011; Beranek *et al.*, 2012; Nelson *et al.*, 2013).

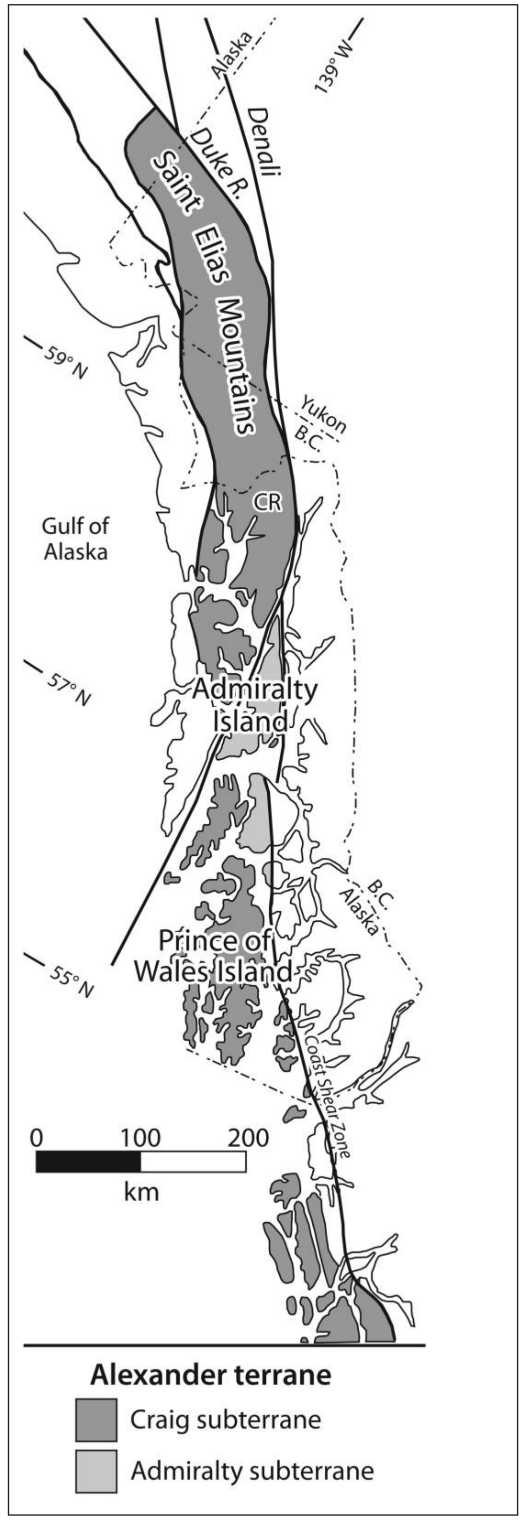


Figure 3-5. *Location map of the Craig and Admiralty subterranes of the Alexander terrane (after Beranek et al., 2012).*

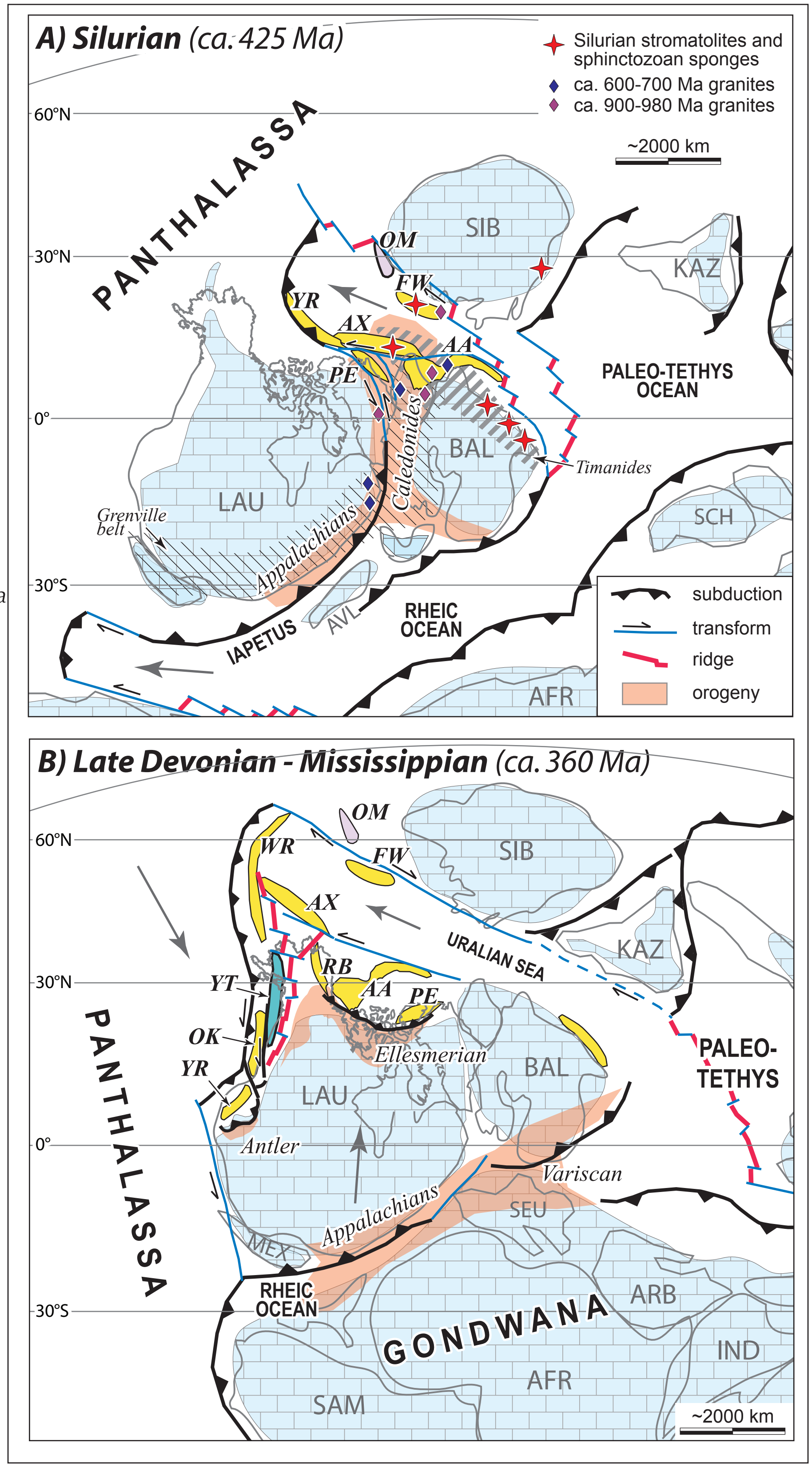


***Figure 3-6.** Schematic paleogeographic reconstruction of peri-Laurentian and Arctic realm terranes in early to mid-Paleozoic time (after Nelson et al., 2013). A) In Silurian, the Arctic terranes started migrating westward as Baltica and Laurentia 'collided' in the Caledonian orogeny. Arctic Alaska (AA, including Wrangel Island and Chukotka) lay against northern Baltica (Miller et al., 2011) and Alexander terrane (AX) at the northern end of the Caledonides (Beranek et al., 2013). Both terranes share affinity with the Timanides of northern Baltica. Locations of Precambrian granitic rocks from Patrick and McClelland (1995) and Gee (2005). Silurian fossil localities from Soja and Antoshkina (1997). B) By Late Devonian to Early Mississippian, subduction had migrated westward and transported many of the Arctic terranes into eastern Panthalassa (Colpron and Nelson, 2009, 2011b). The subduction zone propagated southward along western Laurentia in Devonian, followed by back-arc rifting, opening of the Slide Mountain ocean and initiation of arc magmatism in Yukon-Tanana terrane (YT). Other terranes: FW – Farewell; OK – Okanagan subterrane; OM – Omulevka; PE – Pearya; YR – Yreka. Continental reconstructions for the paleogeographic maps are modified after Scotese (2002). AFR – Africa; ARB – Arabia; BAL – Baltica; IND – India; KAZ – Kazhakstan; LAU – Laurentia; MEX – Mexico; SAM – South America; SCH – South China; SIB – Siberia.*

In northwestern BC and southeastern Alaska, the Alexander terrane includes Norian basalts that are confined to a single rift zone that hosts the giant Windy Craggy Besshi-type volcanogenic massive sulphide (VMS) deposit in BC and the Greens Creek VMS mine in Alaska. In southwestern Yukon, the Alexander terrane is juxtaposed to Wrangellia along the Duke River fault (Plate 1; Fig. A10).

Alexander/Wrangellia relationships

Gardner *et al.* (1988) showed demonstrably that the Alexander terrane and Wrangellia were amalgamated into one large *superterrane* by the Pennsylvanian by identifying and dating key plutons of the St. Elias suite that intrude across the boundary of both terranes. Further evidence suggests that the two terranes likely shared a geologic history as far back as the latest Devonian. An unconformable contact between Late Devonian gabbro complexes (~363 Ma) and Permian sedimentary rocks of the Hasen Creek Formation (Wrangellia) occurs in southwest Yukon (Sharp, 1943; Read and Monger, 1976; Israel *et al.*, 2014). The chemistry of the gabbro indicates they formed in a non-arc, likely rift environment (Israel *et al.*, 2014). Underlying the Permian sedimentary rocks of Wrangellia are the volcanic rocks of the Station Creek Formation. The oldest volcanic rocks in the Station Creek Formation are ~353 Ma and have back-arc to EMORB geochemical signatures. The age, distribution and geochemical character of the rocks suggests a back-arc rift initiated on the flanks of the Alexander terrane and led to back-arc spreading and eruption of the lower Station Creek basalt (Israel *et al.*, 2014). Re-initiation of the arc and subsequent closure of the back-arc occurred in the Pennsylvanian. Devonian and Mississippian arcs and back-arc rifts are common in many of the accreted terranes of the northern Cordillera, suggesting that these shared a common tectonic setting relative to the Laurentian margin (Fig. 3-8).

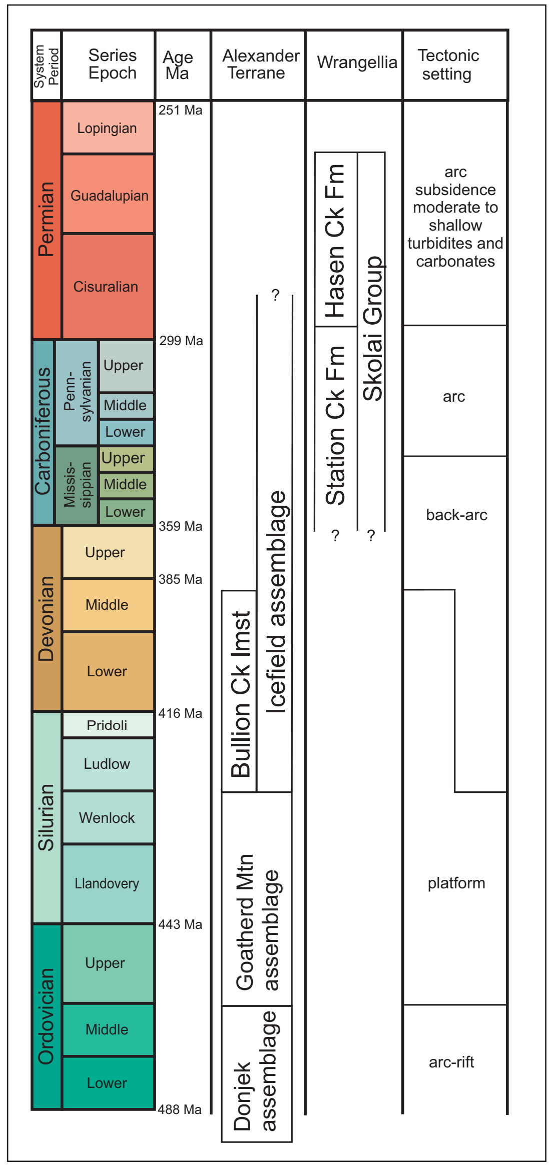


Figure 3-7. Alexander terrane and Wrangellia stratigraphy from NW British Columbia, Yukon and eastern Alaska (from Israel et al., 2014).

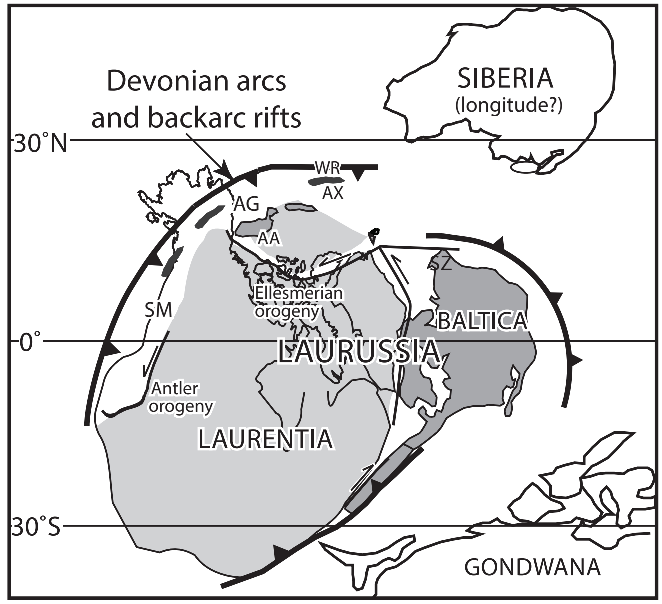


Figure 3-8. *Schematic Devonian-Mississippian paleogeographic setting for the Alexander terrane and Wrangellia (after Israel et al., 2014). AA- Artic Alaska, AG- Angayucham, AX-Alexander, SM-Slide Mountain, WR-Wrangellia.*

Bear Creek assemblage

The Bear Creek assemblage is an enigmatic package of metavolcanic and metasedimentary rocks found between the Insular and Intermontane terranes (Plate 1; shown as Taku terrane on Fig. A10). It is cut to the south by the Denali fault and is inferred to be in fault contact with the Kluane schist to the north. It is overlain by the Jura-Cretaceous sedimentary rocks of the Dezadeash Formation across a structurally modified unconformity (Israel *et al.*, 2014b). The assemblage is divided into a lower volcanic dominated unit and an overlying upper sedimentary dominated unit. Metavolcanic rocks are mainly basalt to basaltic andesite, with rare, thin felsic horizons (Fig. 3-9). A U-Pb zircon age from a strongly deformed felsic layer yielded a date of ~204 Ma. It is difficult to determine whether this is truly a felsic volcanic layer, or a younger felsic dike that was caught up in the overprinting deformation. Therefore this date is considered an upper age limit for the volcanic unit. The sedimentary section of the Bear Creek assemblage appears to conformably overly the volcanic rocks and includes black shale, mudstone, siltstone and sandstone. Two detrital zircon samples, one from near the contact of the underlying volcanic rocks and another near the interpreted top of the section both resulted in an age distribution plot with one peak at ~162 Ma (Fig. 3-10). This indicates that the sedimentary unit of the Bear Creek assemblage has a Jurassic maximum depositional age. More work is needed in order to elucidate the true tectonic and stratigraphic significance of these rocks, and their terrane affinity.

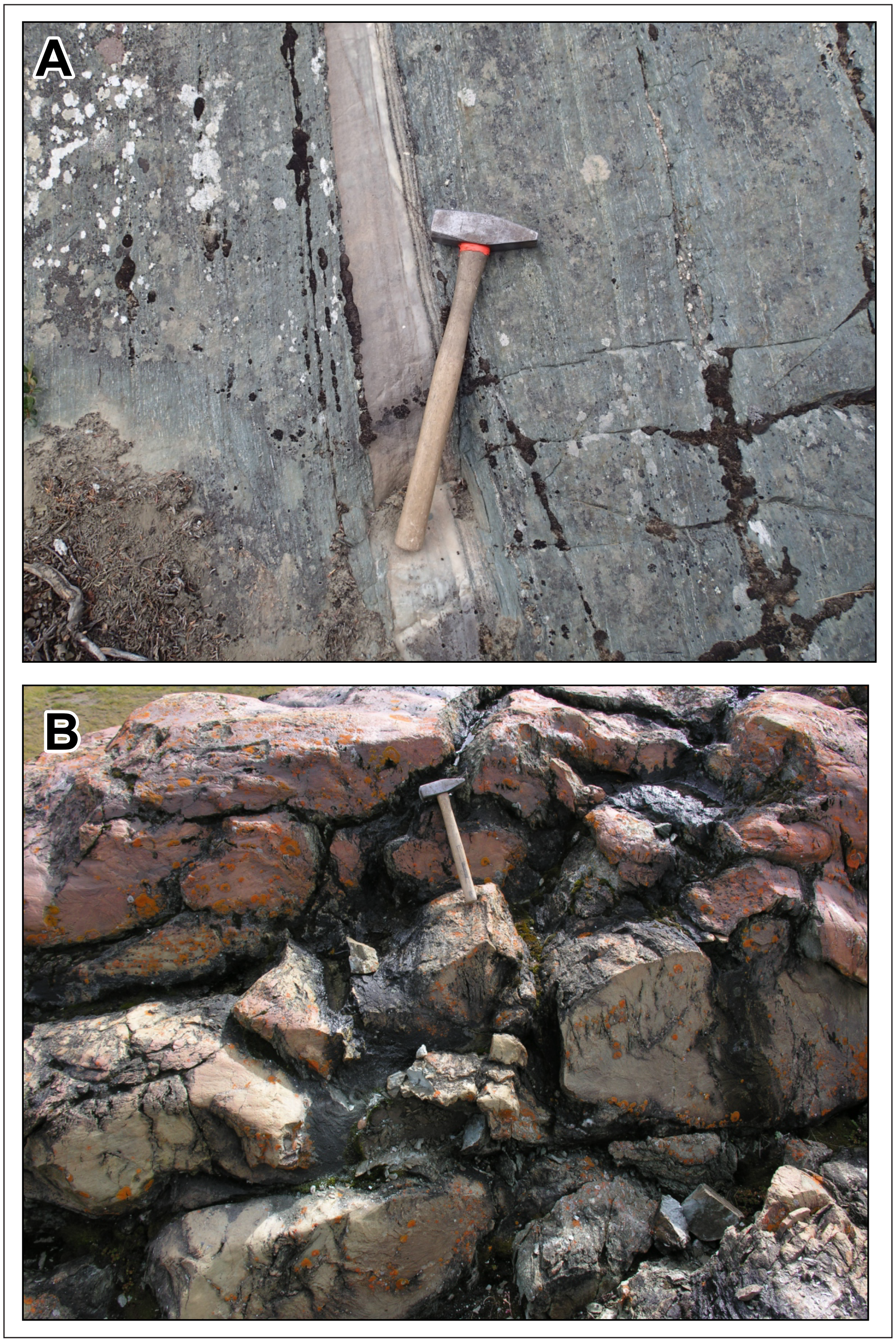


Figure 3-9. *Metavolcanic rocks from the lower Bear Creek assemblage. A) foliated andesitic basalt with thin carbonate horizon, B) Strongly deformed pillow basalt.*

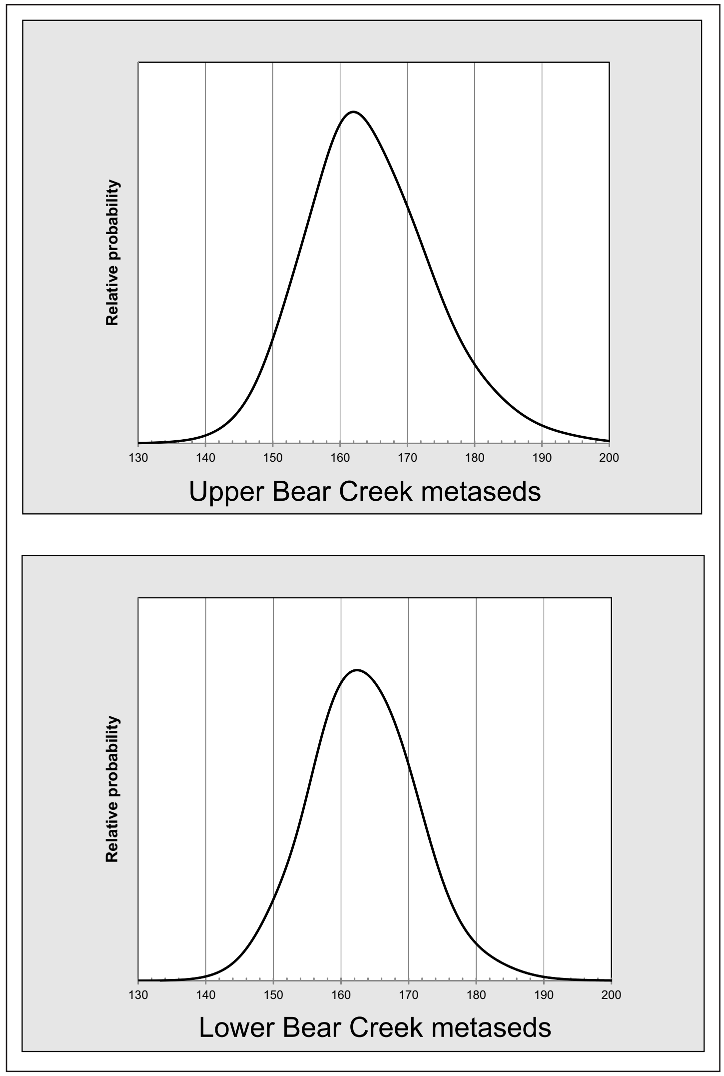


Figure 3-10. *Normalized age probability plots for detrital zircons from the upper Bear Creek assemblage. Peaks in age for both samples are at ~162 Ma.*

Dezadeash Formation

The Dezadeash Formation is a northwest-trending belt of mainly deep-marine siliciclastic strata, 10-40 km wide and 150 km long, bounded to the southwest by the Denali fault and flanked to the northeast by the Kluane Schist (Plate 1; Lowey, 2007). It was deposited in Late Jurassic to Early Cretaceous in a collapsing back-arc basin developed between the Intermontane terranes, to the northeast, and the Insular terranes, to the southwest. It forms the central part of the Gravina-Nutzotin belt of Berg *et al.* (1972) that unconfomably overlies both Wrangellia and Alexander terranes.

The Dezadeash Formation comprises approximately 3000 m of thick to thin-bedded sandstone/mudstone and sandstone/siltstone couplets (turbidite), massive sandstone and minor conglomerate, volcaniclastic rocks and limestone (Eisbacher, 1976; Lowey, 2007). The age of the Dezadeash Formation is constrained by pelicypods of Late Jurassic (Oxfordian) to Early Cretaceous age (Valanginian; Eisbacher, 1976). Paleocurrent indicators suggest a general eastward to northeastward paleoflow direction (Lowey, 2007). Detrital zircon from the broadly equivalent Gravina belt, in southeastern Alaska, indicate a mixture of sources in contemporaneous Jura-Cretaceous arc-related plutons and Paleozoic rocks of the Alexander terrane, to the west, and in middle Paleozoic and older rocks of the Yukon-Tanana and related terranes, to the east (Kapp and Gehrels, 1998). The Dezadeash Formation may gradationally overlie Triassic rocks of the McCarthy Formation of Wrangellia, based on occurrences of Early Jurassic fossils in the Tatamagouche succession, a Triassic to Cretaceous sedimentary sequence that may be in part equivalent to the lower Dezadeash Formation (Read and Monger, 1976; Israel *et al.*, 2006). In southern Alaska, the Nutzotin Mountains sequence is possibly an equivalent of the Dezadeash Formation that was offset by ~370 km to the northwest along the dextral strike-slip Denali fault system in the Eocene (Eisbacher, 1976; Lowey, 1998).

Detrital zircon analyses from the Dezadeash Formation in southwest Yukon suggest possible sources that include both the Intermontane and Insular terranes (Fig. 3-11). A strong peak at ~160 Ma may correspond to arc plutonism and volcanism found within the Alexander terrane (Beranek *et al.*, submitted); however, earliest Jurassic and latest Triassic grains reflect more of an Intermontane source terrane.

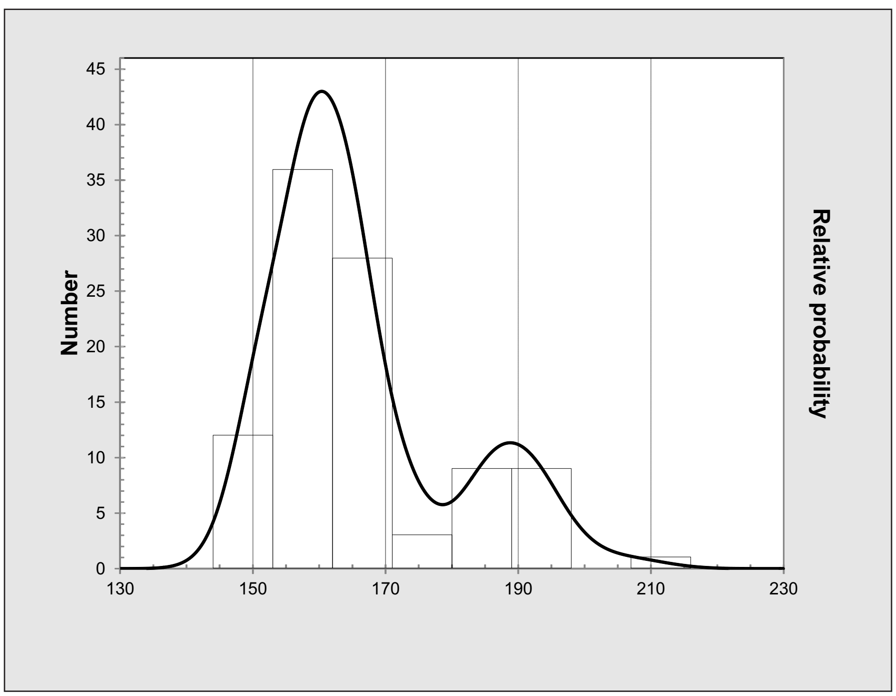


Figure 3-11. *Normalized age probability plots for detrital zircons from the Dezadeash Formation.*

Day 3 – Trip Log

The last day of this excursion will begin by examining volcanic rocks of the Nikolai formation on the west side of Kluane Lake and be followed by two short hikes along old mining trails. In the morning, we will hike along the Slims River and discuss Wrangellia and Alexander terranes. In the afternoon, a walk along Bear Creek, near Haines Junction, will examine the Bear Creek assemblage and Dezadeash Formation.

From the Kluane Lake Research Station, return to the Alaska Highway, turn right and travel southwestward to the Slims River crossing.

km 1640.0 the highway crosses the Denali fault at about this position.

km 1644.3 exposures of granodiorite of the Early Cretaceous Kluane Ranges suite.

km 1648.8 entrance to the Sheep Mountain visitor centre of Kluane National Park.

Stop 3-1 – Nikolai basalt (Wrangellia)

UTM 7v, 634812E, 6768234N, elev 810 m

km 1650.6 Turn left into the parking area at the start of the Soldier Summit trail, ~2.8 km past the Slims River bridge. The large blocks in this rock slide are typical of basalts of the Nikolai formation, which underlie the dip-slope above (Fig. 3-12). Maroon to olive green basalt of the Nikolai formation are locally plagioclase and pyroxene-phyric, but are more commonly massive and highly vesicular and amygdaloidal. Amygdules are filled by chlorite, quartz, epidote and zeolites. These Upper Triassic basalts are the hallmark of Wrangellia, as they characterize the terrane from southern Vancouver Island to southern Alaska. Current models suggest that they are the result of a mantle plume that formed under the Paleozoic strata of Wrangellia (Hulbert, 1997; Greene *et al.*, 2009). Note that part of the island on the right is also made up of slide debris.

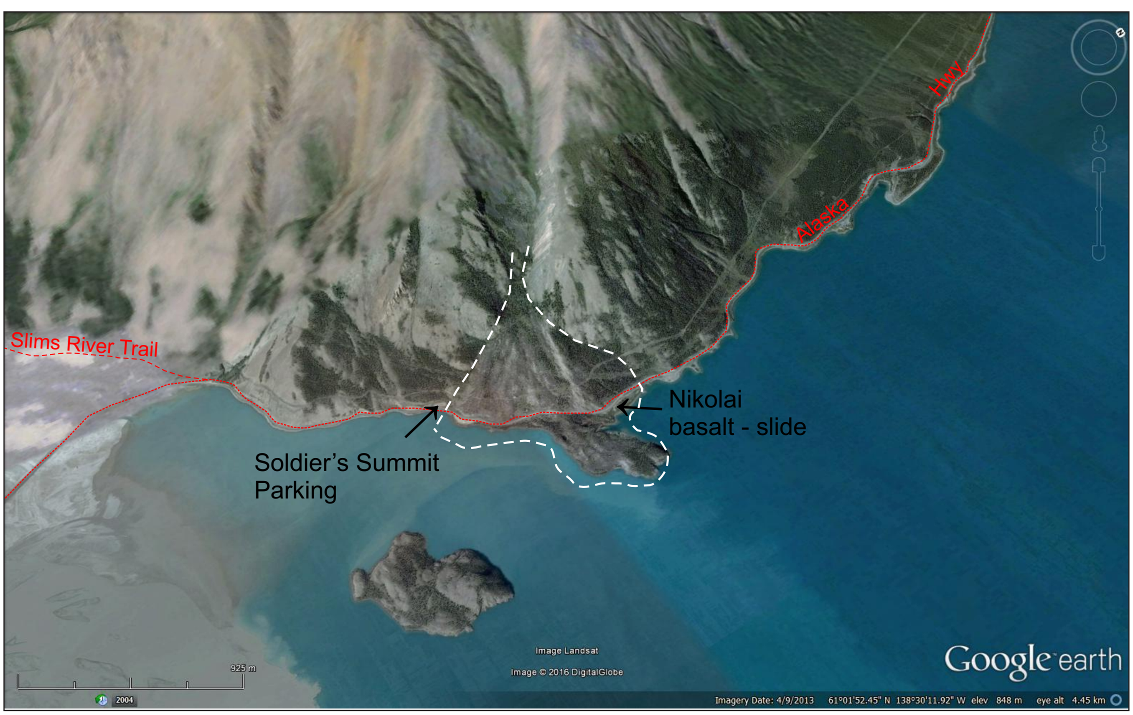


Figure 3-12. *Google Earth image of southern Kluane Lake showing the distribution of slide rock near Soldier's Summit. The slide is composed entirely of basalt of the Triassic Nikolai formation (Stop 3-1).*

Turn right on the Alaska Highway from Soldier's Summit parking area and retrace the route back to the Slims River road.

km 1649.7 Drive down the Slims River road to the parking area and the start of the Slims River trail, ~2 km from the highway.

Stop 3-2 – Hike along the Slims River, Kluane National Park

Park at the gate marking the boundary for Kluane National Park (UTM 7v, 632830E, 6766101N, elev 785 m). We will be hiking along the Slims River west trail to a high point that will give a stunning view of the St. Elias Mountains and the relationship between the Alexander terrane and Wrangellia (Fig. 3-13). Rocks that outcrop near the trail head have been mapped as Jura-Cretaceous sedimentary rocks of the Dezadeash Formation.

From the Slims River parking lot, return to the Alaska Highway, turn right and drive east towards Haines Junction, approximately 57 km to the turn off to the Bear Creek subdivision.

km 1589.1 Turn right onto the Bear Creek road.

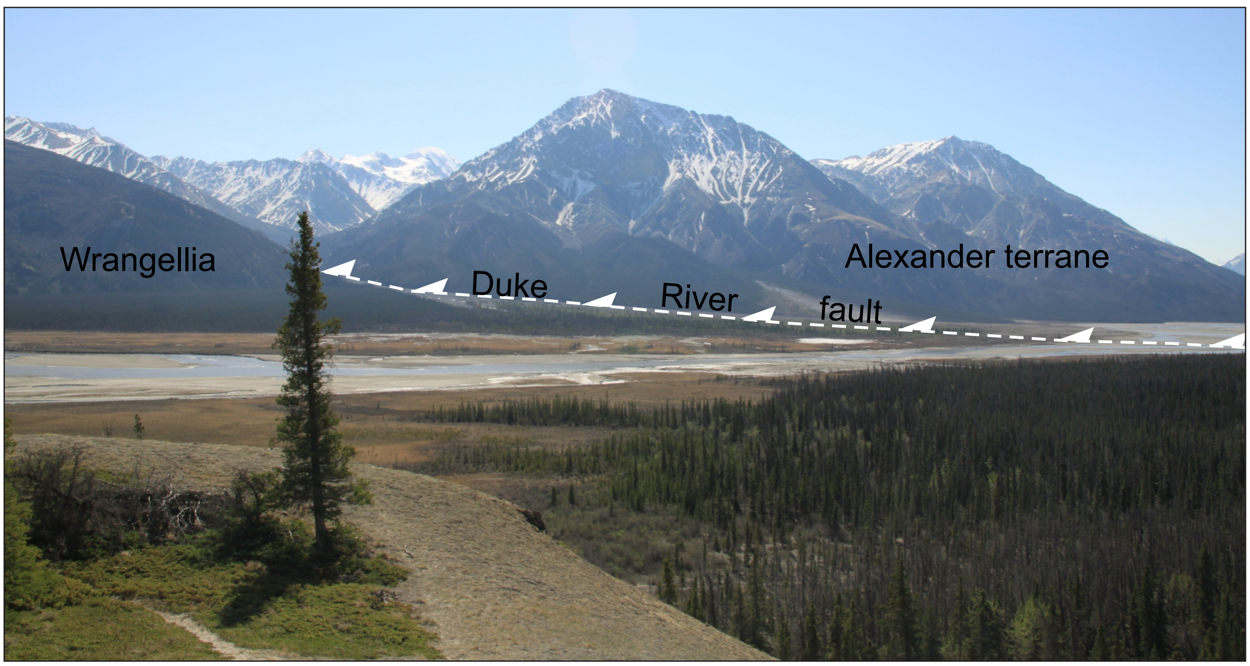


Figure 3-13. *View looking south up the Slims River at mountains composed of the Alexander terrane and Wrangellia (part of Stop 3-2). The Duke River fault that separates the two terranes has a protracted history that involves mid-Cretaceous and Miocene oblique thrusting. The fault is still active today with numerous low magnitude earthquakes occurring every year.*

Stop 3-3 – Dezadeash Formation (Bear Creek)

Drive south past turn-around point (~0.8 km) onto dirt road. Park vehicle and begin walking along dirt road. Cross small creek at ~1.5 km and continue on track for another 1.2 km. Stop at the outcrop in opening in the road at ~2.7 km (UTM 8v, 353293E, 6740713N, elev 605 m).

These outcrops are of weakly to moderately metamorphosed, locally strongly sheared, sandstone/siltstone turbidites of the Jura-Cretaceous Dezadeash Formation (Fig. 3-14). They occur near the structural base of the formation, where it is faulted against Triassic metabasalt and metasedimentary rocks farther down the Alsek valley (Eisbacher, 1976). The fault is likely a structurally modified unconformity (Israel *et al.*, 2014). The mountains to the south are composed entirely of deformed Dezadeash Formation but of generally lower metamorphic grade.

This stop marks the end of this transect of the northern Canadian Cordillera. From here, we drive back to Whitehorse, ~250 km.

Figure 3-14. *Strongly deformed greywacke and mudstone of the Dezadeash Formation (Stop 3-3). Detrital zircon plot (Fig. 3-11) was taken from this site.*

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