Heavy Mineral Sampling and Provenance Studies for Potentially Diamond-Bearing Source Rocks in the Jurassic Laberge Group, Atlin-Nakina Area (NTS 104N), Northwestern British Columbia

By Dante Canil[1], Mitchell G. Mihalynuk[2] and Courtney Charnell[1]

INTRODUCTION

The mineralogy of clastic sedimentary rocks provides a record of the source regions uplifted and eroded during orogeny (Dickinson et al., 1983). The Jurassic Laberge Group is part of a fold and thrust belt exposed in the northern Cordillera (Fig. 1). The paleontological and sedimentary record in the Laberge Group mark the uplift and erosion of crust during the early Jurrasic and the deposition and burial of detritus in a marine fore-arc basin (English et al., in press; Johannson et al., 1997). Garnet-rich horizons of immature wacke and conglomerate occurring in the Laberge Group southwest of Sloko River were first recognized during a regional mapping and magnetic survey program (Mihalynuk and Lowe, 2002). Subsequent heavy mineral sampling in the Atlin-Nakina area, aimed at tracing the source of anomalous diamonds in placer gold operations of the northern Cordillera (Casselman and Harris, 2002), showed evidence for diamond indicator minerals, which were traced to a garnetiferous conglomerate horizon in the Jurassic Laberge Group exposed near Sloko River (Canil et al., 2004). Further detailed study of heavy minerals from one composite sample in the garnet-rich conglomerate showed it to contain clasts of eclogite, and garnets and pyroxenes from peridotite of mantle origin (Fig. 2, 3). Thermobarometric studies revealed that the detrital garnets and pyroxenes in this sample equilibrated at mantle depths approaching the diamond stability field (MacKenzie et al., in press), on geothermal gradients expected in cratonic mantle lithosphere (Fig. 4).

Detrital mantle minerals are known in other clastic sediments (McCandless and Nash, 1996). The angular nature and lack of weathering of detrital grains in the Laberge Group require proximal sources and rapid deposition (McCandless, 1990). Potential sources for the garnet and pyroxenes in the Laberge Group could be the erosion of peridotite and eclogite as xenoliths in an alkaline igneous rock such as kimberlite or lamproite, or outcrop-sized massifs exposed by uplift and exhumation. Potential source rocks of either type that are the requisite age (pre-Jurassic) are not known in the Atlin-Nakina area. The lack of picroilmenite in a heavy mineral sample of the Laberge conglomerate argues against derivation from xenoliths in alkaline igneous rocks (i.e., kimberlite; MacKenzie et al., in press). No eclogite or garnet peridotite, as either xenoliths or massifs, has yet been recognized in outcrop in the Atlin-Nakina area. Furthermore, the source of peridotitic garnets and pyroxenes in the garnetiferous wacke unit of the Laberge Group is not likely to be from ophiolite and mélange that constitutes parts of the Cache Creek Terrane to the east. Mantle peridotite from ophiolite in the Cache Creek Terrane is of lower pressure origin, in which spinel, not garnet, is stable. Furthermore, the latter rocks have been investigated by field mapping, and although blueschist assemblages have been discovered in the Cache Creek Terrane near Dease Lake (Fig. 1), no eclogite has been recognized (Fig. 1; Ghent et al., 1993); Mihalynuk et al., 2004).

Thus, the source of eclogitic and peridotitic detritus in the Laberge Group sediments remains undefined, but has important implications for the crustal evolution of the northern Cordillera. In one interpretation of paleocurrent data for exposures in southern Atlin Lake, the source area for the Laberge Group sediments must lie somewhere to the west (Johannson et al., 1997). Nonetheless, further detailed study in other horizons of the Laberge Group is warranted to identify the source and provenance of mantle minerals, and whether the sources for sediment changed in space or time during deposition in the basin. The occurrence of diamond in northwestern British Columbia and southern Yukon (Casselman and Harris, 2002) also remains enigmatic, but could be sourced in sediments that contain other detrital minerals of demonstrable high-pressure origin required for diamond formation (Fig. 4). To this end, we performed detailed paleocurrent measurements, sedimentology and a more thorough sampling for heavy minerals in different horizons of the Laberge Group. The principal goals were to examine the lateral and stratigraphic extent of the garnetiferous horizons within the Laberge Group, to understand their appearance in the sedimentary record of this basin, and to deduce the source direction for sediments containing detrital mantle minerals, and potentially diamonds.

[1] *School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, dcanil@uvic.ca*

[2] *Geological Survey Branch, Ministry of Energy and Mines, Victoria, BC*

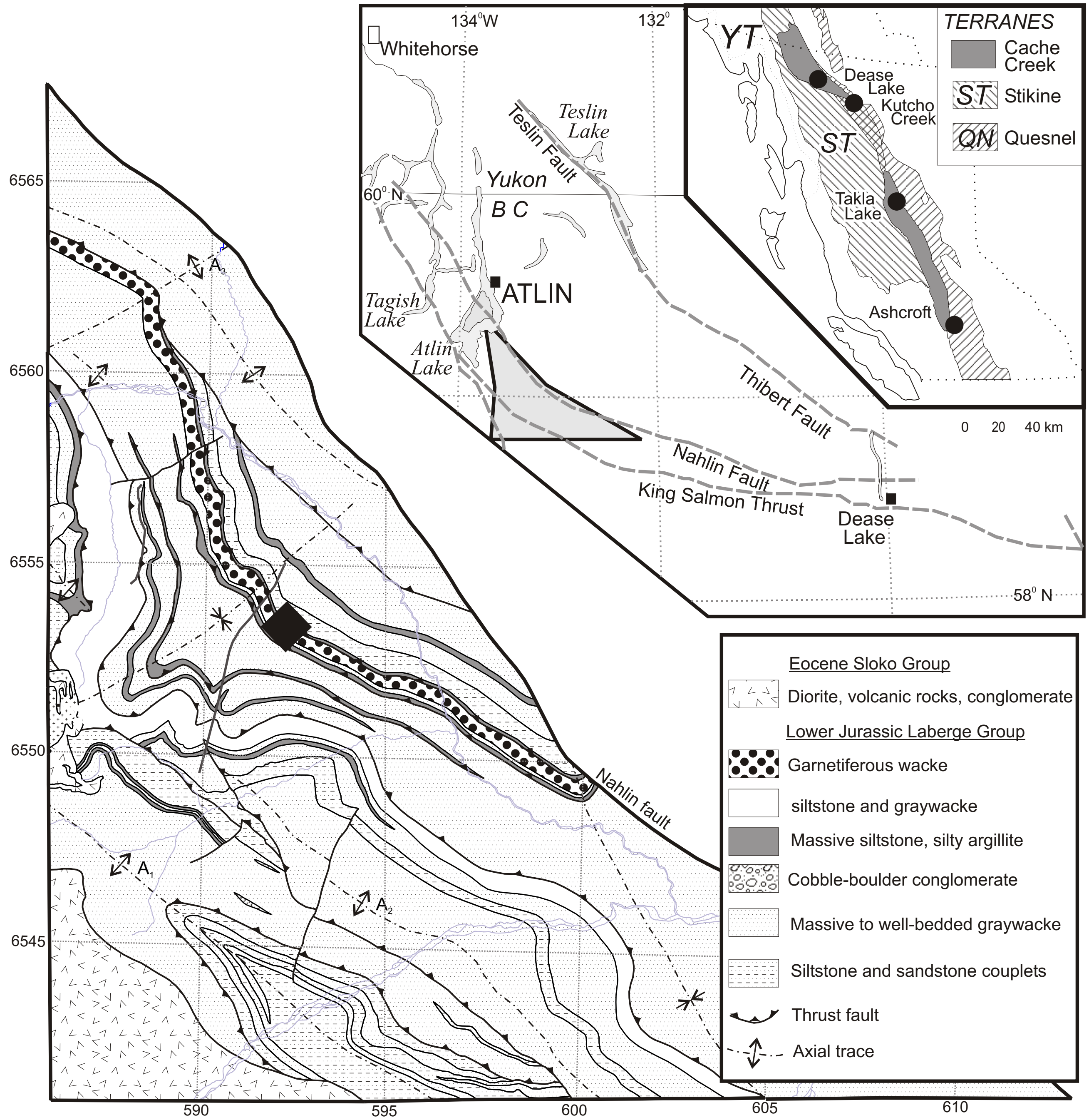

Figure 1. Geological map of part of the Laberge Group highlighting the garnetiferous wacke–pebble conglomerate. Inset shows the location of the Laberge Group in the northern Cordillera (after Johannson et al., 1997; English et al., 2002; Mihalynuk et al., 2003). Location of Eclogite Ridge is shown by the diamond.

REGIONAL GEOLOGY

The Jurassic Laberge Group is contained within the Whitehorse Trough, an early to middle Jurassic marine fore-arc basin that extends from southern Yukon into northern British Columbia in the Atlin-Nakina region. Strata in the Laberge Group near southern Atlin Lake are of Sinemurian to Pliensbachian age (197–183 Ma; Palfy et al., 2000), as constrained by biostratigraphy and U-Pb ages of tuffs and granitoid boulders in conglomerate (Johannson et al., 1997). Sediments in the basin have been tilted, folded and thrust faulted prior to Late Cretaceous, or Middle Jurassic time. Bordering Laberge Group rocks to the east is the Nahlin Fault and rocks of the Cache Creek Terrane, an accretionary assemblage of largely Mississippian to Triassic limestone, chert, and Permian ophiolite (Monger, 1991; Mihalynuk et al., 2003). West of the Laberge Group, are Devonian to Late Triassic volcanic-arc strata of Stikinia (Fig. 1). Quartz-rich pericratonic strata of the Yukon-Tanana Terrane in part form the basement to Stikinia. Meta-

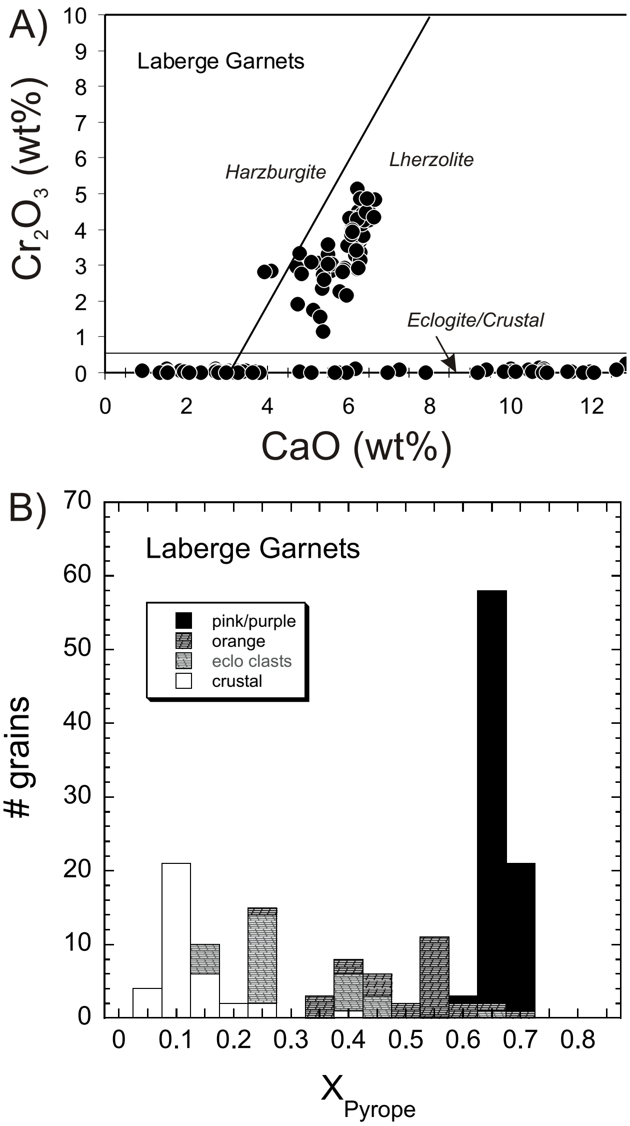

Figure 2. Plots showing compositional data for garnets from heavy mineral concentrate and eclogite clasts in the garnetiferous wacke of the Laberge Group: **A)** CaO vs. Cr_2O_3 plot used to distinguish the protolith of the detrital mantle-derived garnets; lherzolite-harzburgite division from Gurney (1984); garnets were classified as 'crustal, 'eclogitic' or 'peridotitic' using the approach of Schulze (2003). **B)** histogram showing mole fraction of pyrope (X_{Pyr}) component ($Mg_3Al_2Si_3O_{12}$) in garnets.

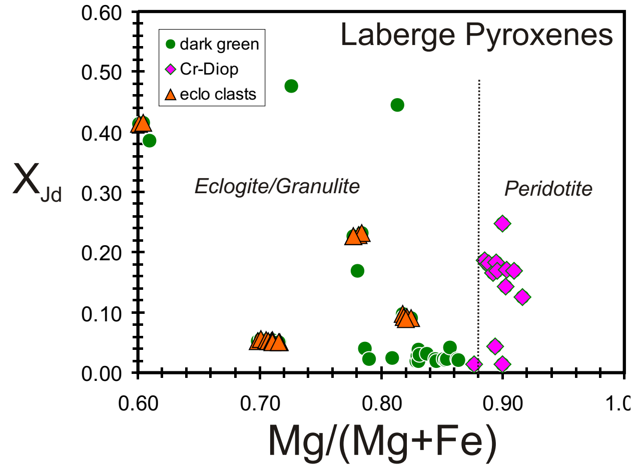

Figure 3. Compositional data for pyroxenes from the Laberge Group sediments. Note the high jadeite component in eclogitic pyroxenes from both clasts and detrital minerals. Peridotitic pyroxenes are distinguished by their emerald green colour and high Mg/Mg+Fe (> 0.9).

morphosed volcanic-arc components of the Yukon-Tanana Terrane are in part correlative with Stikinia. Isotopic data from igneous and sedimentary rocks in Stikinia, and U-Pb geochronology of detrital zircons in metasediments of the Yukon-Tanana Terrane support a uniform source for quartz-rich basement strata, possibly rifted from the North American craton (Gehrels et al., 1990; Gehrels et al., 1991; Jackson et al., 1991; Mihalynuk et al., 1999).

FIELDWORK

Garnet-bearing conglomerates of the Laberge Group were examined in detail along a northwest-trending ridge,

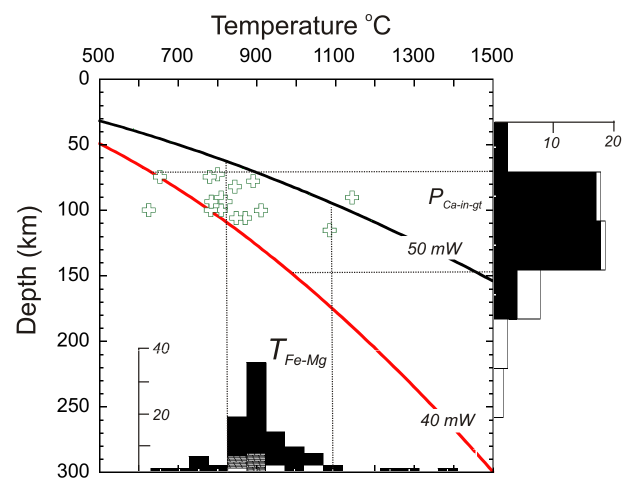

Figure 4. Plot summarizing thermobarometric calculations on detrital garnets, pyroxenes and eclogite clasts in the garnetiferous wacke (MacKenzie et al, in press). Crosses show P-T results for detrital peridotitic clinopyroxenes using the Cr-in-clinopyroxene thermobarometer (Nimis and Taylor, 2000). Histogram on bottom shows results of Fe-Mg exchange thermometry for eclogite clasts and peridotitic garnets, assuming they equilibrated at 3 GPa (O'Neill and Wood, 1979; Krogh, 1988), and for Ni-in-garnet thermometry (Canil, 1999). Note the dominant mode at 800–950ºC and similarity to P-T results for the Cr-in-clinopyroxene method. Histogram on right shows pressures calculated based on Ca-content of garnets ($P_{Ca-in-gt}$), assuming they were in equilibrium with clinopyroxene at 900ºC, the median T by the Cr-in-clinoproxene method (Brenker and Brey, 1997). Thermobarometric pressures were converted to depths. Geothermal gradients typical of Archean (40 mW•m^{-2}) and Proterozoic (50 mW•m^{-2}) continental lithosphere were calculated using the approach in MacKenzie in Canil (1999). Note the occurrence of some garnets and pyroxenes from depths below 100 km, and some as deep as the diamond stability field.

herein called Eclogite Ridge, located 8 km east of Paradise Peak in the southwest Atlin mapsheet (104N; Fig. 1). Eclogite Ridge is composed of distinct buff-weathering siltstone, sandstone and conglomerate (Fig. 5a) that form a unit ~290 m thick (Fig. 6), informally referred to here as the ‘Eclogite formation’. Good outcroppings of Eclogite formation occur along the bedding-parallel ridge axis, and excellent cliff-face exposures have been created where the ridge is truncated by east-flowing stream valleys (Fig. 5a). Thickness of the Eclogite formation appears to decrease to the northwest, and possibly to the southeast, suggesting a lens-shaped cross-section that is more than 10 km long. Attempts to trace the unit north of the Sloko River have been unsuccessful, and it is presumed to be truncated to the southeast by the crustal-scale Nahlin Fault. Thus, its mapped distribution corresponds to the extents of the positive anomaly seen in the results of the aeromagnetic total field survey (Dumont et al., 2001; Lowe et al., 2003). Prominent features of the unit are depositional ‘cycles’ in which parallel layered argillaceous siltstone and wacke are truncated by channellized granule to cobble conglomerate in onlapping and stacked lens-shaped beds (Fig. 7a). These ‘cycles’ repeat every 10 to 40 m (Fig. 6).

Stratigraphically beneath the Eclogite formation is a section of dark green to brown and orange-brown weathering wacke with an average magnetic susceptibility of ~0.3. It is separated from the Eclogite formation by an ~20 m prominent recessive covered interval. Where well exposed on the north end of the ridge, the recessive unit consists of ~15 m of parallel, laminated to centimetre-scale bedded siltstone and immature, medium-grained carbonaceous arkosic sandstone with muddy matrix (wacke) showing soft-sediment deformation. No appreciable unconformity is developed where the recessive unit is in contact with the first granule conglomerate of the Eclogite formation, which has a stronger magnetic susceptibility of 15. Above the basal contact, however, angular rip-ups up to 0.5 m diameter are a lithological match for the recessive unit, suggesting that at some point the basal conglomerate cuts down into the recessive unit.

Nonconglomeratic portions of the Eclogite formation may include a conspicuous black and white banded sediment (Fig. 7b). Banding is formed by 3 to 50 mm thick intercalation of dark, organic-rich siltstone with thicker cream-coloured 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. 7a). 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 are more resistant to weathering than adjacent finer grained layers, enabling them to be traced along strike for kilometres (Fig 5b). Concentrated within these steep-sided conglomerate layers are conspicuous detrital

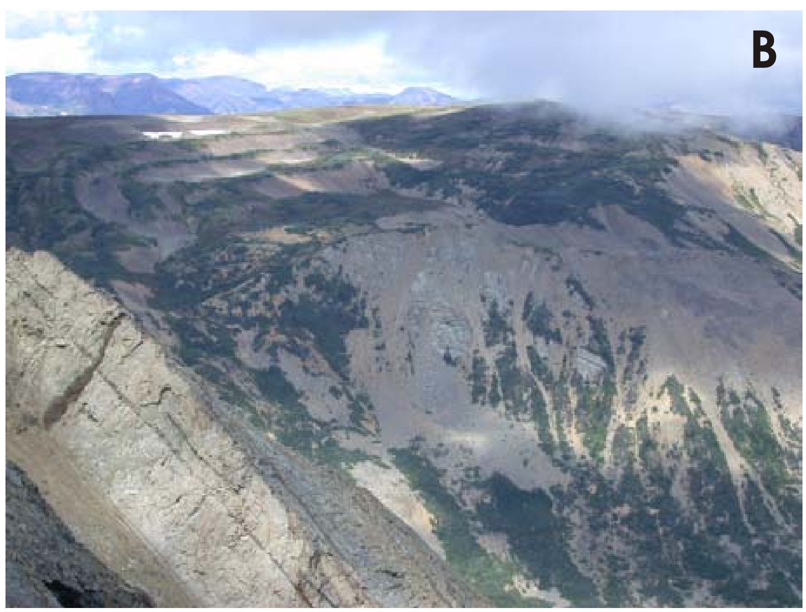

Figure 5. **A)** View of the Laberge Group to the east, showing buff-coloured ridge of garnetiferous conglomerates and wackes (‘Eclogite Ridge’ with arrow) underlain by garnet-free sediments (darker coloured). **B)** View from the north slope of Eclogite Ridge to the northwest, showing highly resistant conglomerate units extending laterally for kilometres along strike.

constituents including red and orange garnets up to 1 cm diameter, emerald green chrome diopside (<3 mm; Fig. 7c), olive green olivine (<3 mm) and sooty black biotite-plagioclase porphyry clasts (Fig. 7d). White-weathering hornblende-feldspar-porphyry clasts are also conspicuous (Fig. 7e), but these are not restricted to the Eclogite formation, occurring in abundance at lower stratigraphic levels. Further southeast along Eclogite Ridge, the conglomerate, sandstone and siltstone beds have similar sedimentological features, but are darker in colour (Fig. 5a), and both garnet and the sooty black porphyry clasts are scarce.

Towards the top of the section, nonconglomeratic strata include orange and black weathering coaly wacke and siltstone. Fossil plant material is dominantly swamp grass and cycad (a palm-like plant) fronds and trunks up to 20 cm in diameter.

'ECLOGITE FORMATION' PALEOFLOW AND DEPOSITIONAL ENVIRONMENT

Asymmetrical lens-shaped cross-sections of conglomerate beds deposited on steeply discordant to concordant erosional surfaces atop finer grained sandstones and siltones (Fig. 7a) are interpreted as lag deposits within channel scours. Crossbedding is locally well displayed, even in coarse-grained units (Fig. 7e), and orientations of trough cross-strata could be deduced in three dimensions with certainty. Pebble-imbrication is also recognized in some places but, unless the pebbles are tiled, imbrication is difficult to distinguish from pebbles lying on ill-defined foresets. Therefore, only where they are tiled can they be used as indicators of unidirectional paleoflow. From these and other paleoflow indicators, paleocurrent directions were interpreted to flow towards the west or southwest (Fig. 8). 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.

Many granules and pebbles are subrounded, but a significant portion of clasts are angular, including mineral grains like garnet, diopside and olivine, as well as porphyritic clasts of probable volcanic origin and argillaceous rip-up clasts. The presence of rip-up clasts and muddy matrix to wacke units suggest deposition by turbidity currents, not winnowing by alluvial or wave action. Some hummocky and swaley cross-strata, however, may be preserved locally within the section suggesting, the impingement of storm surge base on the depositional environment. Channellized gravels suggest alluvial deposition, but such gravels may be deposited in an aggrading submarine channel deposit. One potential problem with the above interpretation is the presence of cycad debris, including substantial trunks, in a submarine environment. Most plant debris is buoyant and therefore not expected in a submarine depositional setting, although cycads could be susceptible to water logging.

A submarine-fan complex interpretation is consistent with previous interpretations for the depositional environment of Whitehorse Trough strata (e.g., Dickie and Hein, 1995; Johannson, 1997). A predominance of southwest-directed paleoflow indicators is, however, inconsistent with the results of previous studies, which generally showed predominantly easterly paleoflow. The data presented here are important because they indicate an east-derived source for high-P detritus, possibly an eclogitic part of the northern Cache Creek Terrane akin to the Pinchi Belt, or dextral translation of the Whitehorse Trough with respect to a high-P belt that may have included the Pinchi eclogite occurrence. Other possibilities are that the eclogite occurrences exposed within the Yukon-Tanana Terrane in the Yukon extend in a cryptic fashion into northern British Columbia and sourced the conglomerate, or that the paleoflow indicators are a local aberration and not indicative of derivation from the eastern source.

Along the shores of southern Atlin Lake are other occurrences of coarse pebble conglomerates and immature

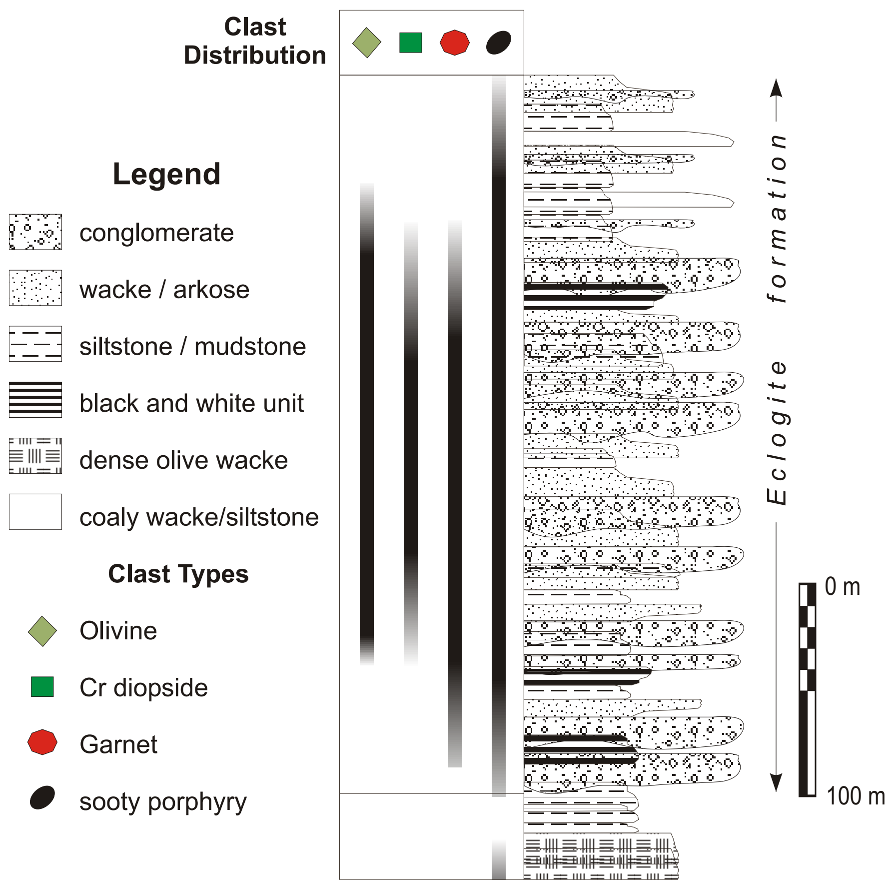

Figure 6. Stratigraphic section through the 'Eclogite formation' exposed on Eclogite Ridge.

Figure 7. **A)** Conglomerates and wackes viewed perpendicular to strike, showing steep-sided contact (arrow) between garnet-bearing conglomerates cutting down through underlying sandstone and silstone units at steep sides. **B)** Banding in units below conglomerates formed by 3 to 50 mm thick intercalations of dark, organic-rich and occasionally petroliferous siltstones with thicker cream-coloured arkose. **C)** Emerald green clinopyroxene grain set in matrix of feldspar and rock fragments in the garnetiferous wacke. **D)** Fragments of rock containing phenocrysts of feldspar and biotite set in a sooty fine-grained matrix in garnetiferous wacke from the ridge. **E)** Coarse pebbles of hornblende porphyry in conglomerate. Note crossbedding in coarser units. **F)** Red pyropic garnets adhering to emerald green Cr-diopside grain from heavy mineral concentrate.

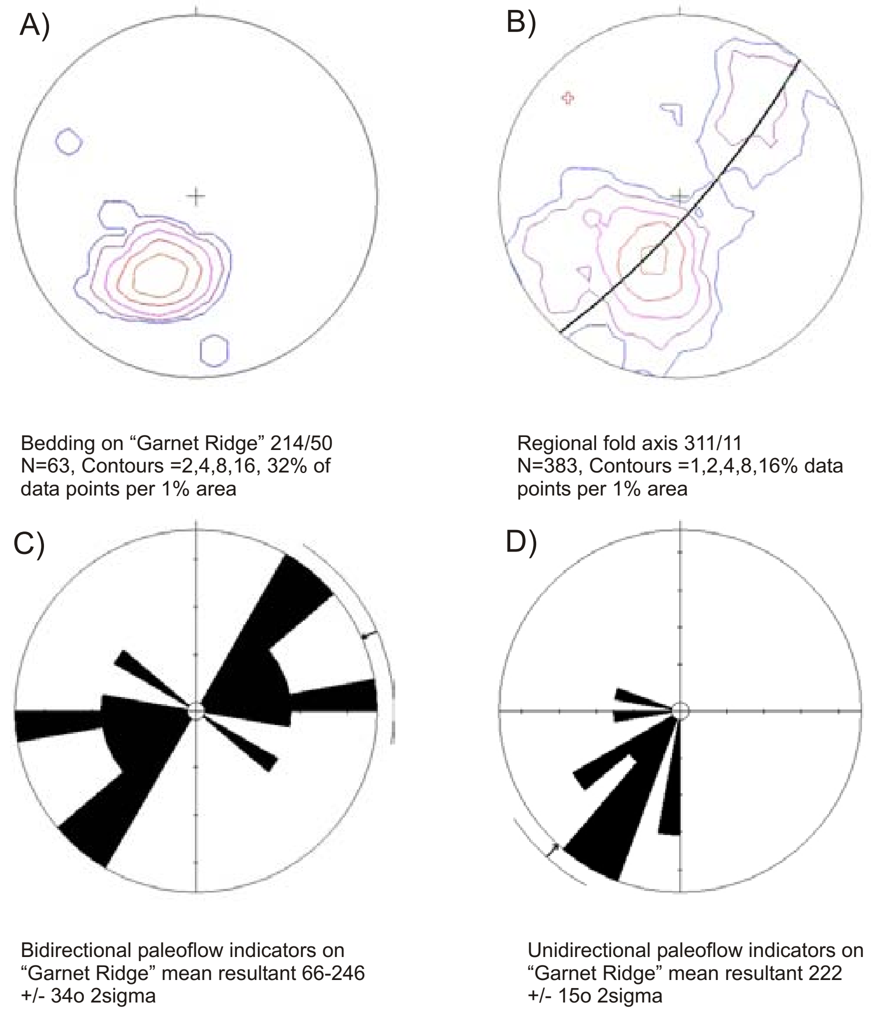

Figure 8. Measurements on bedding (A), fold axes (B) and paleoflow directions (C, D) for units exposed on Eclogite Ridge.

wackes (Johannson et al., 1997). Exposures on the northernmost islands near Janus Point contained visible garnet, but further south, on Sloko and Bastion Islands, garnet was notably absent in outcrop. Garnet-bearing units near Janus Point are along strike from those on Eclogite Ridge, 20 km to the southeast, suggesting that they are part of the Eclogite formation.

PROVENANCE

Six thin sections from samples of the wacke along Eclogite Ridge were studied petrographically and point counted (n > 800) to determine their modal mineralogy. The rock contains mainly feldspar and lithic fragments, notable angular detrital garnet and pyroxene, and rare olivine, amongst 3 to 8 mm clasts of pristine arc volcanics (hornblende andesite, dacite), granitoids and metamorphic rocks (mica schist, amphibolite), including rare eclogite or granulite (garnet+pyroxene+rutile). The rock has a high detrital magnetite content (~2–3%) which is likely the source of its anomalous aeromagnetic signature (Lowe et al., 2003).

The relative proportions of lithic fragments, plagioclase, K-feldspar and quartz in clastic sediments has been used to deduce the tectonic setting of deposition and provenance in other basinal strata (Dickinson et al., 1983; Marsaglia and Ingersoll, 1992). Proportions of these components in Laberge Group garnet-bearing conglomerate is consistent across samples (Fig. 9). Detrital components of both the wacke and conglomerate suggest they were derived by early dissection of a nascent continental arc (Fig. 9). Two samples contain anomalously high K-feldspar, suggesting derivation from an exposed basement or plutonic-arc root (Boggs, 2001).

HEAVY MINERALS

Samples of coarse conglomerate and wacke weighing between 0.5 and 4.0 kg were collected from five locations along Eclogite Ridge and seven locations along the shores of southern Atlin Lake. These were processed for heavy mineral extraction at Vancouver Indicator Processors Inc., Vancouver. First, they were crushed to sand-sized particles in a jaw crusher and sieved. Sieved samples were wet screened to less than 0.25 mm fraction. The +0.25 mm fraction was passed through a magnetic separator operating at 2.1 Tesla. The magnetic fraction underwent heavy liquid separation to specific gravities greater than 3.33. Resultant concentrates were examined and hand-picked at the University of Victoria.

Heavy minerals (specific gravity > 3.33) make up between 0.004 and 0.6% of the samples. The largest percentage of heavy minerals occurs in rocks containing visible garnet and clinopyroxene in outcrop (e.g., at Eclogite Ridge and near Janus Point on Atlin Lake). Samples collected further to the south, and presumably deeper in the sedimentary section, display a rapidly decreasing percentage of heavy minerals and an absence of visible garnets in hand sample. The heavy mineral population is dominated by garnet, followed by clinopyroxene, opaque minerals and minor amounts of olivine. Garnet adheres to both clinopyroxene and olivine grains, suggesting that it is derived from both peridotite and eclogite (Fig. 7f). Further chemical analysis is in progress.

DISCUSSION

The above results require that garnet peridotite and eclogite derived from mantle lithosphere at least 100 km thick was exhumed and exposed in the northern Cordillera and shed as detritus into a fore-arc basin now preserved as the Laberge Group. Exceptional preservation of pristine mantle detritus in Laberge Group wacke and conglomerate is attributable to proximal deposition, rapid burial and an absence of metamorphism or penetrative deformation documented in this part of Whitehorse Trough during the last 170 Ma (Mihalynuk et al., 2003). Angular garnets, the presence of detrital olivine, and their mixture with pristine volcanic and feldspathic clasts indicate minimal physical or chemical attrition. This could be attributed to an arid or extremely cold climate during subaerial erosion, and rapid transport and deposition in a submarine environment. Late Early Jurassic (Toarcian) ammonite faunas in the Whitehose Trough include the Boreal genus *Pseudolioceras*, indicating deposition from relatively cool water in high latitudes (Jakobs, 1997); however, the Jurassic was a warm period in the Earth's history, with a global lack of evidence for glaciation. An arid environment cannot be fully discounted, although the presence of coal layers, including the 20 cm diameter trunks of cycads, argues against severe aridity.

Primary alkaline igneous rocks are one potential source of the garnet peridotite and eclogite detritus. For example, Oligocene sediments in the Uinta Mountains and Green River Basin of the western United States contain garnets and pyroxenes that are thought to be sourced from Eocene kimberlite and lamproite intrusions a few hundred kilometres away, in the Wyoming Province (McCandless and Nash, 1996). The opaque fraction of heavy minerals from the Laberge Group sediments, however, contains only Mg-poor magnetite; none of the Mg- or Cr-rich spinel or ilmenite expected from an alkaline igneous source (e.g. kimberlite) are observed. Thus, an alkaline igneous source for the mantle detritus in the Laberge Group is discounted..

The only other source for the mantle detritus could be large masses of garnet peridotite and eclogite, which are volumetrically minor components of many collisional orogens, commonly occurring as septa or kilometre-size massifs within larger supracrustal metamorphic terrains (Medaris, 1999; Brueckner and Medaris, 2000). Orogenic garnet peridotite massifs have been recognized in other arcs such as the Lesser Antilles and in Sulawesi (Kadarusman and Parkinson, 2000; Abbott et al., 2001). Such massifs are often small (~1 km^3), but even small masses of rocks like garnet peridotite and eclogite, which contain between 5 and 50% modal garnet, could contribute the amount of garnet observed in the heavy mineral fraction of the Laberge sediments (< 0.5 %).

Potential sources of orogenic garnet peridotite and eclogite are not known in terranes immediately adjacent to the Whitehorse Trough. Heavy durable minerals can travel far and be recycled in the sedimentary environment. River systems are known to deliver durable heavy minerals across continental-scale drainage systems (Rainbird et al., 1997.), but the latter depositional setting results in mature quartz-rich clastic sediments (Roscoe, 1973), not immature poorly sorted angular detritus as observed in the Laberge Group sediments. Thus, it appears that the source region of the uplifted and exposed mantle rocks must have been proximal to the fore-arc basin in which they were deposited.

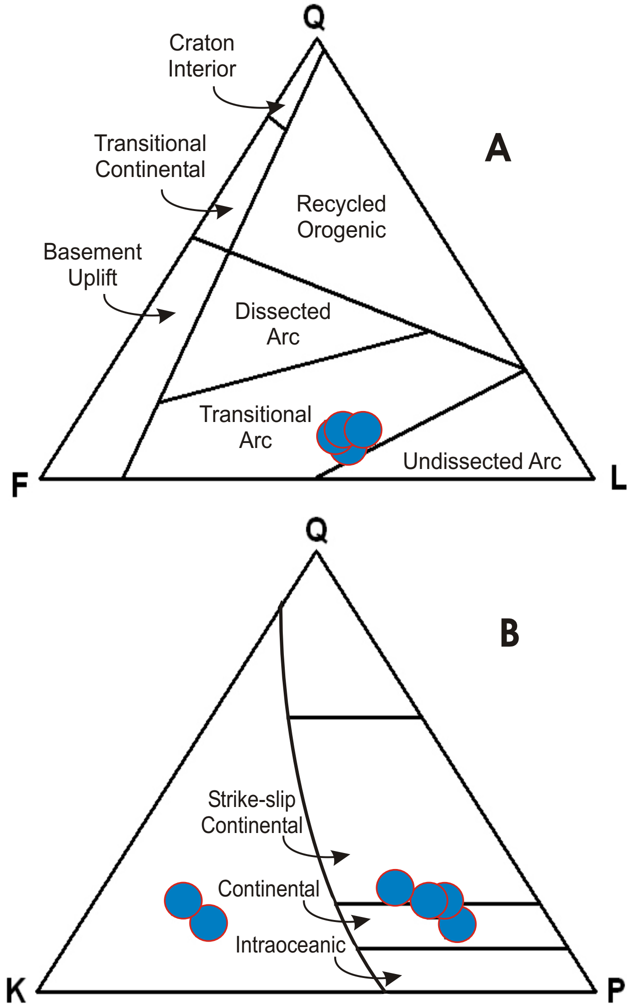

Figure 9. Ternary diagrams used to determine provenance and tectonic setting of clastic sediments: **a)** Diagram showing the proportion of quartz (Q), feldpsar (F) and lithic fragments (L) of Dickinson et al (1983). **b)** Diagram showing the proportion of quartz (Q), K-feldpsar (F) and plagioclase (P) of Marsaglia et al (1992). The Laberge Group wacke and conglomerates (circles) plot within newly dissected continental arc setting.

Exhumation and erosion of garnet peridotite and eclogite was apparently short lived, because the derived detritus appears in only one part of the Laberge Group that extends from Eclogite Ridge to Janus Point. This detritus was mixed with poorly sorted arc detritus, possibly including tuffaceous units. In current interpretations, these units would be some of the youngest sediments preserved in the Laberge Group at this latitude (English et al., in press). Although we have no age constraints as yet, the anticipated geochronological age determinations provided by a tuffaceous unit at Eclogite Ridge will provide age constraints for the sudden exposure and erosion of orogenic peridotite and eclogite at the surface.

Rapid uplift, exhumation and deposition, in the late Triassic and early Jurassic, of the Stikinia arc is substantiated by many lines of evidence in the Laberge Group and in correlative rocks along strike in the Cordillera. The U-Pb age of a granitic boulder in a conglomerate and the biostratigraphically controlled depositional age of sands adjacent to this conglomerate in the Laberge Group are dated to within a few million years, suggesting intrusion in the arc, and rapid uplift, incision and deposition (Johannson et al., 1997). Farther north in a correlative belt of rocks in Yukon, the extent and timing of early Jurassic subduction, crustal thickening, uplift and deposition are well documented. Field mapping, metamorphic isograds, and U-Pb geochronology in the Aishihik Lake area of southwestern Yukon show that crust from 30 km depths was uplifted at rates of 2 to 10 mm/year and shed into the Whitehorse Trough (Johnston and Erdmer, 1995; Johnston et al., 1996).

The strange occurrences of diamond in northwestern British Columbia (Casselman and Harris, 2002) are most likely derived from rocks that contain minerals of demonstrable high pressure origin (within the diamond stability field, Fig. 4). While we have yet to identify diamond in the heavy mineral concentrates of the Laberge Group, these garnetiferous strata are a possible source of anomalous diamond discovered during placer mining near Atlin, approximately 30 km to the northeast.

ACKNOWLEDGMENTS

In Atlin, we thank Norm Graham of Discovery Helicopters for getting us places, Gary Hill for a boat charter, and Brian Grant for good cheer and editing.

REFERENCES

Abbott, R.N., Draper, G. and Keshav, S. (2001): Garnet peridotite found in the Greater Antilles; *EOS, Transactions of the American Geophysical Union*, Volume 82, pages 381–388.

Boggs, S.J. (2001): Principles of Sedimentology and Stratigraphy; *Prentice-Hall*, Upper Saddle River, New Jersey, 726 pages.

Brenker, F.E. and Brey, G.P. (1997): Reconstruction of the exhumation path of the Alpe Arami garnet-peridotite body from depths exceeding 160 km; *Journal of Metamorphic Geology*, Volume 15, pages 581–592.

Brueckner, H.K. and Medaris, L.G. (2000): A general model for the intrusion and evolution of 'mantle' garnet peridotites in high-pressure and ultra-high pressure metamorphic terranes; *Journal of Metamorphic Geology*, Volume 18, pages 123–133.

Canil, D. (1999): The Ni-in-garnet geothermometer: calibration at natural abundances; *Contributions to Mineralogy and Petrology*, Volume 136, pages 240–246.

Canil, D., Mihalynuk, M., MacKenzie, J.M., Johnston, S.T., Ferreira, L. and Grant, B. (2004): Heavy mineral sampling of stream sediments for diamond and other indicator minerals in the Atlin-Nakina area (NTS 104N and 105N); *in* Geological Fieldwork 2003, *BC Ministry of Energy and Mines*, Paper 2004-1, pages 19–26.

Casselman, S. and Harris, W. (2002): Yukon diamond rumour map and notes; *Yukon Geology*.

Dickie, J. R. and F. J. Hein (1995): Conglomeratic fan deltas and submarine fans of the Jurassic Laberge Group, Whitehorse Trough, Yukon Territory, Canada; fore-arc sedimentation and unroofing of a volcanic island arc complex; Chough, S.K. and Orton, G.J., Editors, Fan Deltas: Depositional Styles and Controls, *Elsevier*, Amsterdam, Netherlands, pages 263-292.

Dickinson, W.R., Beard, L.S., and Brakenridge, G.R. (1983): Provenance of North American Phanerozoic sandstones in relation to tectonic setting; *Geological Society of America Bulletin*, pages 222–235.

Dumont, R., Coyle, M. and Potvin, J. (2001): Aeromagnetic total field map British Columbia, Sloko River, NTS 104N/3; *Geological Survey of Canada*.

English, J., Johannson, G.G., Johnston, S.T., Mihalynuk, M.G., Fowler, M. and Wight, K.L. (in press): Structure, stratigraphy and hydrocarbon potential of the central Whitehorse Trough, northern Canadian Cordillera; *Bulletin of Canadian Society of Petroleum Geology*, in press.

English, J.M., Mihalynuk, M.G., Johnston, S.T., Orchard, M.J., Fowler, M. and Leonard, L.J. (2002): Atlin TGI, Part VI: Early to middle Jurassic sedimentation, deformation and a preliminary assessment of hydrocarbon potential, central Whitehorse Trough and northern Cache Creek Terrane; *in* Geological Fieldwork,*BC Ministry of Energy and Mines*, Paper 2003-1, pages 187–201.

Gehrels, G.E., McClelland, W.C., Samson, S.D., Patchett, P.J. and Jackson, J.L. (1990): Ancient continental margin assemblage in the northern Coast Mountains, southeast Alaska and northwest Canada; *Geology*, Volume 18, pages 208–211.

Gehrels, G.E., McClelland, W.C., Samson, S.D., Patchett, P.J. and Jackson, J.L. (1991): U-Pb geochronology of detrital zircons from a continental margin assemblage in the northern Coast Mountains, southeastern Alaska; *Canadian Journal of Earth Sciences*, Volume 28, pages 1285–1300.

Ghent, E. D., Stout, M. Z. and Erdmer, P. (1993): Pressure-temperature evolution of lawsonite-bearing eclogites, Pinchi Lake, British Columbia: *Journal of Metamorphic Geology*, Volume 11, pages 279–290.

Gurney, J.J. (1984): A correlation between garnets and diamonds in kimberlites; *Kimberlites, Occurrences and Origin (University of Western Australia)*, Volume 8, pages 143–166.

Jackson, J.L., Gehrels, G.E., Patchett, P.J. and Mihalynuk, M.G. (1991): Stratigraphic and isotopic link between the northern Stikine terrane and an ancient continental margin assemblage, Canadian Cordillera; *Geology*, Volume 19, pages 1177–1180.

Jakobs, G. K. (1997): Toarcian (Early Jurassic) ammonoids from western North America; *Geological Survey of Canada*, Bulletin 428, 137 pages.

Johannson, G.G., Smith, P.L. and Gordey, S.P. (1997): Early Jurassic evolution of the northern Stikinian arc: evidence from the Laberge Group, northwestern British Columbia; *Canadian Journal of Earth Sciences*, Volume 34, pages 1030–1057.

Johnston, S.T. and Erdmer, P. (1995): Hot-side-up aureole in southwest Yukon and limits on terrane assembly of the northern Canadian Cordillera; *Geology*, Volume 23, pages 419–422.

Johnston, S.T., Mortensen, J.K. and Erdmer, P. (1996): Igneous and metamorphic age constraints for the Aishihik metamorphic suite, southwest Yukon; *Canadian Journal of Earth Sciences*, volume 33, pages 1543–1555.

Kadarusman, A. and Parkinson, C.D. (2000): Petrology and P-T evolution of garnet peridotites from central Sulawesi, Indonesia; *Journal of Metamorphic Geology*, Volume 18, pages 193–209.

Krogh, E.J. (1988): The garnet-clinopyroxene Fe-Mg geothermometer – a reinterpretation of existing experimental data; *Contributions to Mineralogy and Petrology*, Volume 99, pages 44–48.

Lowe, C., Mihalynuk, M.G., Anderson, R.G., Canil, D., Cordey, F., English, J.M., Harder, M., Johnston, S.T., Orchard, M.J., Russell, J.K., Sano, H. and VIleneuve, M.E. (2003): Overview of the Atlin Integrated Geoscience Project, northwestern British Columbia, year three; *Geological Survey Canada*, Current Research, 2003-A11, pages 1–10.

MacKenzie, J.M. and Canil, D. (1999): Composition and thermal evolution of cratonic mantle beneath the central Archean Slave Province, NWT, Canada; *Contributions to Mineralogy and Petrology*, Volume 134, pages 313–324.

MacKenzie, J.M., Canil, D., Johnston, S.T., English, J.E., Mihalynuk, M.G. and Grant, B. (in press): First evidence for ultrahigh pressure garnet peridotite in the North American Cordillera; *Geology*, in press.

Marsaglia, K.M. and Ingersoll, R.V. (1992): Compositional trends in arc-related, deep-marine sand and sandstone: a reassessment of magmatic-arc provenance; *Geological Society of America Bulletin*, Volume 104, pages 1637–1649.

McCandless, T.E. (1990): Kimberlite xenocryst wear in high-energy fluvial systems: experimental studies; *Journal of Geochemical Exploration*, Volume 37, pages 323–331.

McCandless, T.E. and Nash, W.P. (1996): Detrital mineral indicator minerals in southwestern Wyoming, U.S.A.: evaluation of mantle environment, igneous host and diamond xploration significance; *Exploration and Mining Geology*, Volume 5, pages 33–44.

Medaris, L.G. (1999): Garnet peridotites in Eurasian high-pressure and ultrahigh-pressure terranes: a diversity of origins and thermal histories; *International Geology Reviews*, Volume 41, pages 799–815.

Mihalynuk, M.G. and Lowe, C. (2002): Atlin TGI, Part I: an introduction to the Atlin Targeted Geoscience Initiative; in Geological Fieldwork, *BC Ministry of Energy and Mines*, Paper 2001-1, pages 1–4.

Mihalynuk, M., Erdmer, P., Ghent, E.D., Cordey, F., Archibald, D.A., Friedman, R.M. and Johannson, G.G. (in press): Coherent French Range blueschist: subduction to exhumation in <2.5 m.y.? *Geological Society of America Bulletin*, in press.

Mihalynuk, M.G., Johnston, S.T., English, J., Cordey, F., Villeneuve, M.E., Rui, L. and Orchard, M.J. (2003): Atlin TGI, Part III: regional geology and mineralization of the Nakina area (NTS 104N/2W and 3); *in* Geological Fieldwork, *BC Ministry of Energy and Mines*, Paper 2002-1, pages 9–15.

Mihalynuk, M.G., Mountjoy, K.J., Smith, M.T., Currie, L.D., Gabites, J.E., Tipper, H.W., Orchard, M.J., Poulton, T.P. and Cordey, F. (1999): Geology and mineral resources of the Tagish Lake area (NTS 104M/ 8, 9, 10E, 15 and 104N/ 12W), northwestern British Columbia; *BC Ministry of Energy and Mines*, Bulletin 105, 217 pages.

Monger, J.W.H. (1991): Upper Devonian to Middle Jurassic assemblages, Part B: Cordilleran terranes; Gabrielse, H. and Yorath, C.J., Editors, Geology of North America, *Geological Society of America*, Denver, Colorado, pages 281–327.

Monger, J.W.H. (1969): Stratigraphy and structure of Upper Paleozoic rocks, northeast Dease Lake map-area, British Columbia (104J); *Geological Survey of Canada*, 41 pages.

Nimis, P. and Taylor, W.R. (2000): Single clinopyroxene thermobarometry for garnet peridotites, Part 1. Calibration and testing of a Cr-in-cpx barometer and enstatite-in-cpx thermometer; *Contributions to Mineralogy and Petrology*, Volume 139, pages 541–554.

O'Neill, H.C. and Wood, B.J. (1979): An experimental study of Fe-Mg partitioning between garnet and olivine and its calibration as a geothermometer; *Contributions to Mineralogy and Petrology*, Volume 70, pages 59–70.

Palfy, J., Smith, P. L. and Mortensen, J. K. (2000): A U-Pb and $^{40}Ar/^{39}Ar$ time scale for the Jurassic; *Canadian Journal of Earth Sciences*, Volume 37, pages 923–944.

Rainbird, R.H., McNicoll, V.J., Theriault, R.J., Heaman, L.M., Abbott, J.G., Long, D.G.F. and Thorkelson, D.J. (1997): Pan-continental river system draining Grenville orogen recorded by U-Pb and Sm-Nd geochronology of Neoproterozoic quartzarenites and mudrocks, northwestern Canada; *Journal of Geology*, Volume 105, pages 1–17.

Roscoe, S.M. (1973): The Huronian Supergroup, a Paleoaphebian succession showing evidence of atmospheric evolution; *Geological Association of Canada*, Special Paper 12, pages 31–47.

Schulze, D.J. (2003): A classification scheme for mantle derived garnets in kimberlite: a tool for investigating the mantle and exploring for diamonds; *Lithos*, Volume 71, pages 191–213.