

First evidence for ultrahigh-pressure garnet peridotite in the North American Cordillera

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ABSTRACT

Constraints on the thickness of mantle lithosphere involved in collisional orogenesis are fundamental for understanding the geodynamics of mountain building and the overall growth of continents by accretionary tectonics. Garnet peridotite and ultrahigh-pressure (UHP) crustal rocks provide such a constraint in many collisional orogens but have hitherto been unrecognized in western North America's Cordillera. Here we show the first evidence for exhumation of UHP (>2.8 GPa) garnet peridotite and eclogite and for deposition of these rocks as detritus in an Early Jurassic forearc basin (Laberge Group, Yukon Territory and British Columbia). Our results suggest that collision in this part of the North American Cordillera must have been thick skinned, involving a Proterozoic continental mass with a lithosphere >100 km (and possibly to 150 km) thick. Our discovery also provides insight into the vigor of uplift and erosion of deep-seated rocks in a nascent continental arc.

Keywords: mantle, garnet, peridotite, exhumation, uplift, Cordillera.

INTRODUCTION

Questions surround the involvement, thickness, and stability of mantle lithosphere when plates collide to build mountains. How thick is the mantle lithosphere before, during, and after collision (Molnar et al., 1993; Pyskylwec et al., 2002), and by what mechanism can it be exhumed, in some cases from extraordinary depths at a rapid tempo (Green et al., 1997; Olker et al., 2003)? Answers to these questions are potentially addressed by the study of garnet peridotite and ultrahigh-pressure (UHP) crustal rocks in collisional orogens (Hacker et al., 1997; Liou et al., 2002; Medaris, 1999).

Western North America's Cordillera results from a young collisional orogeny (Monger, 1993), yet it is a suspicious circumstance that garnet peridotite and other UHP rocks recognized in other orogens are absent in this mountain belt. Only sparse occurrences of crust and mantle rocks derived from moderate depths (<60 km) are recognized (Canil et al., 2003a; Erdmer et al., 1998), a fact supporting a model of thin-skinned accretion of crustal flakes over a fixed deeper substrate of the continent (Cook et al., 2004). In contrast, exhumation of mantle lithosphere requires thick-skinned accretion involving deeper parts of

the crust and mantle. These contrasting mechanisms for collision not only bear on the growth of the Cordillera but also have broader implications, as this orogen is used as a classic example of continental growth by accretion (Patchett and Gehrels, 1998).

We present the first evidence for exhumation of UHP (>2.8 GPa) garnet peridotite and eclogite in the Cordillera, and we describe sedimentary rocks of the Lower Jurassic Laberge Group that record the erosion of the peridotite and eclogite. We highlight how collision must have been thick skinned, involving a Proterozoic continental block having a lithosphere of considerable thickness (>100 km). Our discovery also provides insight into the efficacy of denudation in juvenile arcs.

GEOLOGIC SETTING

The Laberge Group sediments were deposited within the Whitehorse Trough, an Early to Middle Jurassic marine forearc basin (Fig. 1) (Johannson et al., 1997). To the east of the Laberge Group are rocks of the Cache Creek terrane, an accretionary assemblage of Mississippian to Triassic limestone, chert, and Permian ophiolite (Mihalynuk et al., 2003; Monger, 1991). To the west of the Laberge Group, Late Triassic to Jurassic volcanic rocks of an east-facing arc define Stikinia. The Yukon-Tanana

terrane is west of and is in fault contact with Stikinia. Isotopic data from igneous and sedimentary rocks and detrital zircons in Stikinia and Yukon-Tanana terrane indicate derivation from a Proterozoic basement that was part of either a rifted fragment of North America or an exotic continental block (Gehrels et al., 1991; Jackson et al., 1991).

A coarse wacke and pebble conglomerate unit (hereafter referred to as garnetiferous wacke) within the Laberge Group contains angular detrital garnet, pyroxene, and olivine scattered among 3–8-mm-wide clasts of pristine volcanic-arc rocks, granitoids, and metamorphic granules and pebbles (mica schist, amphibolite) including rare eclogite or granulite (garnet + pyroxene + rutile). The ~200-m-thick garnetiferous wacke has a strike length of at least 20 km (English et al., 2005; Lowe et al., 2003). Eight polished thin sections of the rock were examined, and a 4 kg sample was processed for heavy minerals (see Appendix DR1 and Tables DR1A and DR1B¹).

¹GSA Data Repository item 2005013, Appendix DR1, methods, and Tables DR1A, DR1B, and DR2, major and trace element data and thermobarometry, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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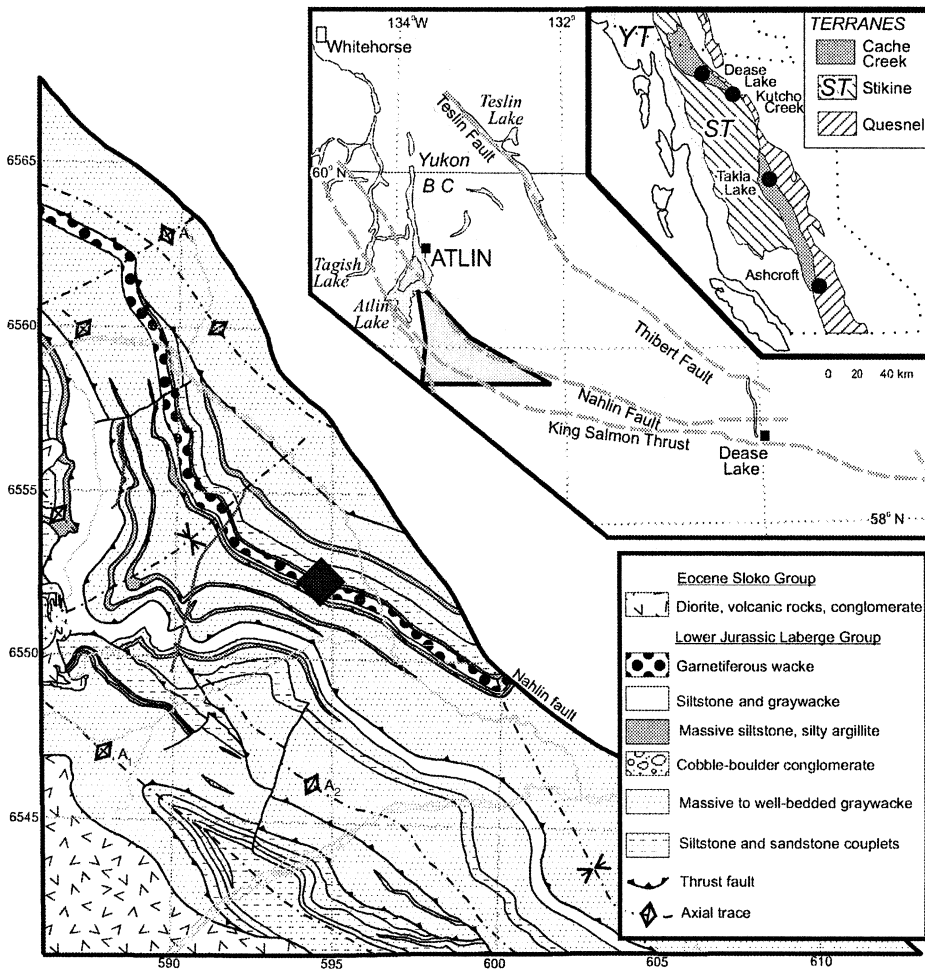


Figure 1. Geologic map of part of Laberge Group, showing garnetiferous wacke and pebble conglomerate and location of composite sample in this study (large black diamond). Location of Laberge Group (light gray shaded areas) in northern British Columbia (BC) is given in inset (after English et al., 2005; Johannson et al., 1997; Mihalyuk et al., 2003).

DETRITAL MANTLE MINERALS Garnet

The garnet fraction comprises ~0.5 wt% of the wacke and is dominated by orange grains and lesser light green, pink, or purple varieties. Many of the orange and light green garnets preserve dodecahedral forms, but pink and purple grains are always anhedral. Approximately 170 garnets were classified by the method of Schulze (2003). Light greenish garnets are andradites, whereas the orange garnets are either almandines from metapelites, or Cr-poor pyropes ($X_{Py} = 0.2-0.6$) from Group B and Group C eclogites (Coleman et al., 1965) or possibly granulite. Five eclogite clasts have garnet chemistry identical to that of many of the orange grains in the heavy-mineral concentrate. The pink and purple garnets commonly have inclusions of spinel, are Cr-rich pyropes ($X_{Py} > 0.6$) that plot mainly within the lherzolite field on a CaO vs. Cr₂O₃ plot, and coexisted with clinopyroxene in a garnet peridotite protolith. A few of the purple grains are classified as harzburgitic.

Clinopyroxene

Clinopyroxene is green and anhedral; it commonly exhibits well-developed cleavage. Darker green grains are poor in Cr, but some are rich in jadeite component (X_{Jd} of 0.1–0.5) and are similar to pyroxenes in the eclogite clasts. The dominance of these pyroxene grains in the wacke also correlates with the great abundance of eclogitic garnets and suggests that they were derived from eclogite or granulite. Less common are bright emerald-green pyroxene grains with Mg- and Cr-rich compositions [$Cr_2O_3 > 0.5$ wt%; $Mg/(Mg + Fe) > 0.89$]; some of these grains contain inclusions of deep red garnet, indicating derivation from a garnet lherzolite protolith.

Olivine

Rare olivine is recognized in thin sections of the garnetiferous wacke but was not identified in any abundance in the heavy-mineral separates. Kink bands in the olivine suggest that it is derived from mantle tectonite.

TRACE ELEMENTS IN PERIDOTITIC GARNETS

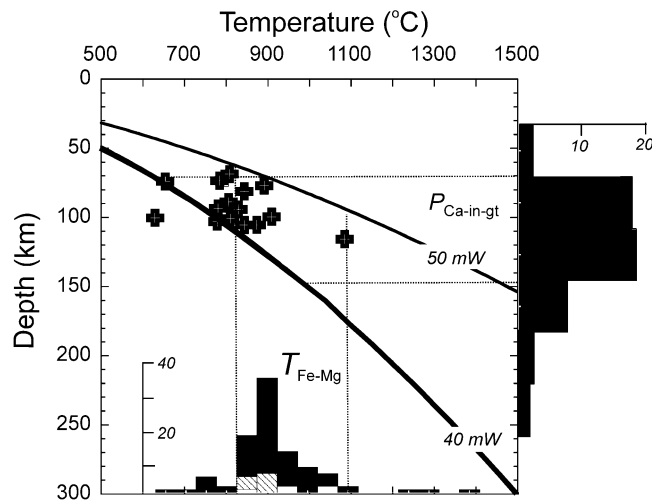
Trace element discriminants can be used to classify the Laberge garnets as having originated in mantle lithosphere of known tectonothermal age: tectons (younger than 1.0 Ga), protons (2.5–1.0 Ga), and archons (older than 2.5 Ga) (see Griffin et al., 1999). Sinuous rare earth element patterns with $(Nd/Y)_n > 1$ are commonly observed in garnet populations from archons (Pearson et al., 1998), but are absent in the Laberge population (Table DR1B; see footnote 1). Subcalcic harzburgitic garnets as observed in the Laberge population (Fig. 2) have not been recognized in mantle from tectons (Griffin et al., 1999). The median and mean values for Y/Ga, Zr/Y, and Sc/V in the Laberge mantle garnets (1.8, 2.3, 0.8, respectively) measure the degree of depletion of their protolith and are within the range reported for protons (Canil et al., 2003b; Griffin et al., 1999).

THERMOBAROMETRY

The Cr content of clinopyroxene in equilibrium with garnet in peridotite is a thermobarometer (temperature, T_{NT} and pressure, P_{NT} , where NT indicates Nimis and Taylor, 2000). Of 25 clinopyroxene grains, 7 gave spurious results and were likely not in equilibrium with garnet, but the remainder have T_{NT} values of 650–1080 °C and P_{NT} values of 2.3–3.6 GPa, typical of conditions within Proterozoic or Archean subcontinental mantle lithosphere (Fig. 2; Table DR2 [see footnote 1]). At the median P_{NT} value (3.0 GPa), five clasts of eclogite record clinopyroxene-garnet Fe-Mg exchange temperatures (T_{KR} , where KR indicates Krogh, 1988) of 850–1070 °C (Fig. 2; Table DR2 [see footnote 1]). At the same median P_{NT} value (3.0 GPa), Fe-Mg exchange temperatures for the peridotitic garnets (T_{OW} , where OW indicates O'Neill and Wood, 1979), if it is assumed that they were in equilibrium with Fo₉₀ olivine, are 600–1300 °C, with a dominant mode between 800 and 950 °C. These T_{OW} values would decrease slightly if lower pressures (~60 °C/GPa) or higher Fo content of olivine (75 °C/mol% of Fo) were assumed. The Ni-in-garnet thermometer (T_{Ni}) has a negligible P dependence (Canil, 1999) and gives results of 850–1050 °C, consistent with T_{OW} at 3 GPa (Fig. 2; Table DR2 [see footnote 1]).

The Ca and Cr contents of peridotitic garnet in equilibrium with clinopyroxene are pressure sensitive ($P_{Ca-in-gt}$; Brenker and Brey, 1997), but can have large uncertainties (± 1.2 GPa; Nimis and Trommsdorff, 2001). The Laberge peridotitic garnets show a population maximum at ~5.5–6.5 wt% CaO (Fig. 2) corresponding to $P_{Ca-in-gt}$ of ~3–6 GPa (Fig. 3; Table DR2 [see footnote 1]) at a median T

Figure 2. Plot summarizing thermobarometric calculations on detrital mantle minerals in garnetiferous wacke. P —pressure; T —temperature. Thermobarometric pressures were converted to depths by using algorithm in Anderson (1989). Geothermal gradients typical of Archean ($40 \text{ mW}\cdot\text{m}^{-2}$) and Proterozoic ($50 \text{ mW}\cdot\text{m}^{-2}$) continental lithosphere are from MacKenzie and Canil (1999). Crosses show results for clinopyroxenes using T_{NT} and P_{NT} (NT—Nimmis and Taylor, 2000). Histogram on bottom shows results of T_{KR} (open), T_{OW} (filled), and T_{Ni} (hachured) for eclogite clasts and peridotitic garnets at 3 GPa (Kr—Krogh, 1988; OW—O'Neill and Wood, 1979). Note dominant mode at 800–950 °C and similarity to T_{NT} method. Histogram on right shows $P_{\text{Ca-in-gt}}$ for garnets assuming equilibrium with clinopyroxene at 900 °C (median T_{NT}). Note minimum of 100 km depth for derivation of some of detrital peridotitic clinopyroxenes in wacke.



based on the geothermometry outlined here (900 °C). Some garnets record much higher $P_{\text{Ca-in-gt}}$ (6–14 GPa), but they invariably have lower CaO contents (< 5 wt% CaO) and thus may not have been in equilibrium with clinopyroxene.

DISCUSSION

The exceptionally pristine preservation of mantle detritus in a forearc basin now preserved as the Laberge Group is attributable to proximal deposition, rapid burial, and an absence of metamorphism or penetrative deformation documented in this part of the Whitehorse Trough since 170 Ma (English et al., 2005; Johannson et al., 1997; Mihalyuk et al., 2003).

A potential source of the mantle detritus could be primary alkaline igneous rocks known to host garnet peridotite and eclogite xenoliths. For example, Oligocene sedimentary rocks in the Uinta Mountains of the western United States contain garnets and pyroxenes that are thought to be derived from Eocene kimberlite and lamproite intrusions within a few hundred kilometers in the Wyoming province (McCandless and Nash, 1996). For the Laberge Group, this type of interpretation would require a Jurassic alkaline igneous source rock proximal to the denuding arc. Alkali olivine basalt and alnoite breccias containing mantle garnets are known in some arcs (Collerson et al., 2000; Stern et al., 1999; Coombs et al., 1986), but are located hundreds of kilometers from forearc basins. River systems are known to deliver durable heavy minerals across continental-scale drainage systems, but the latter depositional setting results in mature, quartz-rich, clastic sedimentary

rocks (Rainbird et al., 1997), not immature wacke with angular detritus. Most critical, however, is that the opaque fraction of the garnetiferous wacke contains no picrochromite or picroilmenite associated with kimberlite or allied alkaline igneous rocks (McCandless, 1990), negating those rocks as a source for the mantle detritus in the Laberge wacke.

The only other source for the mantle detritus could be orogenic garnet peridotite and eclogite, which are volumetrically minor components of many collisional orogens (Brueckner and Medaris, 2000; Medaris, 1999) and are recognized in some arcs (Abbott et al., 2001; Kadarusman and Parkinson, 2000). Nevertheless, even small massifs (~1 km³) of garnet peridotite and eclogite, with 5%–50% modal garnet, can, when eroded, easily contribute the mass of garnet observed in the heavy-mineral fraction of the Laberge garnetiferous wacke.

Detrital garnets are known from other immature sandstones in the Laberge Group (G.G. Johannson, 2004, personal commun.). All are of Pliensbachian age (192–183 Ma) (Johannson et al., 1997), the interpreted but poorly constrained age of the garnetiferous wacke. If correct, it would appear that exhumation and erosion of the garnet peridotite was the result of a Pliensbachian tectonic event. Rapid uplift and exhumation of lithosphere west of the Whitehorse Trough is substantiated by the observation that the U-Pb age of granitic boulder in a Laberge Group conglomerate is within a few million years of the biostratigraphically controlled depositional age of Pliensbachian sandstones interbedded with the conglomerates (Johannson et al., 1997). In Yukon Territory to the north, crust from ≥30 km depths

was uplifted and exhumed during the Pliensbachian at rates of 2–10 mm/yr; detritus was shed east into the Whitehorse Trough (Johnston and Erdmer, 1995; Johnston et al., 1996).

We are unable to constrain the actual age of mantle rocks before their denudation at the surface and thus cannot quantify their rate of uplift from mantle depths. Nonetheless, rapid exhumation seems to be required for emplacing deep-seated mantle rocks at the surface (England and Holland, 1979; Rubatto and Hermann, 2001). The presence of detrital olivine and the pristine nature of the mantle-derived detritus suggest that it was not affected by prolonged surface exposure or alluvial abrasion prior to deposition in the Whitehorse Trough (McCandless, 1990). Mantle rocks were uplifted, exposed, and eroded without any prolonged residence time at shallow structural levels. The intimate association of fresh, deep-seated lithospheric mantle rocks with high-level volcanic-arc rocks in detritus of a forearc basin requires rapid and deep incision of a nascent arc.

The emplacement of mantle-derived rocks in mountain belts has always been enigmatic (Benson, 1927). This study provides an important new piece of information on the involvement of mantle lithosphere during accretion within the North American Cordillera and beyond. We show that the original thickness of a large continental block involved in collisions within the orogen was at least 100 km and was likely Proterozoic in age. Our data do not distinguish whether this lithosphere was originally North American or exotic, but its collision involved intercalation of mantle and crust, suggesting thick-skinned accretion. Our discovery encourages the search for other evidence of UHP mantle and crustal rocks in the Cordillera.

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