Sedimentary record for exhumation of ultrahigh pressure (UHP) rocks in the northern Cordillera, British Columbia, Canada

Dante Canil[†]
School of Earth and Ocean Sciences, 3800 Finnerty Road, University of Victoria, Victoria, British Columbia V8W 3P6, Canada

Mitchell Mihalynuk
Geological Survey Branch, British Columbia Ministry of Energy and Mines, 1510 Blanshard Road, Victoria, British Columbia V8X 3H6, Canada

Courtney Charnell
School of Earth and Ocean Sciences, 3800 Finnerty Road, University of Victoria, Victoria, British Columbia V8W 3P6, Canada

ABSTRACT

We use field relationships, paleoflow indicators, petrography, and major and trace element mineral chemistry to examine the protolith and provenance of detrital mantle-derived ultrahigh pressure (UHP—2.8 GPa) minerals in immature clastic sediments of an Early Jurassic basin (Laberge Group) in northwestern British Columbia, Canada. Our results show that fresh mantle detritus in the Laberge Group was derived from mantle lithosphere that equilibrated at >2.8 GPa and temperatures of 850–1100 °C, exhumed in orogenic massifs and quickly deposited over a restricted time interval. Two models are proposed for the exhumation and denudation of the UHP rocks in either (1) an arc-continent collision between the Stikinia and Yukon Tanana terranes, or (2) an exposed forearc and accretionary mélange in a convergent margin in the Cache Creek terrane. A collision between the Stikinia and Yukon Tanana terranes has not previously been documented, but this scenario is the most consistent with widespread evidence for rapid exposure of deep-seated rocks at the required time period for deposition of UHP detritus ~185 m.y. ago.

Keywords: mantle, ultrahigh pressure, exhumation, Cordillera, thermobarometry, sediments.

INTRODUCTION

Ultrahigh pressure (UHP) rocks, now documented in >20 localities in several mountain belts, are a revelation in our understanding of the depth, scale, and tempo of collisional orogeny, and the recycling of continental crust into the mantle (Liou et al., 2003; Medaris, 1999). These occurrences share the common structural and lithological characteristics that the UHP conditions have been recorded in volumetrically subordinate peridotite and eclogite pods within subhorizontal slabs, mostly of continental composition (Liou et al., 2003). The subduction, burial, and exhumation cycles of the UHP terranes show that rocks were buried to >100 km depths and returned to the surface in tens of millions of years or faster (Hacker et al., 2003; Rubatto and Hermann, 2001).

Detrital grains of fresh, mantle-derived pyroxenes and garnets were recently recognized in Jurassic coarse pebble conglomerates in the northern Cordillera. An initial study of these grains showed many of them to be of UHP origin, derived from mantle protoliths equilibrated at depths as great as 100 km (MacKenzie et al., 2005). Geologic evidence for UHP rocks in the northern Cordillera was hitherto unrecognized but speaks to the involvement of plates with thick lithospheres and deep-seated unroofing in arc-continent or continent-continent collisions, or to return flow in subduction zones that assembled crust in this mountain belt. The involvement of deeper parts of the lithosphere in the assembly of the Cordilleran orogen contrasts with a recent synthesis, based on seismic reflection data, that interprets much of the accretion in the northern Cordillera as thin-skinned flakes over a fixed Precambrian substrate of the western edge of North America involving no basement deeper than ~5 km (Cook et al., 2004).

Clastic sediments that accumulated proximal to orogenic belts can provide a useful record of their exhumation history but also send a mixed signal of differing tectonic processes, climate, relief, depositional systems, and preservation (Franzinelli and Potter, 1983; Potter, 1978). In this contribution we examine the geological setting and provenance of Laberge Group sediments that contain detrital UHP mantle minerals in the northern Cordillera. We test whether minerals exhumed from mantle depths are restricted to one stratigraphic zone that represents one punctuated exhumation, erosion, and depositional event. Sedimentary structures are used to derive possible source areas, and additional detailed major and trace element analyses of the mantle minerals are used to refine their protoliths and depth of origin. Together the results shed light on the lithospheric source and processes involved in the exhumation and erosion of these UHP rocks during a collisional orogeny.

GEOLOGIC SETTING

The northern Cordillera of British Columbia contains, from west to east, an arc terrane (Stikinia), an arc marginal basin (Whitehorse Trough), an ophiolite and accretionary complex (Cache Creek) that English and Johnston (2005) interpret as a magmatic arc, a forearc basin, a forearc basement, and a subduction complex, respectively, developed in Late Permian to Early Jurassic time (Fig. 1). The Jurassic Laberge Group was deposited in a marine forearc basin (Whitehorse Trough) that extended from southern Yukon into the Atlin-Nakina region of northern British Columbia (English et al., 2005; Johannson et al., 1997) (Fig. 1). Laberge Group strata in the Atlin-Nakina area accumulated in Sinemurian to Pliensbachian (Early Jurassic) time (197–183 Ma), as constrained by

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[†] E-mail: dcanil@uvic.ca.

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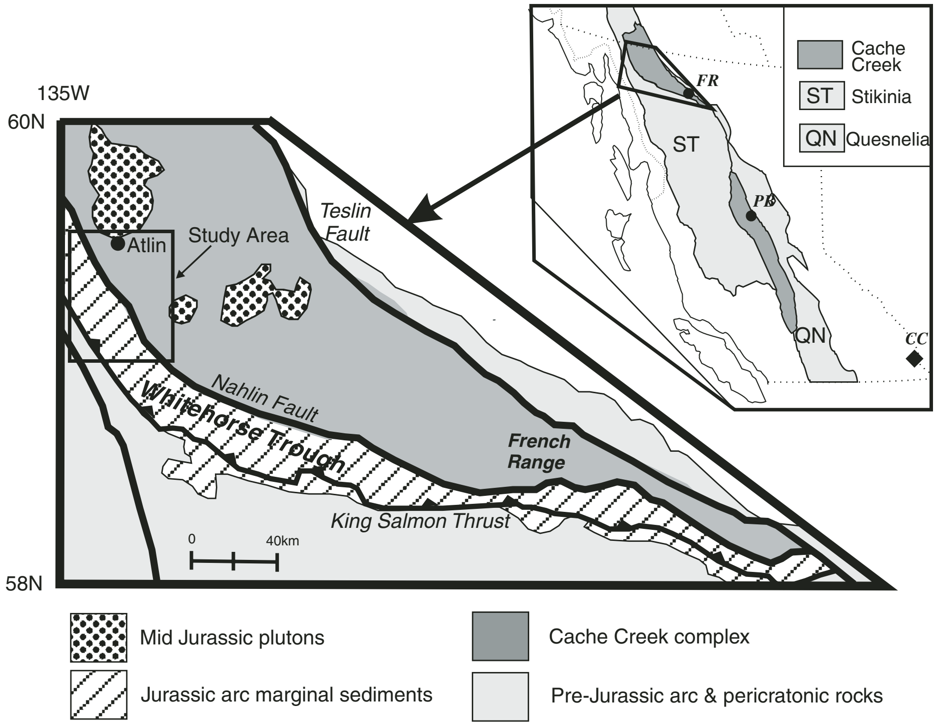


Figure 1. Simplified geology of the northern Cordillera in British Columbia (after English and Johnston, 2005). Box shows study area (shown in more detail in Fig. 2). Inset shows extent of Cache Creek, Stikinia, and Quesnellia terranes in the Cordillera, locations of the Crossing Creek kimberlite (CC), and blueschist and eclogite occurrences in the French Range (FR) and Pinchi Belt (PB).

biostratigraphy and U-Pb ages of tuffs and granitoid boulders in these rocks (Johannson et al., 1997). Detritus for the Laberge Group sediments was derived from arc strata within the Stikinia terrane (Triassic Stuhini and Jurassic Hazleton Groups) to the west and southwest (Fig. 1) but shifted later (ca. 170 Ma) to an easterly source area likely in the Cache Creek terrane.

The Laberge Group sediments were tilted, folded, and thrust faulted during the Middle Jurassic, after which they underwent block faulting related to extension and emplacement of bimodal volcanics of the Eocene Sloko Group (English et al., 2005). The Nahlin Fault, developed prior to the Late Cretaceous, juxtaposes rocks of the Laberge Group to the west with the Cache Creek terrane, an accretionary assemblage of largely Mississippian to Triassic limestone, chert, and Permian ophiolite (Mihalynuk et al., 2003; Monger, 1993) to the east. West of Whitehorse Trough, quartz-rich pericratonic strata of the Yukon Tanana terrane form, in part, the basement to the Stikinia terrane. Isotopic data from igneous and sedimentary rocks in the Stikinia terrane, and U-Pb geochronology of detrital zircons in metasediments of the adjacent Yukon Tanana terrane, support a uniform source for the quartz-rich basement strata that were derived from either a rifted fragment of the North American craton or from a distant microcontinent (Gehrels et al., 1990; Jackson et al., 1991; Mihalynuk, 1997; Mihalynuk et al., 1992).

Eclogite Ridge Section

Conglomerates with a high detrital garnet content were first reported in the Laberge Group by English et al. (2002). This occurrence was examined in detail along a NW-trending ridge, herein called Eclogite Ridge, southeast of Atlin townsite (Fig. 2). Eclogite Ridge is composed of distinctive buff-weathering siltstone, sandstone, and conglomerate that form a unit ~290 m thick and >10 km in length that we informally refer to as the Eclogite formation (Fig. 3). Good exposures of the Eclogite formation occur along the bedding-parallel ridge axis and on cliffs where the ridge is truncated by east-flowing streams (Fig. 4A). The thickness of the Eclogite formation decreases to the northwest, and possibly to the southeast, suggesting that this unit is lens shaped in cross section. The unit cannot be traced in outcrop north of the Sloko River and is presumed to be truncated to the southeast by the Nahlin Fault (English et al., 2002). The mapped distribution of the Eclogite formation corresponds to the positive aeromagnetic anomaly seen in the aeromagnetic total field survey results (Lowe et al., 2003). Prominent features of the Eclogite formation are depositional "cycles," repeating every 10–40 m, in which layered argillaceous siltstone and wacke are truncated by channelized granule to cobble conglomerate in onlapping and stacked lens-shaped beds (Fig. 4B, C). The conglomerate of the Eclogite formation also has a high magnetic susceptibility (χ) of 15 SI units.

Stratigraphically beneath the Eclogite formation is a section of green to brown and orange-brown-weathering wacke with a magnetic susceptibility of 0.3 SI units, separated from the Eclogite formation by a ~20-m-thick prominent recessive covered interval. Where well exposed on the north end of Eclogite Ridge, the recessive unit is ~15 m of laminated to centimeter-bedded siltstone showing soft-sediment deformation, and immature, medium-grained carbonaceous arkosic sandstone with a muddy matrix (wacke). Above the basal contact of the Eclogite formation, angular rip-up clasts up to 0.5 m diameter are similar to rocks in the recessive unit, suggesting that the basal conglomerate cuts down into the recessive unit.

Parts of the Eclogite formation are locally characterized by a conspicuous black and white banded rock (Fig. 3), formed by 3- to 5-cm-thick intercalations of dark, organic-rich siltstone with thicker cream-colored arkose. Dark layers are locally petroliferous. These units are incised by granule- to pebble-conglomerate–filled scours with axes that trend northeasterly. Scours are commonly asymmetric in cross section, with one steep margin (Fig. 4A). The steep-sided bedforms extend laterally into more tabular bodies that vary from 0.5 to 5 m in thickness. Differential compaction around the relatively strong conglomerate causes warping of the finer-grained layers around the lens, an effect that is particularly enhanced at the steep margin. Conglomerate layers weather out above adjacent finer-grained layers and can be traced along strike for kilometers (Fig. 4A). Concentrated within the steep-sided conglomerate layers are conspicuous detrital red and orange garnets up to 1 cm diameter, emerald green clinopyroxene (<3 mm), and sooty black biotite-feldspar-porphyry clasts (up to 12 cm diameter). White-weathering hornblende-feldspar-porphyry clasts (up to 20 cm diameter) are conspicuous and also occur in abundance at stratigraphic levels below the Eclogite formation. Farther southeast, stratigraphically below the units at Eclogite Ridge, the conglomerate, sandstone, and siltstone beds

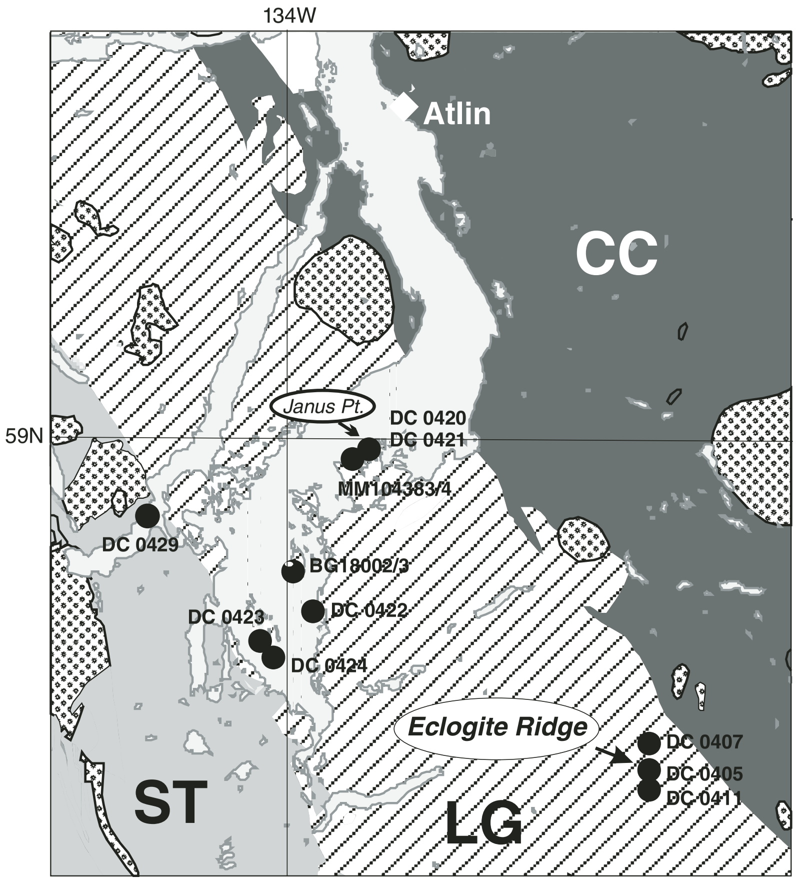


Figure 2. Simplified geology of the Atlin-Nakina area, showing Stikinia (ST), Laberge Group (LG), Cache Creek terrane (CC), mid-Jurassic plutons (dotted) and location of Eclogite Ridge. Major faults and Eocene Sloko Group outcrops removed for clarity. Heavy mineral sample locations and numbers are shown as black dots with numbers. All samples are from Laberge Group sediments, except DC0429, which was taken from the Triassic Stuhini absarokite. Atlin Lake and other water bodies are shown in blue.

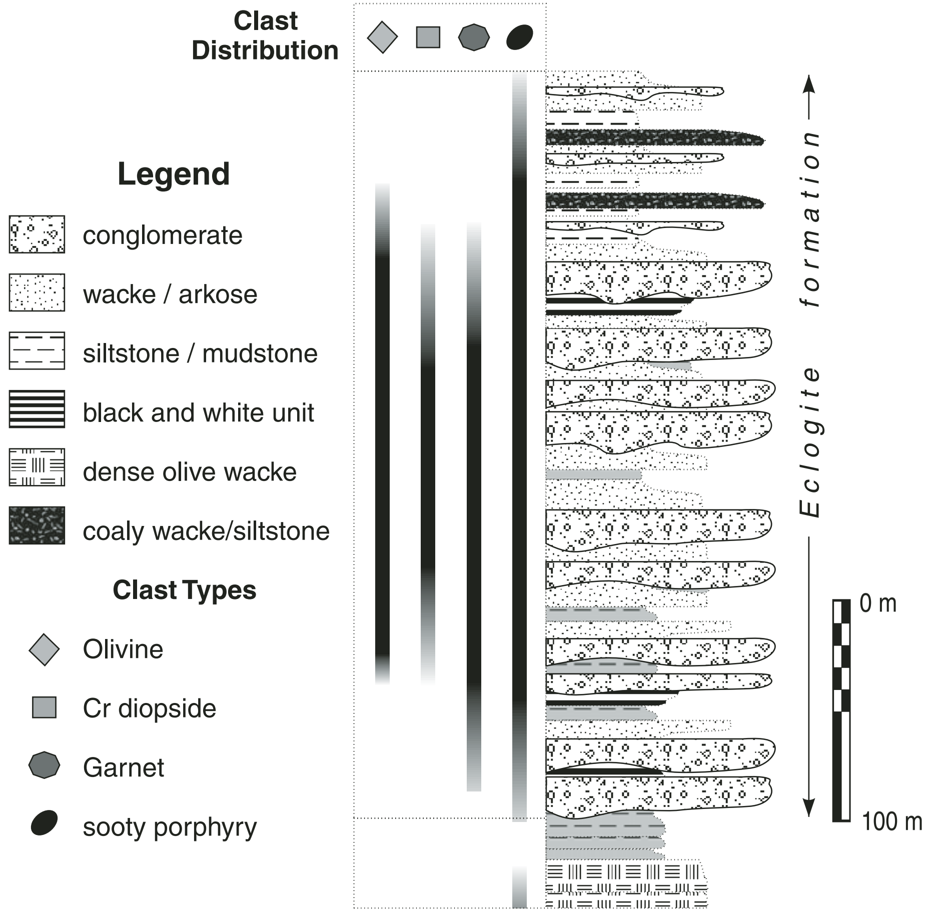


Figure 3. Stratigraphic section for Laberge Group sediments at Eclogite Ridge (see Fig. 2 for location).

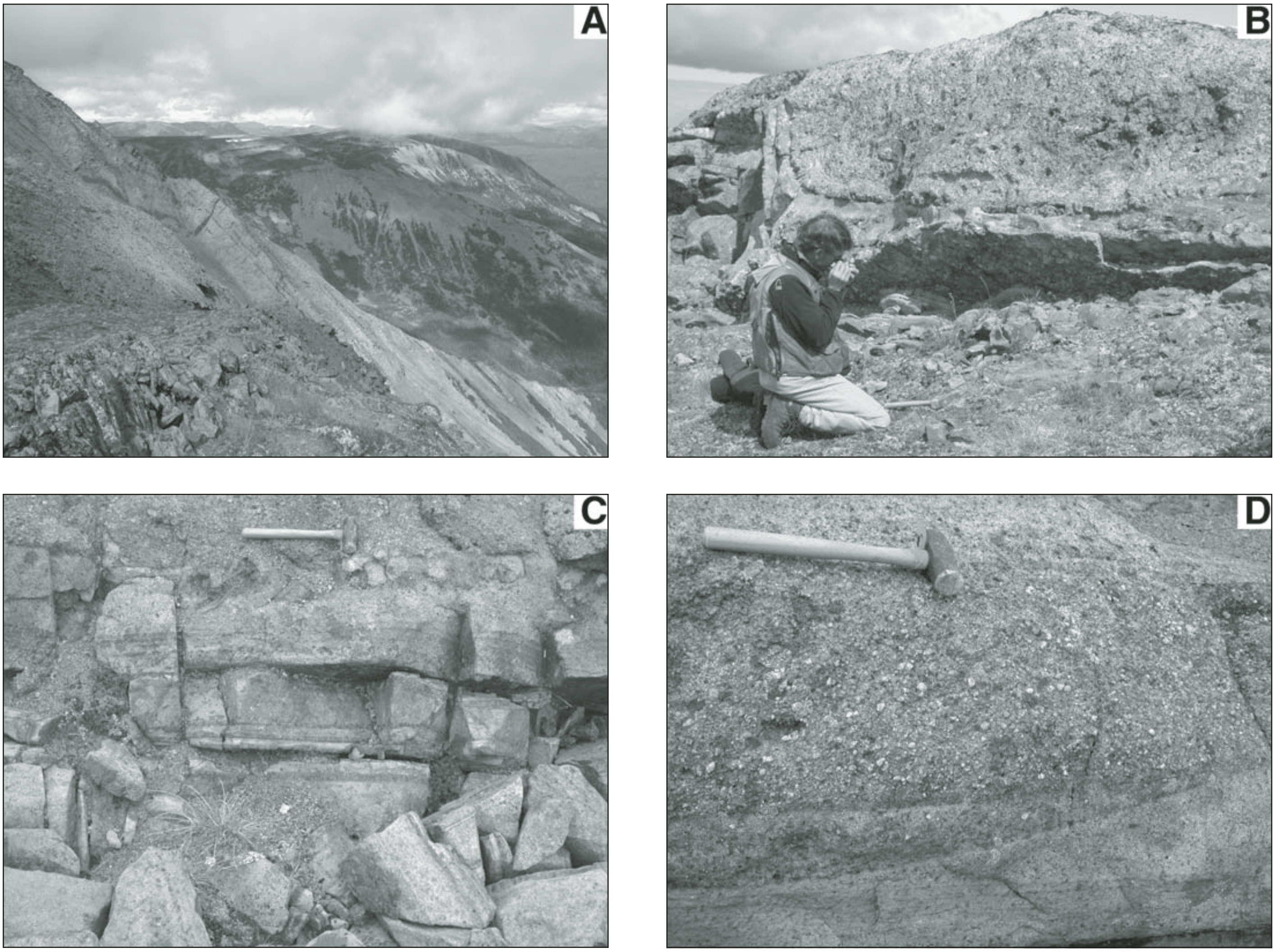


Figure 4. Photographs of Laberge Group sediments at Eclogite Ridge. (A) Highly resistant coarse pebble conglomerate units can be traced for kilometers in the view to the northwest. (B) Asymmetric steep-sided contact of garnet-bearing conglomerates cutting down through underlying sandstone and siltstone units. (C) Banding in units below conglomerates formed by 3- to 5-cm-thick intercalations of dark, organic-rich siltstones, some of which are petroliferous, with thicker cream-colored arkose. (D) Coarse pebbles of granitoid and hornblende porphyry (white) in conglomerate. Note cross-bedding in coarser units.

have similar sedimentologic features but are distinctly darker in color, and both garnet and the sooty black porphyry clasts are absent.

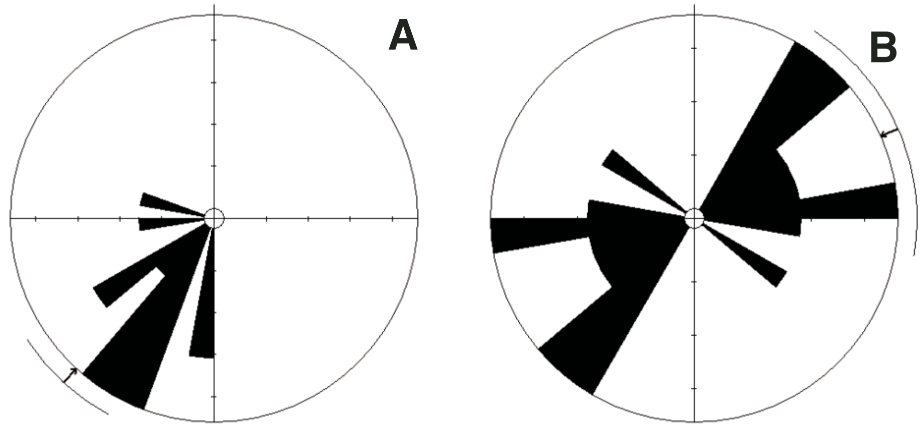
Toward the top of the section, black-weathering coaly wackestone and siltstone contain fossil plant material of dominantly swamp grass and cycad (a palm-like plant) fronds and trunks up to 20 cm diameter.

Paleoflow and Depositional Environment

Asymmetrical lens-shaped conglomerate beds deposited on erosional surfaces atop finer-grained sandstones and siltstones (Fig. 4C, D) are interpreted as lag deposits within channel scours. Cross-bedding is well displayed, even in coarse-grained units (Fig. 4D), and orientations of trough cross-strata could be deduced in three dimensions. Pebble imbrication is recognized in some places but is difficult to distinguish from pebbles lying on ill-defined foresets. Only where the pebbles were tiled could they be used as an indicator of unidirectional paleoflow. From the dip direction of foresets, paleocurrent directions were interpreted to flow toward the west or southwest (Fig. 5). Other bidirectional flow indicators include channel scour orientation and the preferred orientation of elongate clasts, including cycad trunks, which are broadly consistent with the unidirectional indicators (Fig. 5).

Some granules and pebbles are subrounded, but most of the clasts are angular, including detrital mantle mineral grains of garnet and clinopyroxene, as well as porphyritic clasts of probable volcanic origin, and argillaceous rip-up clasts. The presence of hummocky cross-strata, rip-up clasts, and the muddy matrix to wacke units, suggests the impingement of storm surge base on the depositional environment. Channelized gravels were deposited in an aggrading submarine channel deposit. The appearance of cycad debris, including substantial trunks, is not expected in a submarine depositional setting but could represent a shallowing upward sequence.

A submarine-fan-complex interpretation is consistent with previous depositional environments proposed for other Whitehorse Trough



Dip direction cross-bed foresets
mean 222 +/- 15 2sigma

Channel scour, pebble orientation
mean 66-246 +/- 34 2sigma

Figure 5. Paleocurrent measurement of Laberge Group sediments at Eclogite Ridge, plotted on rose diagrams, based on (A) dip directions of cross-bed foresets (unidirectional) and (B) channel scour and pebble orientation (bidirectional).

strata (e.g., Dickie and Hein, 1995; Johannson et al., 1997). The predominance of southwest-directed paleoflow indicators for the sediments at Eclogite Ridge is similar to measurements in Laberge Group strata to the north in the Atlin Lake area (Johannson et al., 1997) .

Other outcroppings of coarse pebble conglomerates and immature wackes in the Laberge Group are well exposed in the southern parts of Atlin Lake (Johannson et al., 1997). Exposures we examined on islands near Janus Point contained visible garnet, but farther southwest, garnet was notably absent in outcrop. Garnet-bearing units near Janus Point are late Pliensbachian(?) and are along strike with those on Eclogite Ridge 20 km to the southeast, suggesting that they are part of the Eclogite member (Fig. 2, samples DC0420, DC0421). These observations are substantiated by subsequent thin section petrography and heavy mineral studies described in the following sections.

PETROGRAPHY

Thin sections of samples from Eclogite Ridge contain abundant feldspar and lithic fragments with lesser quartz, garnet, pyroxene, olivine, and opaques; among 3–8 mm clasts of pristine arc volcanics (hornblende andesite, dacite), granitoids and metamorphic rocks (mica schist, amphibolite) including rare eclogite (garnet + pyroxene + rutile + quartz) or granulite (garnet + pyroxene + plagioclase + rutile + quartz). The samples from Eclogite Ridge and near Janus Point have a high detrital magnetite content (~1.5%), which is likely the source of its anomalous magnetic susceptibility (15) and aeromagnetic signature (Lowe et al., 2003). Most minerals are fresh, but feldspars are moderately sericitized. All samples have significant matrix, primarily of zeolites, clay minerals, and sericite (Fig. 6A).

Modal abundances in samples from Eclogite Ridge and underlying units were determined, using a modified version of the Gazzi-Dickinson point-counting technique (Ingersoll et al., 1984), which eliminates the need to count various size fractions individually. Between 600 and 900 grains were counted per slide to minimize the statistical variance according to the range of grain sizes present (0.5–8 mm), the size of the thin section, and the grid spacing used (Solomon, 1963) (Table DR1).[1] The relative abundances of framework quartz, feldspar, and lithic fragments (Dickinson et al., 1983), or of quartz, K-feldspar, and plagioclase feldspar (Marsaglia and Ingersoll, 1992), show that sediments from Eclogite Ridge were derived from supracrustal rocks in an incipient state of erosion in a nascent continental arc (Fig. 7). Two samples contain anomalously high K-feldspar contents, suggesting derivation from an exposed basement or plutonic arc root (Boggs, 2001). Samples from darker colored units stratigraphically below Eclogite Ridge show similar detrital components but are notable for containing minor carbonate and minor polycrystalline quartz framework, a higher degree of alteration (>10%), and no detrital mantle minerals.

HEAVY MINERALS

Samples of coarse conglomerate and wacke weighing between 0.5 and 4.0 kg were collected from three localities along Eclogite Ridge and seven along the shores of southern Atlin Lake (Fig. 2). Absarokites (high-K basalts) of the nearby Triassic Stuhini Group were also sampled (Fig. 2, sample DC0429). Heavy minerals were extracted from these samples, using methods reported in MacKenzie et al. (2005), to augment their initial study of only two samples from Eclogite Ridge.

The heavy mineral fraction for each sample varies in concentration from 1.6% to 0.01% (Fig. 8). The largest percentage of heavy minerals occurs in sediments that contain visible garnet and clinopyroxene as individual minerals or clasts in outcrop—for example, at Eclogite Ridge, and along-strike to the northwest at Janus Point on Atlin Lake (Figs. 2, 8). Samples collected farther to the south, lower in the stratigraphic section, display a marked decrease of heavy minerals and an absence of visible garnets in hand sample. The heavy mineral population is dominated by orange garnet and opaque minerals, followed by clinopyroxene and minor sulfides. Garnet adheres to clinopyroxene and includes minute grains of spinel, suggesting that it was derived from both eclogite and garnet-spinel peridotite (Fig. 6).

Clinopyroxene

Clinopyroxene grains are angular, show well-developed cleavage, and vary in color from dark green to bright emerald green. Both color variations of clinopyroxene contain some inclusions of garnet (Fig. 6B) or occur with garnet in granule-sized clasts with quartz, rutile, or plagioclase (Fig. 6C), suggesting that these pyroxenes are derived from eclogite, granulite, or peridotite. Mineral chemical data help to further distinguish these three different protoliths for single-grain clinopyroxenes (Table DR2).

Individual clinopyroxene grains low in Cr#, and Mg#, but having a jadeite component (X_{Jd}) greater than 0.2, are omphacites (Fig. 9) when classified according to Morimoto et al. (1988). When present in garnet + clinopyroxene clasts, such pyroxenes are deep green in color, are associated with orange garnet, and show no correlation between the jadeite component and Mg# (Fig. 10). In contrast, clinopyroxene in garnet + clinopyroxene clasts with X_{Jd} <0.2 can be present with plagioclase (An_{40}), show a correlation

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[1] GSA Data Repository item 2006146, Tables DR1–DR4, is available on the Web at http://www.geosociety.org/pubs/ft2006.htm. Requests may also be sent to editing@geosociety.org.

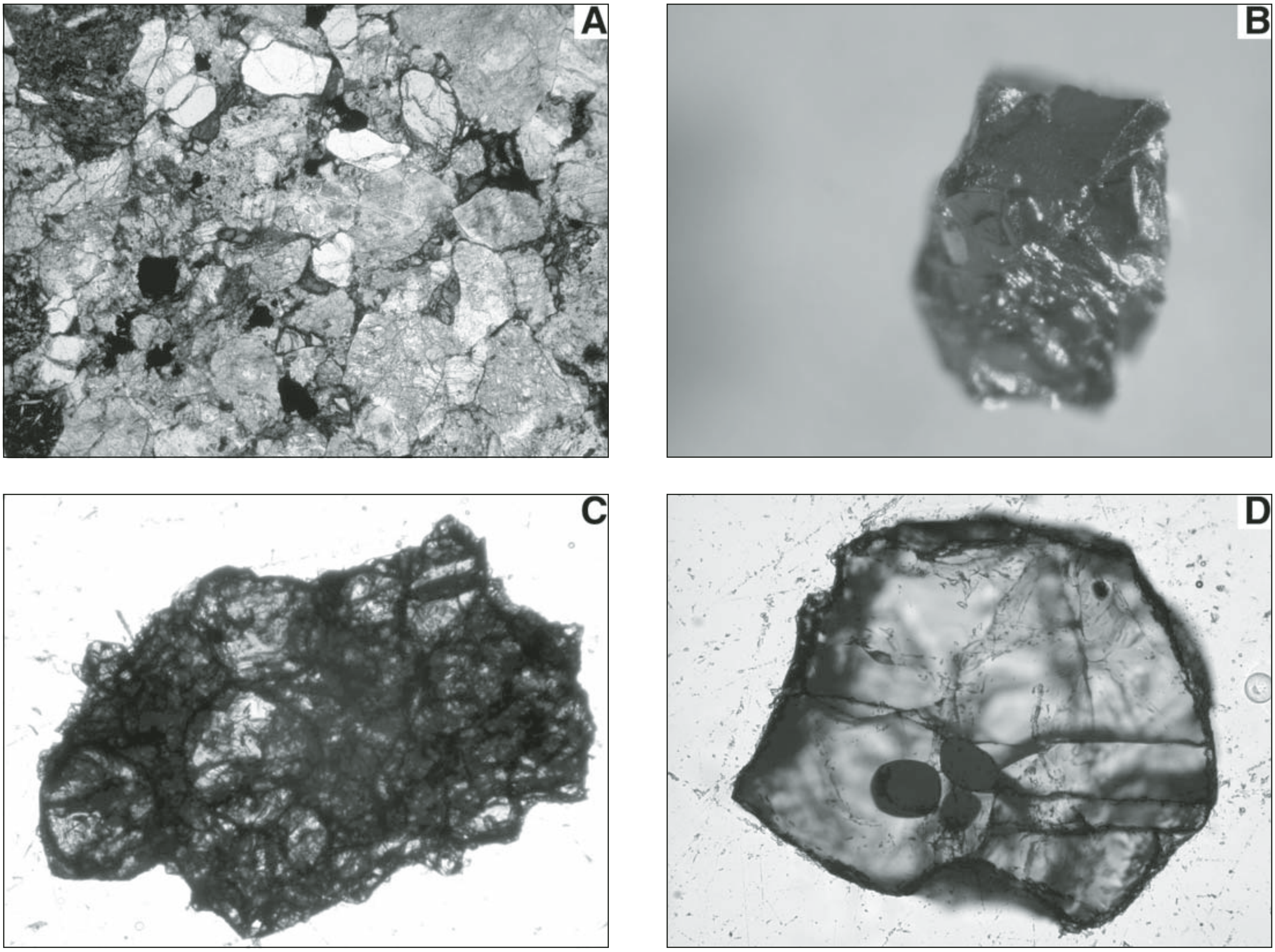


Figure 6. Petrography of detrital components in Laberge Group sediments. (A) Photomicrograph of pebble conglomerate in cross-polarized light. Note subangular clasts and poor sorting. Width of photo, 4 mm. (B) Angular, emerald green clinopyroxene grain with inclusion of red garnet. Width of photo, 2 mm. (C) Angular clast of garnet + pyroxene. Width of photo, 2 mm. (D) Subangular, purplish pink garnet with inclusions of spinel. Width of photo, 2 mm.

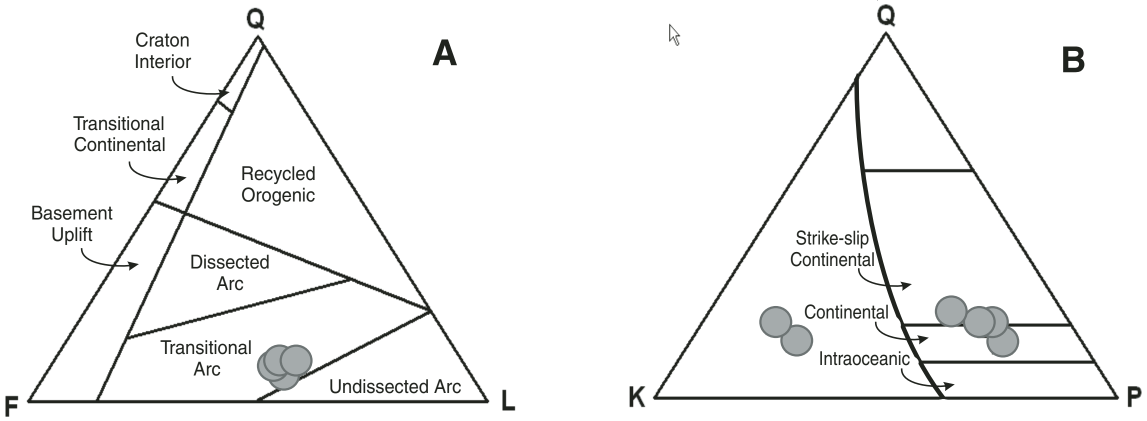


Figure 7. Ternary diagrams showing proportions of (A) quartz (Q), feldspar (F), and lithics (L); and (B) quartz (Q), K-feldspar (K), and plagioclase (P) in Laberge Group sediments, measured by point counting. Data from Table DR1. Fields for different settings are from Marasagli and Ingersoll (1992).

with Mg# (Fig. 10), and are interpreted as having been derived from granulite.

Pyroxene grains having bright emerald green colors are high in Mg# and Cr#, low in X_{Jd} (<0.2), and can occur with reddish garnet and are classified as Cr-diopsides from a peridotite protolith (Figs. 9–11). The Mg# of Cr-diopsides is considerably lower (0.77–0.92) when compared to clinopyroxene in other mantle-derived garnet peridotites (Mg# >0.91) but are not unlike those in other UHP terranes, some of which can be Fe-rich (Carswell et al., 1983). As already noted, absarokites (K-rich basalts) of the Triassic Stuhini Group served as a source for some of the detritus deposited in the Laberge Group during the Early Jurassic. Mg- and Cr-rich pyroxene phenocrysts are present in absarokites of the nearby Stuhini Group (Mihalynuk, 1997), but the latter are distinctly Ti-rich when compared to peridotitic clinopyroxene (Fig. 11). At least two grains classified as Cr-diopside, and several "others" that are intermediate in Mg#, Cr#, and Ti content, may in fact be detrital pyroxene phenocrysts from the Stuhini absarokites (Fig. 11). The thermobarometric calculations discussed in the next major section show that these "other" pyroxenes do not belong to a high-pressure peridotitic paragenesis.

Garnet

Garnets vary in shape from angular to subrounded and show pink, purplish pink, and orange colors. Orange garnets are by far the most common in the heavy mineral fractions in the Eclogite formation (>90%), followed by pink and purplish pink varieties. The population of the purplish pink garnets is classified compositionally, using the CaO versus Cr_2O_3 plot and the scheme of Schulze (2003). The purplish pink garnets vary from ~1 to 5 wt% Cr_2O_3 and have high pyrope components (>0.6 wt%) (Table DR2), within the range for mantle lherzolites (Fig. 12). Orange and pink garnets are all lower in Cr (<0.5 wt%), are richer in Ca, and contain intermediate pyrope (0.3–0.6 wt%) (MacKenzie et al., 2005). Crustal garnets from skarn or other origins have low pyrope components (<0.2 wt%).

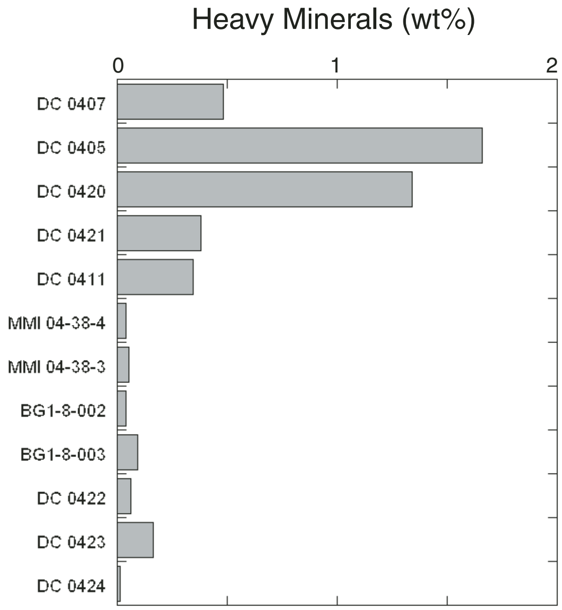


Figure 8. Percentages of heavy minerals extracted from 0.5 kg samples from Laberge Group sediments. Samples are arranged in stratigraphic order on the basis of field mapping (see Fig. 2 for locations).

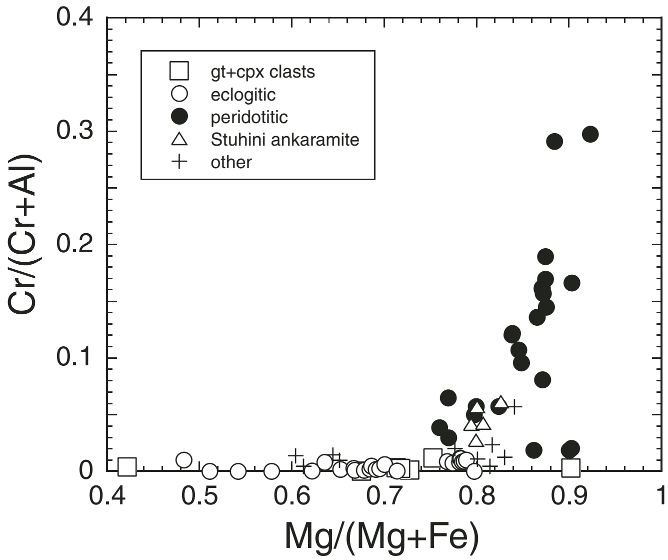


Figure 9. Covariation of Mg# and Cr# in clinoproxenes from heavy mineral concentrates, in garnet + pyroxene clasts, and in phenocrysts of the Stuhini ankaramite. Note overlap of some Stuhini pyroxenes with some "peridotitic" clinopyroxenes. Abbreviations: gt—garnet; cpx—clinopyroxene.

The trace element patterns of Cr-pyrope garnets are related to the pressure, temperature, and protolith composition and are useful in deducing the thermal and tectonic setting of the mantle they represent (Griffin et al., 1999). A range of chondrite-normalized patterns is recognized in Cr-rich mantle garnets from normal convex-upward, LREE (light rare earth elements) depleted and HREE (heavy rare earth elements) enriched, to LREE (La–Nd) enriched, or sinuous patterns with strong enrichment in the MREE (medium rare earth elements). Pearson et al. (1998) assign a shape to the REE pattern by use of the Nd/Y ratio, which increases from normal to sinuous patterns, respectively. The Cr-pyrope garnets from the Laberge Group all have normal REE patterns and are typified by low Nd/Y ratios (Fig. 13; Table DR3).

The Y and Ga contents of mantle garnets are sensitive to the degree of depletion such that both Y and Ga decrease with increasing partial melting of a peridotite protolith, but to a different degree (Griffin et al., 1999). Garnets from the Laberge Group have a limited range of Y/Ga (Fig. 13; Table DR3), commensurate with the

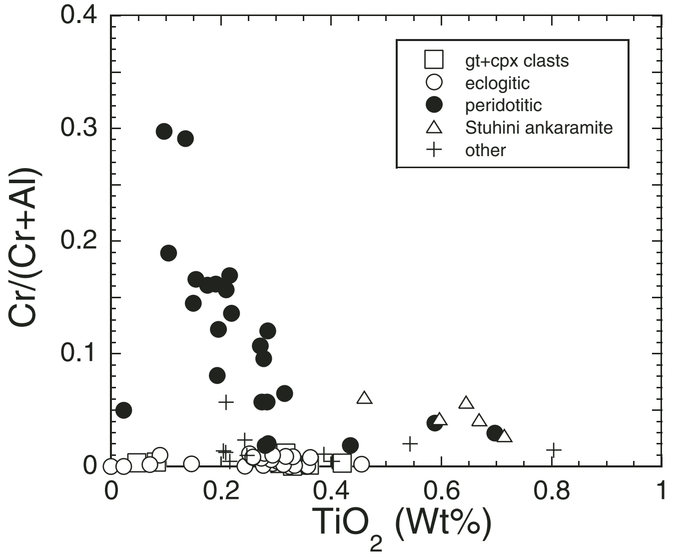


Figure 10. Covariation of TiO_2 and Cr# in clinoproxenes from heavy mineral concentrates, garnet + pyroxene clasts, and the Stuhini absarokite.

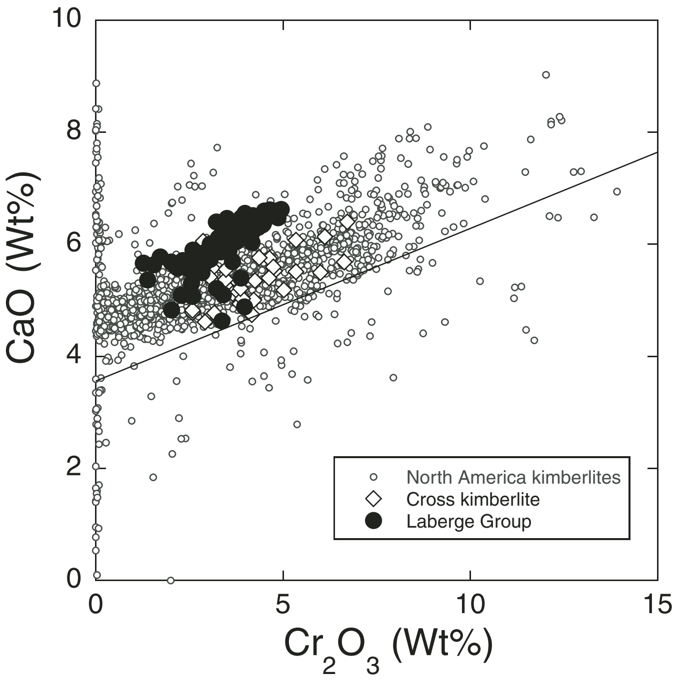


Figure 12. Covariation of CaO and Cr_2O_3 in purplish pink garnets from the Laberge Group in comparison with garnets from Crossing Creek (Cross) and other kimberlites from North America (Canil et al., 2003b; Scully et al., 2004). Line divides field for lherzolite and harzburgite (Schulze, 2003). Note limited levels of Cr in Laberge garnets in comparison with kimberlite-borne garnets.

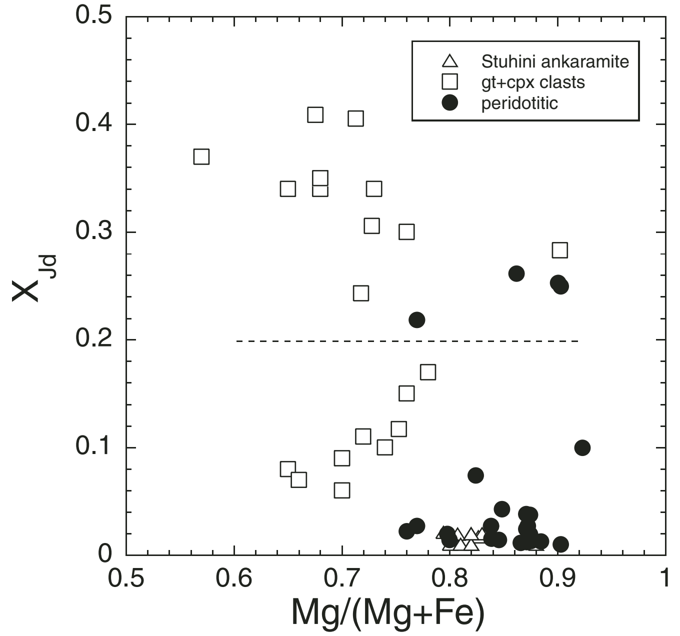


Figure 11. Covariation of jadeite component (X_{Jd}) and Mg# in emerald green, Cr-rich clinoproxenes (peridotitic); pyroxenes from garnet + pyroxene clasts; and pyroxene phenocrysts from the Stuhini ankaramite. In the garnet + pyroxene clasts, pyroxenes containing X_{Jd} >0.2 (dashed line) show no correlation with Mg# and are classified as omphacites from eclogite, whereas those with XJd <0.2, show a trend with Mg# and are classified as augites or diopside from granulite or garnet pyroxenite.

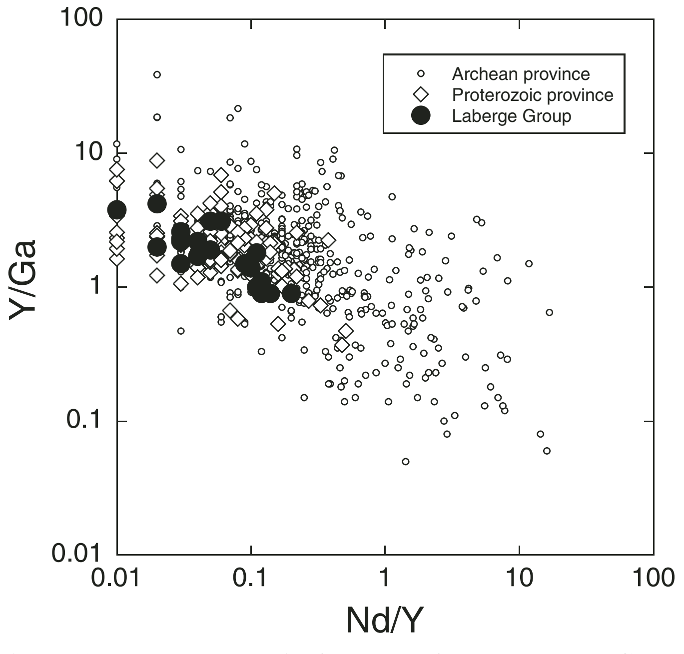


Figure 13. Trace element ratios for garnets from the Laberge Group in comparison with mantle garnets from kimberlites that intrude Proterozoic and Archean provinces in North America (Canil et al., 2003b; Scully et al., 2004). Note limited level of depletion (Y/Ga) for Laberge garnets.

limited degree of depletion suggested by their Cr contents (Table DR2). Other key trace element ratios in garnet (Zr/Y, Sc/V, Sc/Y) show identical trends and relationships, as Y/Ga and Nd/Y given previously, but are not shown for brevity.

Spinel

The opaque minerals in heavy mineral concentrates are almost exclusively euhedral magnetite (>99%) with inclusions of apatite or quartz, suggesting a derivation from granitoid rocks common as detritus in the Eclogite formation. Brown spinels recognized as inclusions in garnet (Fig. 6D), and more rarely as separate grains in the heavy mineral fractions, are Cr- and Mg-rich (Cr# = 0.7–0.85; Mg# = 0.36–0.61), similar to chromites recognized in mantle xenoliths and in diamonds, or in some orogenic massifs (Barnes and Roeder, 2001). Spinel phenocrysts are also recognized in the nearby Stuhini Group absarokite but are lower in Mg# and Ti, and higher in Cr#, than chromites in the Laberge Group (Table DR2).

THERMOBAROMETRY

Single mineral thermobarometers applied to heavy mineral fractions in diamond exploration (Griffin et al., 1993; Nimis, 2002) can be used to estimate the temperature (T) and pressure (P) of equilibration of mantle-derived detritus in this study. Petrographic evidence suggests that the Cr-diopside grains could have been in equilibrium with peridotitic garnet (Fig. 6B). The exchange of Cr between clinopyroxene and garnet is sensitive to both T and P and was applied to Cr-diopside grains with the constraint of having a minimum level of Cr (a_{CrTs} >0.003) recommended by Nimis and Taylor (2000). Seven single grains gave spurious results (P <1.0 GPa) using this approach, and were either not in equilibrium with garnet or were misidentified as being from a garnet peridotite protolith. The remaining grains gave a T_{NT} of 660–920 °C and a P_{NT} of 1.9–3.2 GPa (Fig. 14; Table DR4). Both T_{NT} and P_{NT} show a strong correlation with the Mg# of clinopyroxene (Fig. 15), which can be interpreted in two ways: either the composition of the mantle, as reflected by the Mg# of clinopyroxene, changes with P (depth), or there is an inherent effect of Mg/Fe on the T_{NT} and P_{NT} thermobarometers. It should be noted that T_{NT} and P_{NT} are calibrated on experiments in peridotite bulk compositions with Mg# >0.88 (Nimis and Taylor, 2000), and the more Fe-rich Laberge clinopyroxenes are out of the calibration range and may produce spurious results.

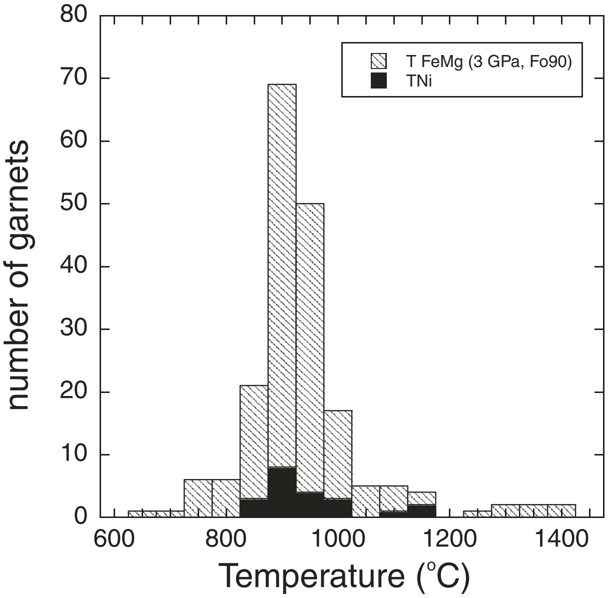


Figure 14. Histogram showing results of Ni-in-garnet thermometry (filled; Canil, 1999) and Fe-Mg exchange thermometry (cross-hatched) for peridotitic garnets, assuming that they equilibrated at 3 GPa with average mantle olivine (Fo_{90}; O'Neill and Wood, 1979).

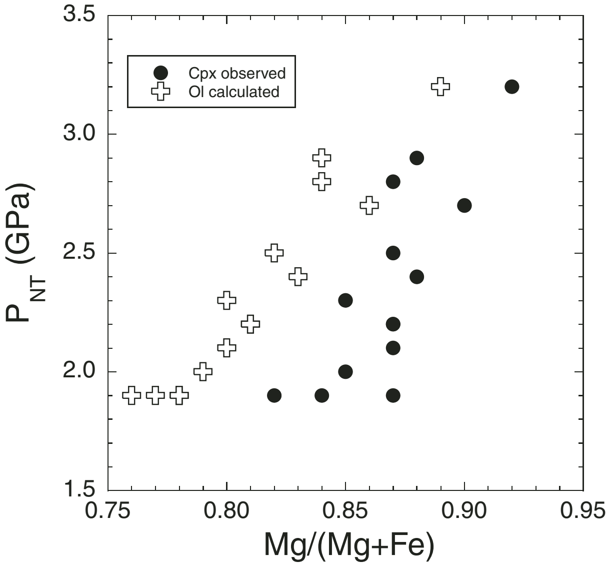


Figure 15. Correlation of Mg# of pyroxene with pressures calculated with Cr-in-clinopyroxene thermobarometer (Nimis and Taylor, 2000). The Mg# of olivine that would have been in equilibrium with each clinopyroxene was calculated using the relationship for KdFe-Mg olivine-clinopyroxene (Ol-Cpx) calibrated as a function of P and T in experiments on peridotitic systems (Brey et al.). Note that "typical" mantle olivine (Fo_{90}) is present only at pressures above 3.0 GPa.

At an assumed P of 3.0 GPa, clasts of eclogite record clinopyroxene-garnet Fe-Mg exchange temperatures (T_{KR}, Krogh, 1988) of 850–1070 °C overlapping only the high T results for T_{NT} (Table DR4). The Fe-Mg exchange temperature calculations do not consider, however, the effect of large amounts of Fe^{3+} in omphacitic clinopyroxenes from eclogites, which can be difficult to estimate using recalculated analyses for microprobe data assuming stoichiometry, and which will lower temperatures significantly (by 200–400 °C (Canil and O'Neill, 1996; Li et al., 2005).

Assuming a P of 3.0 GPa, and an equilibrium with typical mantle olivine (Fo_{90}), the Fe-Mg exchange temperatures for the peridotitic garnets (T_{OW}, O'Neill and Wood, 1979) are 600–1400 °C, with a dominant mode at 900 °C (Fig. 16). These temperatures are at the high end of the range in T_{NT} for clinopyroxene grains with an Mg# of 0.9, and would decrease slightly at lower assumed pressures (~60 °C/GPa), or increase for a lower Fo content of olivine (75 °C/mol% Fo). The Ni-in-garnet thermometer (T_{Ni}) has a negligible P dependence (Canil, 1999) and was applied to a subset of the Cr pyropic garnets analyzed by laser ablation (LA) inductively coupled plasma–mass spectroscopy (ICP-MS), giving a dominant mode at 900 °C, also consistent with T_{OW} at 3 GPa, assuming equilibrium with Fo_{90} olivine (Fig. 16).

The transition from spinel to garnet peridotite is a useful geobarometer (O'Neill, 1981) that depends strongly on the Cr/Al content of spinel and less on the Mg/Fe of coexisting olivine (Girnis and Brey, 1999). Assuming that spinel inclusions in the Laberge peridotitic garnets (Fig. 6D) were in equilibrium with typical mantle olivine (Fo_{90}) at the average T_{NT} recorded by Cr-diopsides (800 °C) gives pressures of 2.9–3.5 GPa and 2.9–3.8 GPa, using the methods of O'Neill (1981) and Webb and Wood (1986), respectively (Fig. 14; Table DR4). These results change <0.3 GPa/100 °C.

DISCUSSION

Were the Detrital UHP Minerals Derived from an Alkaline Igneous Rock?

The UHP minerals and clasts in the Laberge Group are detrital components in a sediment, not actual rocks in outcrop. The erosion of mantle xenoliths and xenocrysts common to alkaline magmas could also have served as a potential source for this detritus (e.g., McCandless, 1990). River systems are known to transport heavy minerals such as garnet (McCandless, 1990).

The Crossing Creek kimberlite in southeastern British Columbia has a garnet population similar to that observed in the Laberge Group (Fig. 12) and is the only known kimberlite in western North America close enough in age (241 Ma; Heaman et al., 2003) and proximity (in present coordinates) to have served as a potential source rock (Fig. 1, inset). Erosion of this kimberlite source and northward transport of mantle-mineral detritus by rivers is one possible scenario. Mantle minerals undergo rapid abrasion when mixed in sand-sized particles during fluvial transport (McCandless, 1990), yet the Laberge garnets and pyroxenes show evidence for minimal attrition, requiring a source proximal to the site of deposition (Whitehorse Trough). A closer proximity of the Whitehorse Trough to a Crossing Creek kimberlite source during the Jurassic, however, is not supported by paleomagnetic data sets (Irving and Wynne, 1990; Vandall and Palmer, 1990). Furthermore, no alkaline igneous rocks of Jurassic age exist in the northern Cordillera to have served as a source of mantle minerals to be mixed with immature arc detritus. Although alkaline volcanics in the Triassic Stuhini Group straddle the western edge of Whitehorse Trough (Mihalynuk, 1997), they contain no mantle material, and their Cr-rich pyroxene phenocrysts do not match those observed in the Laberge Group (Figs. 9–11). Lastly, an examination of >100 opaque mineral grains from the Laberge Group revealed few picrochromites and no picroilmenites, indicator minerals used in diamond exploration of alkaline igneous rocks (Fipke et al., 1995). All these arguments refute an alkaline igneous source for the mantle detritus in the Laberge Group.

Tectonothermal Setting of UHP Rocks

A more likely source for the UHP detritus is massifs of garnet peridotite, garnet pyroxenite, granulite, and eclogite, known to occur in collisional orogens as septa or blocks within larger fault-bounded supracrustal slabs, commonly of continental composition (Liou et al., 2003; Medaris, 1999). Orogenic peridotites are known in some arc-continent collisional settings such as the Lesser Antilles and Sulawesi (Abbott et al., 2005; Kadarusman and Parkinson, 2000). Such massifs are commonly small in volume (~1 km^3) but have lithologies containing sufficient garnet (5%–50%) that upon erosion could contribute the amount observed in the heavy mineral fraction of the sediments of the Eclogite member (<0.5%).

Carswell et al. (1983) recognize two distinct compositional groups of orogenic garnet peridotite in the Western Gneiss region of Norway: (1) an Fe-Ti type associated with ilmenite and Fe-rich olivine ($Fo_{67–82}$), occurring with garnet pyroxenites and eclogites; and (2) an Mg-Cr type

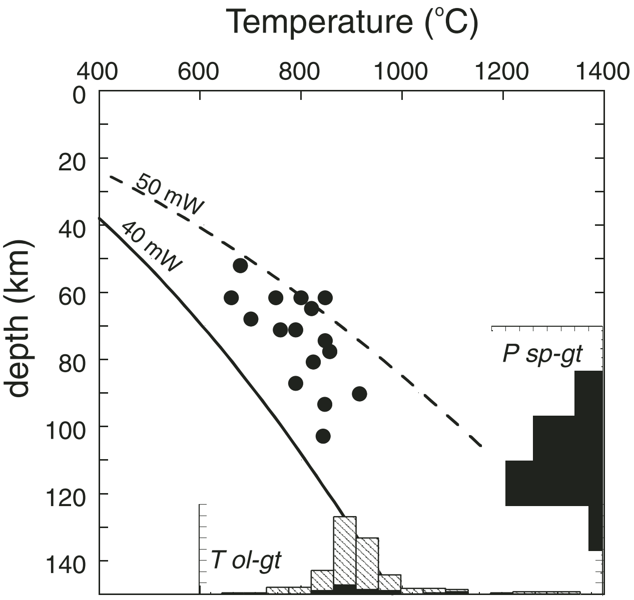


Figure 16. Plot of results of thermobarometric calculations for peridotitic garnets, pyroxenes, and spinels in the Laberge Group. Filled circles show pressure-temperature (P-T) results for detrital peridotitic clinopyroxenes using the Cr-in-clinopyroxene thermobarometer (Nimis and Taylor, 2000). Histogram at base of diagram shows results of Fe-Mg exchange thermometry (cross-hatched) for peridotitic garnets, assuming they equilibrated at 3 GPa with average mantle olivine (ol, Fo_{90}; O'Neill and Wood, 1979), and for Ni-in-garnet thermometry (filled) (Canil, 1999). Histogram on right shows pressures calculated, based on the coexistence of spinel (sp) and garnet (gt) (O'Neill, 1981; Webb and Wood, 1986). Thermobarometric pressures were converted to depths. Geothermal gradients typical of Archean (40 mWm^{-2}) and Proterozoic (50 mWm^{-2}) continental lithosphere are shown for reference and were calculated as in MacKenzie and Canil (1999).

with more Fe-poor olivine (Fo$_{82–92}$), intercalated with garnet pyroxenite in Alpine-type peridotite bodies. Protoliths for the Fe-Ti and Mg-Cr types are thought to be deep crustal mafic and ultramafic cumulates, and depleted mantle lithosphere, respectively. Medaris (1999) further distinguishes orogenic garnet peridotites into two distinct P-T regimes: a high P-T regime associated with subduction and a low P-T regime that requires a mechanism of hot upwelling and asthenospheric flow.

No bulk compositions are available for the Laberge UHP assemblages, but olivine compositions in equilibrium with the Cr-diopsides can be estimated using Kd$_{ol-cpx}$ Fe-Mg determined by experiment in peridotitic systems (Brey et al., 1990). Olivines calculated to be in equilibrium with the Laberge Cr-diopsides at their respective T$_{NT}$ and P$_{NT}$ values vary from Fo$_{75}$ to Fo$_{89}$ (Fig. 15). Thus, both the Fe-Ti and Mg-Cr garnet peridotite types of Carswell et al. (1983) are represented in the Laberge detritus, and, furthermore, they occur along the high P-T regime of Medaris, not unlike that of the Western Gneiss region of Norway (Fig. 17). In this way the Laberge Group detritus is associated with the subduction process and likely involves a depleted mantle wedge and deep cumulate protoliths.

Key major and trace element patterns can help in identifying potential protolith and tectonothermal ages of mantle represented by garnet from Archean, Proterozoic, or younger lithosphere (Canil et al., 2003b; Griffin et al., 1999; Griffin et al., 1993, 1999). Cr contents of garnet are the result of a complex interplay with Ca and the P and T of equilibration, but are generally a reflection of the level of depletion in the mantle protolith. The Cr contents of the Laberge peridotitic garnets suggest a limited degree of depletion when compared to kimberlite-borne garnets from western North America (Fig. 12). The Cr-pyrope garnets from the Laberge Group all have normal REE patterns, typified by low Nd/Y, and a high but limited range of Y/Ga, similar to garnet xenocrysts from kimberlites erupted through Proterozoic terranes and unlike significant populations of garnet in kimberlites emplaced in Archean terranes (Fig. 13). Although the age of the protolith of the peridotitic garnets is not known, all major and trace element characteristics are consistent with Proterozoic or younger mantle lithosphere as a source.

In this framework the Laberge UHP detritus could be interpreted as mafic and ultramafic protoliths that were initially emplaced in the crust, or that existed in the mantle wedge, before transport to higher-pressure conditions in a subducting plate to become garnet pyroxenites, granulites, eclogites, and peridotites. The presence of both granulites (plagioclase + clinopyroxene + garnet ± quartz ± rutile) and eclogites (clinopyroxene + garnet ± quartz ± rutile) could represent a continuum of mafic crustal protoliths subducted across the granulite-eclogite transition, which varies with bulk composition (Green and Ringwood, 1967). The P-T range of Cr-diopsides and its correlation with Mg# (Fig. 15) could be a spurious outcome of the compositional dependence of the P$_{NT}$ barometer, or it may be indicative of the range of depths from which peridotitic cumulates (Fe-Ti type) or lithosphere of the mantle wedge (Mg-Cr type) was exhumed. If the latter is true, it appears that the more Fe-Ti-rich peridotite types existed at shallower depths than the more depleted Mg-Cr type.

Provenance, Exhumation, and Deposition of UHP Detritus

Eclogites are known throughout the North American Cordillera (reviewed in Erdmer et al., 1998), but exposures of orogenic peridotite are scarce. Orogenic garnet peridotite (Den Tex, 1969) has been recognized in the Kigluaik Mountains of western Alaska (Till, 1981). Geochronological data are lacking, but the region likely was uplifted and exhumed in the Early Cretaceous (Patrick and Liebermann, 1988) and thus was too young to have served as the source of the Laberge Group sediments. An orogenic spinel-plagioclase peridotite body exposed in the Buffalo Pitts region, ~400 km northwest of the Atlin-Nakina region (Canil et al., 2003a), was exhumed from 30 km depths and has a granulite facies aureole dated by U-Pb methods as latest Permian (262–258 Ma; Johnston et al., 2006). The Buffalo Pitts orogenic peridotite was hosted by the Yukon Tanana terrane, west of the Whitehorse Trough, which underwent widespread and rapid uplift between 188 and 185 Ma, as constrained by ^{40}Ar-^{39}Ar ages in eastern Alaska (Dusel-Bacon et al., 2002) and U-Pb ages in southern Yukon (Johnston et al., 1996).

Rapid exposure of the UHP rocks at the surface is supported by their occurrence in only one restricted sedimentary zone of the Laberge Group. This depositional event was concomitant with, or it shortly postdated, active continental arc magmatism in the Stikinia terrane, explaining the admixture of arc volcanic and UHP minerals at this stratigraphic level. The Buffalo Pitts peridotite body in the Yukon Tanana terrane lacks garnet, but the possibility exists that both this body and the protolith of the Laberge UHP rocks are related, having been derived from deep crust and mantle of a ~100-km-thick continental block that was hinterland to a Stikinia–Yukon Tanana collision west of the Whitehorse

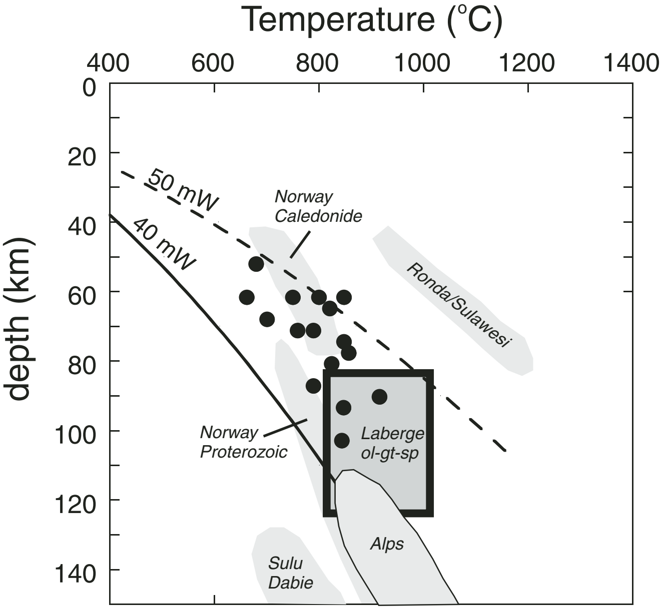
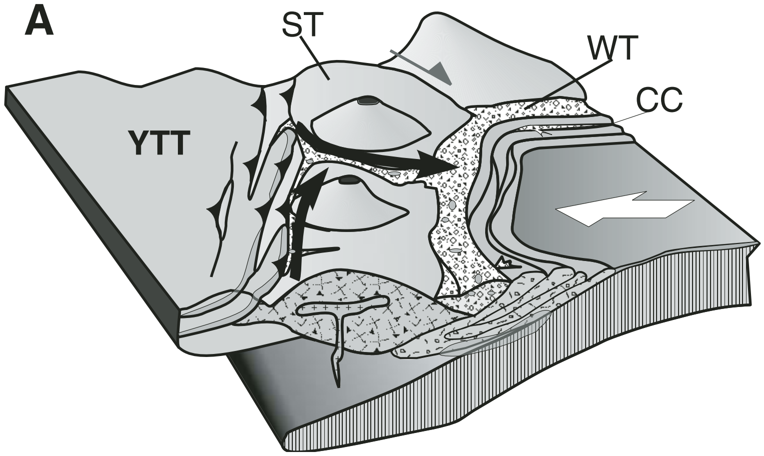


Figure 17. Thermobarometric calculations for peridotitic garnets, pyroxenes, and spinels in the Laberge Group from Figure 14, compared with the P-T regime derived for Eurasian orogenic garnet peridotites (after Medaris, 1999). The olivine-garnet-spinel (ol-gt-sp) field encompasses the crossover of results for T$_{ol-gt}$ with P$_{sp-gt}$ from Figure 14, and mostly lies at pressures and temperatures above those recorded by clinopyroxenes.

Trough and was rapidly uplifted at ca. 185 Ma (Fig. 18A). The Yukon Tanana terrane has two key geological and isotopic relationships with the substrate of Stikinia farther south: (1) quartz-rich pericratonic strata of the Yukon Tanana terrane in part form the basement to Stikinia; (2) arc metavolcanics of the Yukon Tanana terrane can be correlated within Stikinia (Jackson et al., 1991; Mihalynuk et al., 1992). Furthermore, the major and trace element imprints of the Laberge peridotitic garnets also support an affinity with mantle from 100-km-thick Proterozoic continental lithosphere, not unlike orogenic peridotites in the Norwegian Caledonides (Figs. 12, 13, 17). Exhumation of continental mantle in or between Stikinia–Yukon Tanana may have ensued during a hitherto undocumented collision between these two terranes. The arrival of a thick (~100 km) continental lithosphere into a subduction zone may have decelerated convergence, allowing rise of high pressure rocks with buoyant continental crust, as inferred for the Alps (Ernst, 1988).

The second potential setting of mafic and ultramafic rocks that would be associated with a high P-T trajectory and subduction, and proximal to a forearc basin, is an accretionary wedge or subduction complex-mélange. Blueschist and eclogite are recognized adjacent to the Whitehorse Trough in the Cache Creek terrane (Fig. 1) as a wide panel of high P-T sediments ~200 km southwest of the study area in the French Range (Mihalynuk et al., 2004) and as eclogite blocks farther south of this region in the Pinchi Lake belt (Ghent et al., 1993, 1996). The occurrence of blueschist and eclogite in the Cache Creek terrane is consistent with the subduction complex and accretionary wedge in the model of English and Johnston (2005). Return flow of material subducted along the Cache Creek subduction zone–complex would maintain the high P-T regime documented for the Laberge peridotitic garnets and pyroxenes (Fig. 18B), and the refrigeration required to preserve related blueschist and eclogite facies assemblages (Ernst, 1988).



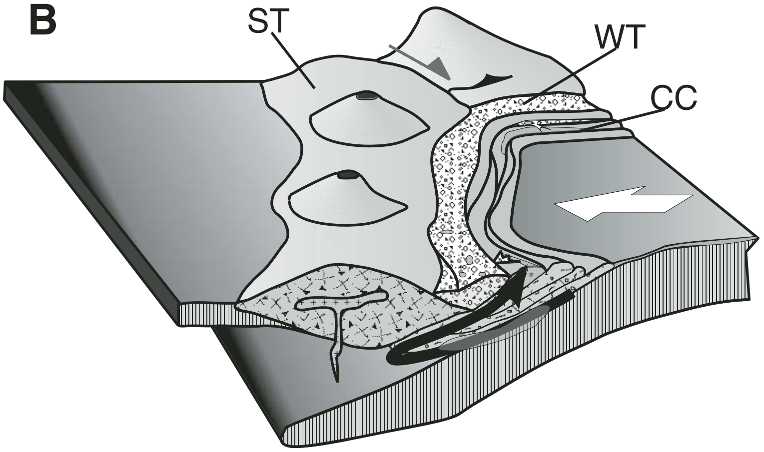


Figure 18. Cartoon depicting possible tectonic scenarios for exhumation (dark arrows) and erosion of UHP rocks with subsequent deposition into Whitehorse Trough (WT) in the northern Cordillera. (A) Arc-continent collision between Stikinia terrane (ST) and Yukon Tanana terrane (YTT). (B) Return flow of UHP rocks into uplifted forearc of Cache Creek terrane (CC). The white arrow shows convergence direction in subduction zone.

Uplifted forearc regions and accretionary mélange in the neighboring Cache Creek terrane are a possible source area for detritus in the Laberge Group rocks exposed on Eclogite Ridge. The Pinchi Lake eclogites and blueschists to the southeast have metamorphic ages of ca. 220 Ma, and a simple erosional unroofing calculation (~1 mm/year) has these rocks exposed to the surface for erosion by 200–185 Ma (Ghent et al., 1996), in perfect agreement as a source of detritus in the Laberge Group at Eclogite Ridge. Collisional orogenesis and uplift of the Cache Creek accretionary complex, however, is linked with deposition of chert pebbles into the Whitehorse Trough at a period that is 10 m.y. younger (Bajocian, 174 Ma) than deposition of Eclogite Ridge rocks (English and Johnston, 2005; Mihalynuk et al., 2004). Uplift or extrusion of high pressure rocks as a source of the Eclogite Ridge detritus along this subduction complex would have to have ensued by at least 185 Ma, 10 m.y. earlier than the emplacement of French Range blueschist (Mihalynuk et al., 2004).

At present we cannot distinguish the exact source area for the UHP detritus in the Laberge Group. Further scrutiny of regions with blueschist and eclogite occurrences in the Cache Creek terrane (French Range and Pinchi Lake) could reveal more evidence for UHP garnet peridotite there, as either primary rocks in outcrop or as detritus in younger sediments. Nevertheless, the Yukon Tanana terrane to the west hosts rocks with the most widespread and convincing evidence for rapid exhumation of deep-seated crustal rocks at the appropriate time period (185 Ma) for deposition of UHP detritus in the Laberge Group (Johnston et al., 1966; Dusel-Bacon et al., 1995, 2002). Better documentation of the relationship between the Yukon Tanana terrane, the Stikinia arc, and the Whitehorse Trough may provide clues to a collision that may have exhumed mantle rocks from considerable depths.

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