Heavy Mineral Sampling of Stream Sediments for Diamond and Other Indicator Minerals in the Atlin-Nakina Area (NTS 104N and 104K)

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INTRODUCTION

Kimberlite and lamproite magmas sample diamonds deep in the mantle and depending on the rapidity of ascent and emplacement, bring them to the surface in various states of preservation. Economic diamond deposits are usually hosted in primary kimberlite and lamproite diatremes that intrude Archean crustal provinces. Placer deposits of diamonds that are sourced in kimberlite from Archean crustal provinces are also well known.

Diamond occurrences have also been documented in more non-traditional settings. For example, some placer diamonds appear to have a source in orogenic belts that border Precambrian crustal provinces (van Roermund et al, 2002; Griffin et al, 2000; Barrows et al, 1996; Walker 1994). Increasing recognition of diamonds in metapelitic metamorphic rocks in recent years has clearly demonstrated the burial of rocks to hundreds of kilometres depth during collisional orogenesis. Although reported decades earlier in ophiolite and 'Alpine" ultramafic rocks in orogenic settings, such occurrences of diamond have met with greater skepticism and controversy. This is due to the lack of evidence for the high pressures required to stabilize diamond in the mineral assemblages typical of ophiolites, for which far lower temperature (T) and pressure (P) conditions are commonly envisioned for origin, exhumation and emplacement.

There are several reports and rumours of 'anomalous' alluvial diamonds in streams and gravels from southeastern Alaska, southwestern Yukon and northwestern British Columbia (Black, 1951, 1953; Casselman & Harris 2002). The source of such diamonds is not obvious. There are no known Archean crustal provinces in these regions and no evidence of diamond-bearing alkaline igneous rocks, which could have been eroded to produce detrital diamond. Alluvial transport is unlikely because drainage patterns in the region are not obviously sourced in any Precambrian crustal province to the east. Glacial transport is unlikely because some regions in southwestern Yukon north of the Denali fault are reported to contain alluvial diamonds, yet they have not been glaciated.

The recognition of microdiamond in harzburgite tectonite from ophiolite elsewhere (van Roermund et al, 2002) begs the question whether diamond occurrences in southeastern Alaska, southwestern Yukon and northwestern British Columbia are sourced in ophiolites or in high pressure-low temperature metamorphic rocks (blueschists and eclogites) in accretionary margins associated with ophiolites. Large mantle tectonite sections of ophiolite have been recognized and documented in greater detail in these regions, and blueschist and eclogite occur in several parts of Yukon, and in the Cache Creek Terrane of British Columbia. To address this question, and ultimately to explain the source of anomalous diamond occurrences in the northern Cordillera, we carried out a comprehensive study of heavy minerals in sediments sampled from streams, which drain ophiolite bedrock in the Atlin-Nakina area of northwestern British Columbia. The Atlin area is known historically for its placer gold mining operations, where one such anomalous diamond occurrence has been reported in Wilson Creek (Casselman and Harris, 2002). We wished to test if other diamonds could be found, by investigating stream sediments for diamonds or minerals, which may be indicative of bedrock that is associated with a high pressures origin and thus could be linked with the occurrence of diamond.

METHODS

Fifteen stream locations were sampled in map areas NTS 104N and 104K. Streams were chosen that drain bedrock of mantle tectonite in ophiolite. Two samples were also collected from commercial placer operations on Wilson and Feather creeks, from the tailings of clean-up sluices. Control samples were also collected from below the placer workings in these two creeks. A sample was collected from McKee Creek, off the sluice box end during active mining within a pay streak.

Stream sediment samples were taken in stream flow gradients that would efficiently concentrate heavy minerals in the bedload. Stream sediments were sieved on site to grain sizes less than 2 mm. The resultant sieved samples (4 to 8 kg) were processed for heavy minerals at Vancouver

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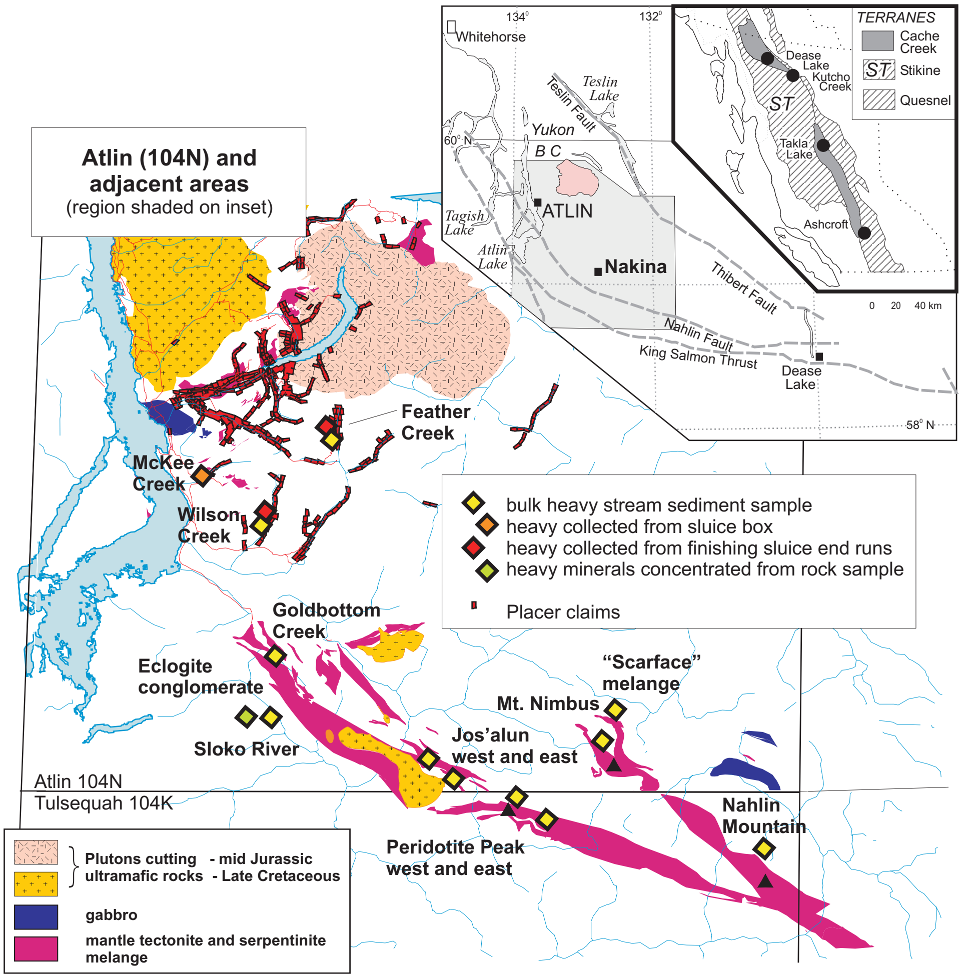

Fig. 1 - Bedrock geology highlighting ultrmafic rocks of the Atlin-Nakina area (after Mihalynuk *et al* 2003) and showing location of heavy mineral samples used in this study.

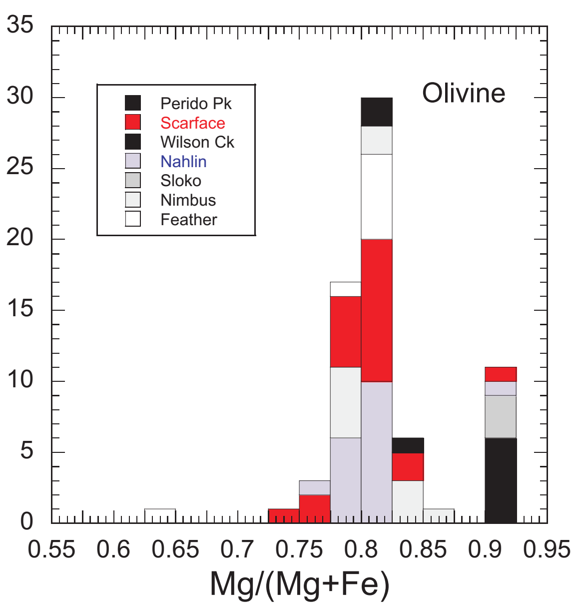

Fig. 2 – Histogram showing olivine compositions in heavy mineral samples at each locality.

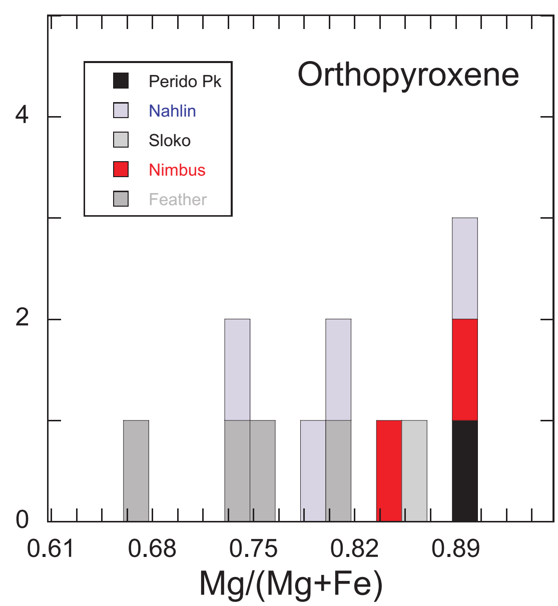

Fig. 3 - Histogram showing orthopyroxene compositions in heavy mineral samples at each locality.

Indicator Processors Inc. Samples were wet screened to less than 0.25 mm fraction, passed through a magnetic separator operating at 2.1 Tesla, and underwent two steps of heavy liquid separation to specific gravities greater than 3.33.

The non-magnetic heavy mineral fractions were picked for diamond and gold by I & M Morrison Geological Services. Magnetic heavy mineral fractions were hand-picked at the University of Victoria. In each sample, 20-30 grains of each mineral were picked, mounted in epoxy, and polished. Major element compositions of the grains in eight of the fifteen samples were determined by electron microprobe analysis at the University of British Columbia. Operating procedures and data reduction methods for this instrument are similar to those described in MacKenzie and Canil, 1999.

RESULTS

NON-MAGNETIC FRACTION

No diamonds were found in any of the non-magnetic heavy mineral fractions. Gold grains up to 1 mm in size were recognized in sediments from north of Hard Luck Peaks, Mt. Nimbus and in Feather Creek. Lack of gold in the McKee Creek sample may be an indication of an efficient placer operation.

MAGNETIC FRACTION

Table 1 lists the major minerals identified in the magnetic heavy mineral fraction from each sample studied. The subdivision into different groups of the same mineral was based in part on optical examination, but mainly on mineral chemical observations that are described in more detail below.

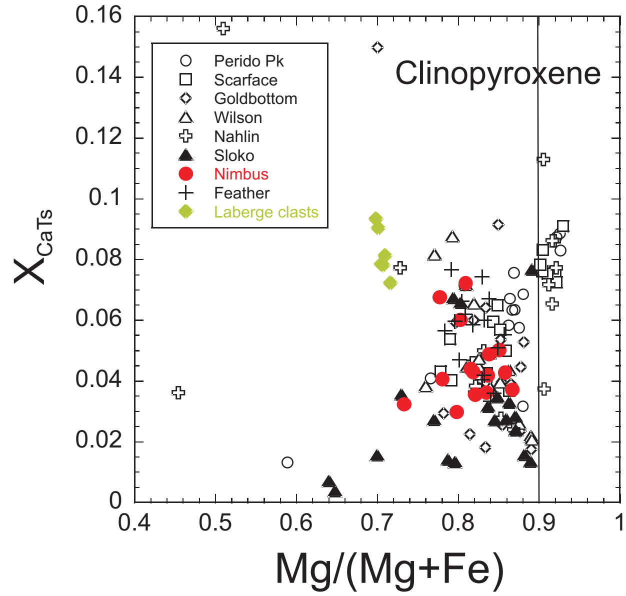

Fig. 4. Plot of Mg# in clinopyoxene in heavy mineral samples versus its Al-content expressed as the mole fraction of its CaTschermaks (CaTs) component ($CaAl_2SiO_6$). Clinopyroxenes from mantle tectonites plot right of the vertical line at Mg# = 0.9.

OLIVINE

Olivine was identified optically in heavy fractions by its light green colour and conchoidal fracture. In some cases, olivine preserved exceptionally well-defined crystal habit and faceted faces, indicative of an igneous origin, and little abrasion during transport from proximal source rock.

Olivine from mantle tectonite in ophiolite has a distinctly high Mg/(Mg+Fe) (Mg# > 0.89) and lower CaO content when compared to olivine from cumulate plutonic rocks, or from phenocrysts in volcanic rocks. This is due to the distinctly higher Mg# and lower Ca content of the bulk

TABLE 1. SUMMARY OF MINERALS IN THE ATLIN-NAKINA HEAVY MINERAL CONCENTRATE SAMPLES

		Gold	Olivine		Clinopyroxene			Garnet		Cr-Spinel	Spinel
Sample #	Location	Grains	Mantle	Cumulate	Mantle	Cumulate	Eclogitic	Eclogitic	Skarn	Mantle	Cumulate
15-4 BB	**Scarface**		*	*	*	*	*	*	*	*	*
24-4b*	Feather Ck. sluice end run	*									
24-1	Feather Ck.	*		*		*		*			*
16-4 BW	**Goldbottom Ck.**					*				*	*
16-3 BW	Hardluck Peaks North	*									
7-1 WB	Hard Luck Peaks East										
16-2*	Laberge Gp. coarse wacke						*	*			
18-1 WW	McKee Ck Sluice box run-off										
18-7 BW	**Mt. Nimbus North**	*		*		*				*	*
18-4 BW	**Nahlin Mtn. North**		*	*	*	*				*	*
11-14 BB	**Peridotite Peak North**		*		*	*		*		*	*
18-5 BW	Peridotite Peak East										
18-6 BW	**Sloko River**		*		*	*	*	*		*	*
18-3 WW	**Wilson Ck.**			*		*		*		*	*
18-2 WW	Wilson Ck. sluice end run										

samples in bold face analysed by EMP

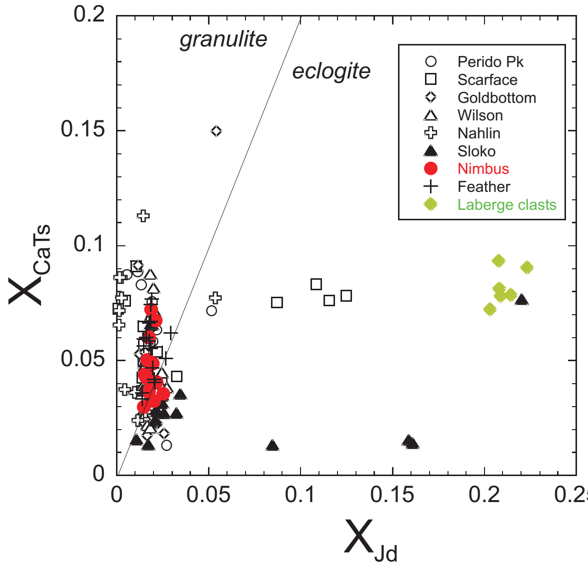

Fig. 5 – Plot of the mole fraction of CaTschermaks (CaTs) component ($CaAl_2SiO_6$) vs its jadeite ($NaAlSi_2O_6$) component in clinopyroxenes from heavy mineral samples and in eclogite clasts in coarse wacke from the Laberge Group. The line dividing the fields of eclogite and granulite pyroxenes is from White (1964).

compositions of mantle tectonites, which represent lithosphere formed as a residue of basalt extraction. Olivine with Mg# greater than 0.89 and low in CaO content (<0.1 wt%) typical of mantle tectonites was sampled at Sloko, Peridotite Peak, Scarface and Nahlin (Fig. 2). Most of the olivines sampled in this study were distinctly lower in Mg# than typical mantle olivine and were likely derived from cumulate rocks which form the basal lower crustal section above mantle tectonite in ophiolite.

ORTHOPYROXENE

Orthopyroxene was identified optically as light green or brown grains. In many cases, what was identified optically as orthopyroxene was later found to be clinopyroxene by electron microprobe analysis. Orthopyroxene was thus poorly represented in the heavy mineral fraction sampled. In what was sampled, orthopyroxene was present at five locations. The $Kd_{Fe\text{-}Mg}$ ol-opx is near unity so orthopyroxene has the same Mg# of olivine in which it is in equilibrium. Orthopyroxene with typical Mg# of mantle tectonites was found only at Peridotite Peak, Nimbus and Nahlin Mountain (Fig. 3). All other orthopyroxenes lower in Mg# appear to be derived from cumulate rocks.

CLINOPYROXENE

Clinopyroxene was identified as grains with either bright emerald green or dark green colour, usually showing well-developed cleavage and a prismatic grain shape. The emerald green colour in many clinopyroxenes is due to the presence of significant Cr^{3+}. Clinopyroxene forms in several igneous and metamorphic environments and its protolith can be difficult to distinguish for grains out of their coexisting mineral paragenesis. Clinopyroxene from mantle tectonite is rich in Cr and Al, and poor in Na, and has

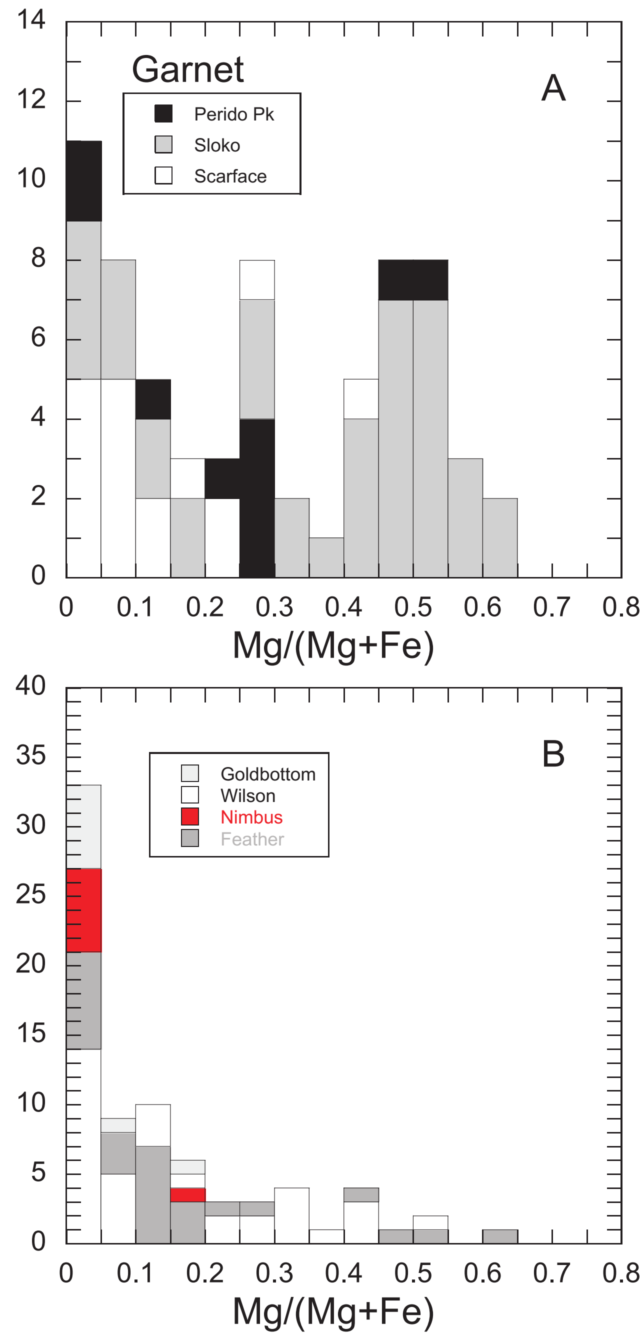

Fig. 6 - Histogram showing mole fraction of pyrope (XPyr) component ($Mg_3Al2Si_3O_{12}$) in garnets from heavy mineral samples at each locality. Arrow shows the compositions of garnet in eclogite clasts in coarse wacke from the Laberge Group. Note the abundance of more pyrope-rich eclogitic garnets in localities in (a) compared to those in (b).

a high Mg#. It is often referred to as 'chrome diopside'. The $Kd_{Fe\text{-}Mg}$ ol-cpx is greater than one such that clinopyroxene from mantle tectonite should have an Mg# greater than 0.9. Clinopyroxenes from mantle residues of basalt extraction are also rich in Cr_2O_3 (> 0.5 wt%) and poor in Na, which is an incompatible element during melting.

Clinopyroxene with Mg# greater than 0.9, and rich in Al as a Ca-Tschermaks (CaTs - $CaAl_2SiO_6$) component is represented only at Nahlin, Scarface and Peridotite Peak (Fig. 4). Clinopyroxenes with lower Mg# and Cr contents at other sample locations must have been eroded from other sources. Many of these grains have high CaTs and so could be derived from cumulate rocks (Fig. 5) but a few of these clinopyroxenes in the Scarface and Sloko samples are distinctly rich in jadeite (Jd - $NaAlSi_2O_6$) component indicative of an eclogitic paragenesis. Clinopyroxenes from the latter locations are almost certainly derived from eclogite source rock, because clasts of this rock type with identical Jd-rich clinopyroxene compositions are recognized in a distinct ridge of garnetiferous wacke within the Laberge group to the west. This source rock is also supported in the chemistry of garnets described below.

GARNET

Garnets were recognized by their pink, purplish pink or orange colour, and in some cases well-developed dodecahedral crystal faces. The dominant garnet in all samples is a pink variety, poor in pyrope (X_{Pyr}<0.05) and rich in almandine component (Fig. 6a). These are likely crustal garnets derived from metapelitic protoliths. Thermal-metamorphic aureoles around Middle Jurassic and younger plutons in the Atlin area are known to contain garnet. Garnets preserved in Early Jurassic strata, however, are too old to be attributed to contact metamorphism around these plutons. A source of older garnets is not known within the study area.

A significant proportion of garnets rich in pyrope component (X_{Pyr} = 0.1 to 0.6) are recognized at Peridotite Peak, Black Caps and Sloko River (Fig. 6b). Many of these garnets are red-orange in color and are identical to the garnets in eclogite clasts from garnetiferous wacke within the Laberge group to the west. Their compositions would correspond to Group C and B (crustal) eclogites according to the classification scheme of Coleman *et al*. Red-orange eclogitic garnets are also found in smaller numbers at Feather and Wilson Creeks.

A notable population of light green garnets with nearly 100% andradite component is common at Scarface and also at Goldbottom and Nimbus. The andradite grains are likely sourced from skarns in areas where limestone units are in contact with felsic intrusive rocks or from meta-rhodingite blocks that are locally abundant within serpentinite melange.

SPINEL

Spinels occur as shiny black conchoidally fractured grains or as euhedral octahedrons and cubes. Most spinel is well–preserved but some grains are rounded with a frosted dull grey sheen. The majority of the spinels in the population are Cr-rich spinel, and at each location show a positive correlation between Cr/(Cr+Al) (Cr#) and Fe/(Fe+Mg) (Fe#) (Fig. 7). The trends for spinels on the latter diagram reflect the interplay of cation exchange equilibrium between spinel and olivine as a function of temperature. The

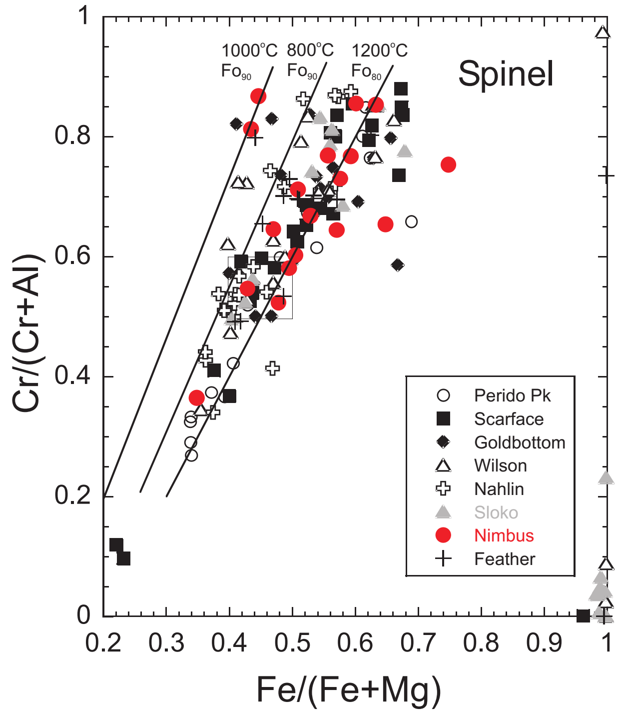

Fig. 7. Plot of Cr# (Cr/Cr+Al) versus Fe# (Fe/Fe+Mg) for spinel grains from heavy mineral concentrates. The lines show trends expected for spinel in equilibrium with various olivine compositions at different temperatures (after Roeder, 1994). Also shown is a field (box) that encompasses the compositions of 40 spinel grains from two harzburgite tectonite samples in outcrop north of Hard Luck Peaks, which equilibrated at 850 to 700ºC as determined by olivine-spinel Fe-Mg exchange thermometry . Note the abundance of spinel compositions that could not be in equilibrium with mantle tectonite olivine (Fo_{90}) at those temperatures of equilibration.

Cr# vs Fe# diagram (Fig. 7) is also useful to distinguish magnetite and 'ferrit-chromit' (an alteration product of Cr-spinel) from Cr-spinels; the former plot along the right hand side of this diagram.

The spectrum of spinel compositions in the heavy mineral samples is compared with trends for spinel in equilibrium at various temperatures with olivine having compositions that encompass the range expected in mantle tectonites (Mg# > 0.89) and that typical of cumulate rocks from ophiolites and layered intrusions (Mg# 0.80). Also shown for comparison is the range of spinel compositions in forty grains from two harzburgite samples from mantle tectonite in outcrop north of Hard Luck Peaks. Application of Fe-Mg exchange thermometry applied to coexisting olivine and spinel in these two samples show they last equilibrated between 700 and 850ºC.

Almost all locations contain some proportion of Cr-spinel that could have been in equilibrium with mantle olivine (Mg# ~ 0.9) at temperatures measured using olivine-spinel geothermometry for the harzburgite samples (Fig. 7). The majority of the spinel grains at each location, however, occur along an array that is indicative of equilibrium with olivine that has a far lower Mg# than typical mantle olivine. The majority of these spinels are apparently derived from rocks in equilibrium with olivine having a Mg# between 0.9 and 0.8, likely in cumulate rocks. The latter interpretation is borne out by the abundance of olivine compositions having Mg# between 0.86 and 0.75 in most samples (Fig. 2), as well as the euhedral nature of many spinel grains, which is expected for magmatic spinel in plutonic ultramafic rocks, but not for spinel recrystallized at high temperature in mantle tectonites.

TITANITE

Titanites were recognized as equant red-brown grains. All of the titanites are low in Al_2O_3 (< 2 wt%) indicative of protoliths from low P environments likely as accessory phases in felsic plutonic rocks.

DISCUSSION AND CONCLUSIONS

The Mg-rich compositions of olivine, clinopyroxene and spinel in samples from Peridotite Peak, Scarface and Sloko suggest a mantle tectonite source for heavy minerals in the samples. Several large masses of mantle tectonite crop out throughout the study area, and sample sites were chosen in the drainages of these regions to examine them as potential sources for diamond (Fig. 1). Ironically, there are many sample sites containing large proportions of olivine and spinel that are not sourced in mantle tectonite. Indeed, somewhat perplexing is the preponderance of olivine, clinopyroxene, spinel and orthopyroxene having mineral compositions with lower Mg# more indicative of cumulate rocks from the crustal section of ophiolites. Although peridotite cumulates are known from the lower crustal section of some ophiolites, they are not as well represented proportionately in outcrops of the Atlin-Nakina area. Only a small section less than 100 m thick of peridotite cumulate is recognized just north of Hard Luck Peaks. Gabbro in the same lower crustal section is very poor in olivine (< 5%). Larger tracts of 104 N/1 are underlain by gabbro, but these are not obviously rich in olivine. Thus, the source for cumulate olivine, spinel and clinopyroxene in the heavy minerals from most of the samples remains puzzling. One possibility is that a large proportion of the serpentinite melange throughout the Atlin-Nakina is an alteration product of cumulate peridotite, rather than mantle tectonite. The melange units, being less competent and easily eroded, could contribute more to stream sediments. If so, it remains unclear how fresh igneous olivine and spinel grains would have been preserved in melange that is heavily altered to serpentine and magnetite.

The presence of eclogitic garnet and clinopyroxene in several heavy mineral samples is also significant. Exposures of this rock type are sporadic in the Cordillera, but known at one locality on the eastern margin of Cache Creek Terrane in British Columbia and further north in Yukon Tanana Terrane of Yukon. The results of this study are intriguing in that they show widespread occurrence of this rock as a source for the heavy minerals from at least five locations, some as far east as Peridotite Peak, yet no eclogite has been recognized in outcrop in the Atlin-Nakina area. Clasts of eclogite have only been recently documented (in the past field season) in a coarse garnetiferous wacke of the Laberge Group to the west. These rare clasts are less than 1 cm, but are likely the source of much of the garnet within this particular unit of the Laberge Group, as evidenced by the great abundance of eclogitic minerals in heavy mineral concentrate from a stream draining this region.

The Laberge Group coarse wacke is the only known bedrock containing eclogitic garnets and pyroxenes in the Atlin region, but is an unlikely source for these heavy minerals throughout the entire study area. The Laberge wacke crops out only in the western portion of the study area west of the Nahlin fault. Ice flow during the last glaciation in the Atlin area was west to east. Glacial transport could explain the presence of eclogitic grains in stream sediments proximal to the Sloko site, such as at Wilson and Feather Creeks. Outside and further south of the Atlin area, however, the orientation of mega-rat-tail features on air photos suggests ice directions were southward, and yet eclogitic garnets are recognized over 100 km to the east near Black Caps Mountain, and Peridotite Peak. These occurrences require a more proximal source for eclogite in outcrop than units of the Laberge Group. Such a source is not obvious, but may lie within the melange units that are widespread in the Atlin-Nakina area. Eclogite blocks are common in the classic Franciscan mélange , and may also be present yet unrecognized in large areas of mélange throughout the Nakina area. As is the case with the source rock for cumulate olivine and spinels, the melange units are easily eroded, and could contribute their eclogitic material to stream sediments.

The source of eclogite clasts, Mg-rich mantle olivine and Cr-spinel in the garnetiferous wacke unit in the Laberge Group is likely to be ophiolite and associated melange that was part of Cache Creek Terrane to the east. Erosion of uplifted ophiolite and eclogite in mélange from the Cache Creek Terrane would have shed detritus into the basin accumulating proximal to the structures along which the ophiolite and melange were exhumed. Similar detritus is present in flysch deposits proximal to many ophiolites, such as the Bay of Islands, Newfoundland and Labrador, and is interpreted to have accumulated after convergence, uplift and collapse. An outstanding problem is that no eclogite units have been found in outcrop in the mélange. Further stream sediment sampling and processing of the remaining seven samples of this study may aid in identifying its location. Future study of the eclogite-bearing conglomerate should include careful paleocurrent study to test whether or not simple turbidity currents could have carried the clasts from the adjacent Cache Creek rocks.

A diamond in the Atlin area was originally reported over 10 years ago by Marvin Sherman in a placer operation on Wilson Creek. The yellowish white diamond was ~6 mm in diameter with a rough rounded shape. None of the heavy mineral samples from this study, including one on Wilson Creek, produced any diamonds. This study shows that the Wilson Creek diamond, if real, was not obviously sourced in mantle tectonite from ophiolite. The Wilson Creek occurrence, as well as those to the north in Yukon, remains enigmatic.

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