Ultramafic Intrusions, Detailed Geology and Geobarometry of the Jurassic Bonanza Arc in the Port Renfrew Region, Southern Vancouver Island (NTS 092C)

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Introduction

Several isolated bodies of ultramafic rock were discovered in the Port Renfrew area of southern Vancouver Island over the past nine years by G. Pearson. A field mapping study jointly funded by Geoscience BC and Emeralds Fields Resources was conducted to ascertain the areal extent of the ultramafic bodies and to determine their relationship with other rocks of southern Vancouver Island. The objective was to use this and other petrological information from the surrounding area to assess the economic significance of the ultramafic bodies as a potential target for Ni-Cu or platinum-group element (PGE) deposits, and the overall structural thickness and setting of the Jurassic Bonanza Arc. This report summarizes results of the geological fieldwork, including detailed mapping, sampling, geobarometry and geochemical assays of the ultramafic rocks.

Field Area and Access

The field area on southern Vancouver Island (NTS 092B, C, F, G) is bordered by the San Juan River to the south, Cowichan Lake to the north, Nitinat Lake to the west and the Fleet River to the east (Figure 1). The area of interest is in and surrounding the NTS 092C map area. The physiography of the area is one of generally steep forested slopes, divided by streams cutting through bedrock and alluvium to create considerable relief. Open valleys are present along the San Juan River and to a lesser degree along the Gordon River.

The area is accessed by a network of logging rods in various states of preservation. Overall, bedrock exposures are best along active logging roads and in elevated areas that have been recently logged. Most areas were accessed by four-wheel drive truck, but a few remote mountaintops with overgrown logging roads could be accessed only by helicopter.

Keywords: *ultramafic, arc, Jurassic, nickel, Bonanza, geobarometry*

Survey Methods

Bedrock geology was mapped at 1:25 000 scale on Terrain Resource Inventory Mapping (TRIM) map sheets and compiled to 1:50 000 scale (Figure 1). Samples for thin-section petrography, geochemistry, fire assay and geochronology were taken (Figure 2). Detailed examinations of select ultramafic bodies could not be compiled onto the 1:50 000 scale geology maps but are described in detail in related papers (Larocque and Canil, 2007, 2009).

Regional Geology Overview

Previous geological maps in the area were mapped at 1:100 000 scale and compiled to 1:250 000 scale (Muller, 1983). Most of the area is underlain by rocks of Wrangellia. The Devonian Sicker Group forms the basement to Wrangellia on Vancouver Island, and consists of mafic and felsic volcanic and volcaniclastic rocks, overlain by epiclastic and carbonate sedimentary rocks of the Permian Buttle Lake Group. Unconformably overlying the Buttle Lake Group are the Triassic Karmutsen basalts, in turn overlain by the Quatsino Formation, a thin (<75 m) sequence of micritic limestone. The Parsons Bay Formation, a 35 m thick sequence of thinly bedded argillaceous mudstone, limestone, siltstone and sandstone, conformably overlies the Quatsino Formation (Nixon and Orr, 2007).

The Port Renfrew region is underlain mostly by rocks of the Jurassic Bonanza Arc, which intrudes, as well as unconformably overlies, the older units of Wrangellia. Clastic sedimentary rocks of the Oligocene Carmanah Group unconformably overlie all older units along the western coast of the island. Quaternary glacial till and alluvium covers stream valleys.

Jurassic Bonanza Arc

In the field area, rocks of the Bonanza Arc are separated from the Jurassic-Cretaceous Pacific Rim Terrane to the south by the San Juan fault and from the Sicker Group to the north by the Cowichan fault. The Jurassic-aged rocks of the Bonanza Arc in Wrangellia include, from base to top, the Westcoast Crystalline Complex (WCC), the Island Plutonic suite and the Bonanza Group volcanics. These rocks have undergone zeolite- to locally greenschist-facies

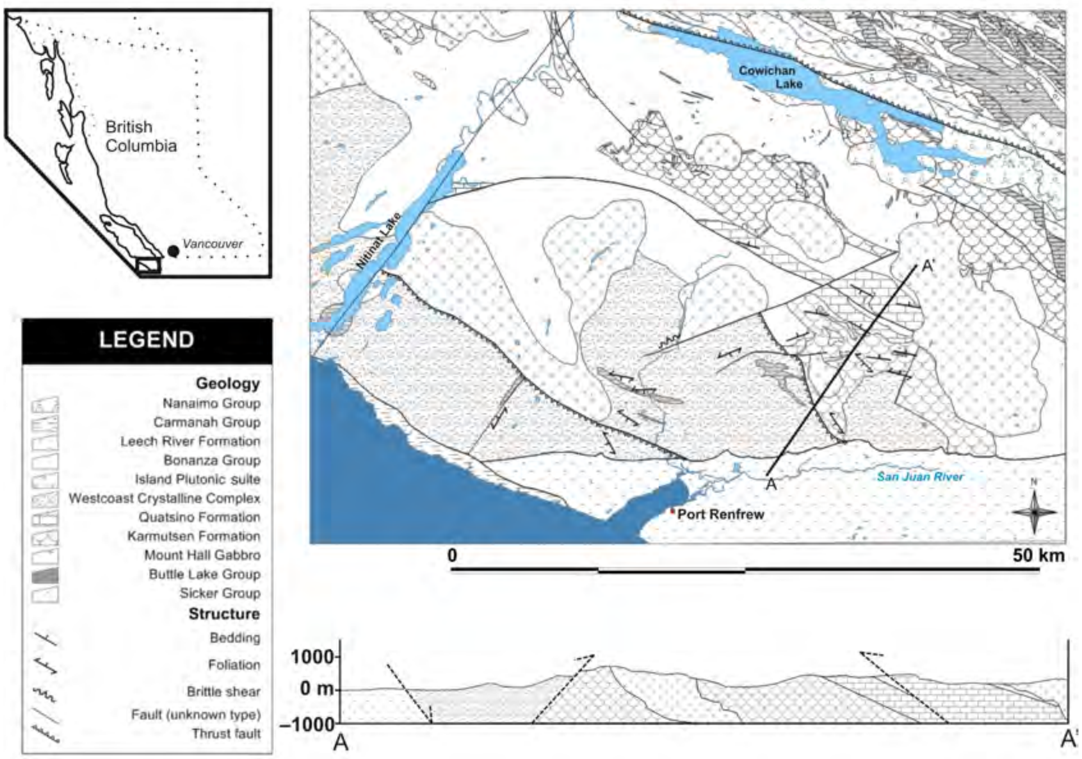

Figure 1. Geology of the field area and location of the field area (inset map), southern Vancouver Island, British Columbia. The cross-section (lower left) is along the line of A-A'. The region was mapped at a scale of 1:20 000 and compiled to 1:50 000 scale. Also shown for reference are the town of Port Renfrew, Nitinat Lake, Cowichan Lake and the trace of the major structures (San Juan fault and Cowichan uplift).

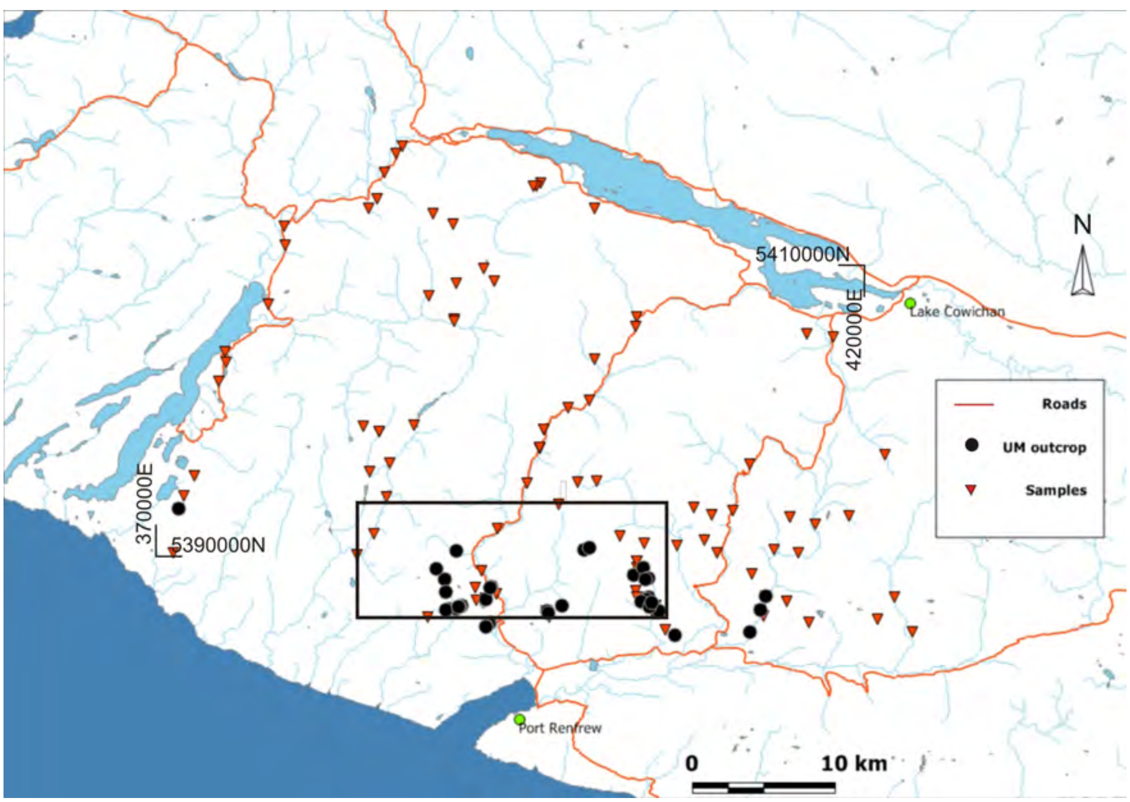

Figure 2. Areas traversed with all sample locations (red inverted triangles), the mainline forestry roads (red lines) and ultramafic outcrop locations (black circles), southern Vancouver Island, British Columbia. The box in the centre shows the location of the Pearson claim block.

metamorphism, but original igneous lithological names are used in their description.

Westcoast Crystalline Complex

The Westcoast Crystalline Complex (WCC) represents the deepest preserved structural level of the Bonanza Arc and is dominantly quartz diorite and gabbro with varying amounts of hornblende, biotite, orthopyroxene and clinopyroxene with accessory magnetite, ilmenite, pyrite and pyrrhotite. Weakly concordant diabase bodies are found locally in the WCC in the field area southwest of the Gordon River. Grain sizes vary from fine grained to pegmatoid and are heterogeneous over a scale of metres.

Distinct units of light grey impure marble 3–10 m thick occur in the diorite. Some marble units can be traced for a few kilometres along an orientation parallel to regional strike. Marble outcrops found in the eastern part of the field area are more irregular in outcrop pattern. Minor magnetite-rich skarn bodies, with variably developed diopside-garnet and magnetite-chalcopyrite-pyrite assemblages, are found at the contact of diorite or diabase with the marble. Due to the metamorphosed nature of these carbonate rocks, they are here suggested to represent fragments and/or faulted slices of carbonate rocks belonging to the Permian Buttle Lake Formation or the older Sicker Group, which are now screens or septa in the intrusive rocks of the WCC.

Ultramafic Rocks

The largest concentrations of ultramafic rocks are present along the Granite Creek mainline and at the top of Fairy mountain (Figure 2). Other bodies are recognized west of the Griersen mainline in the Twin Lakes area. Details of their geochemistry, petrology and origin can be found elsewhere (Larocque, 2008; Larocque and Canil, 2009)

Ultramafic rocks occur as discrete bodies within the WCC diorite, ranging in size from a metre to several tens of metres. Although their borders are often obscured by overburden, there is some lateral continuity or concentration of the ultramafic bodies over distances of up to 1 km. Contact relationships between the ultramafic bodies and the WCC diorite are quite variable. Smaller bodies, which tend to be more olivine rich, have either abrupt, undeformed contacts

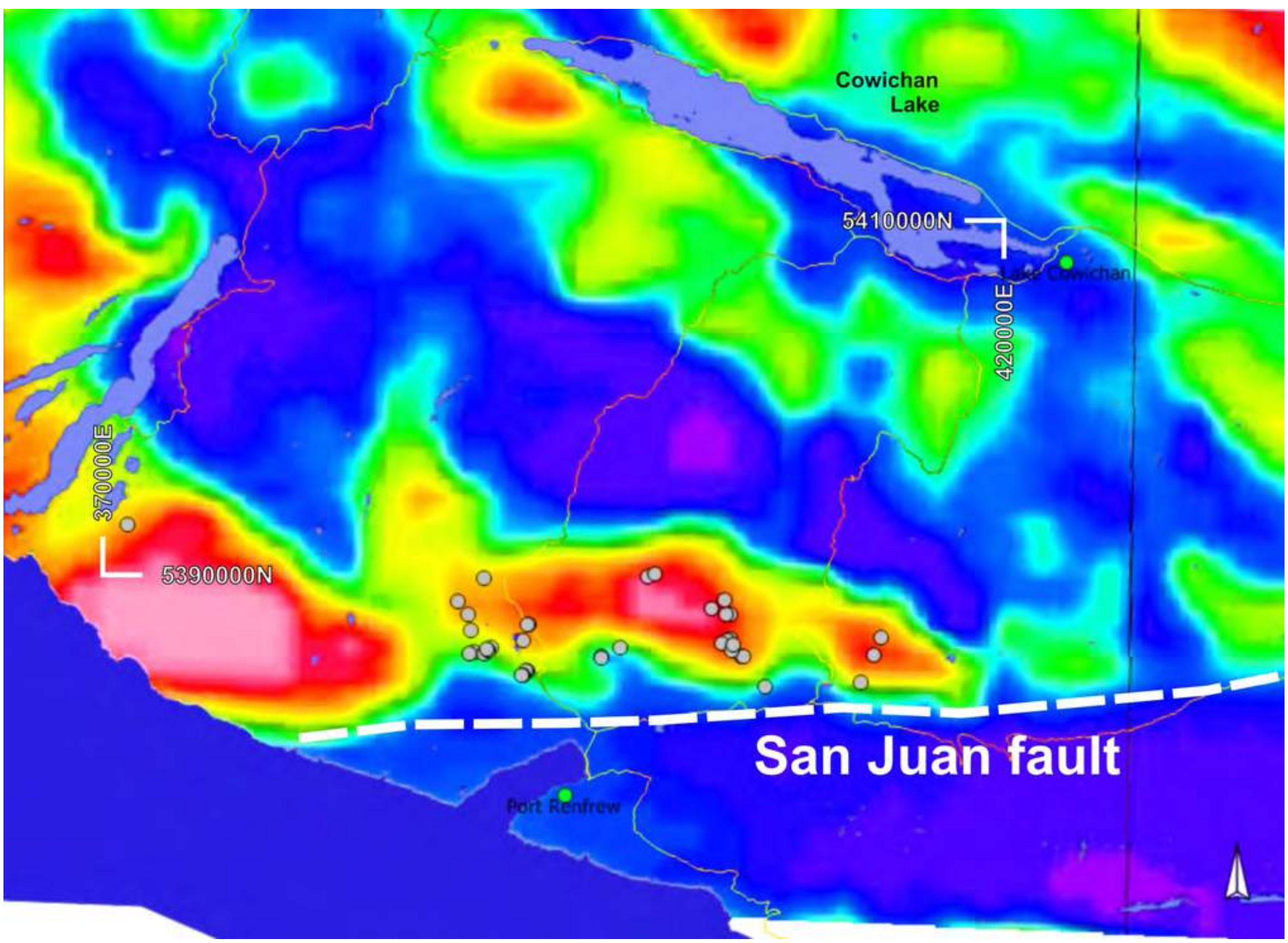

Figure 3. Regional aeromagnetic map (from BC Geological Survey, 2009) superimposed on locations of ultramafic rocks (grey circles) in the map area, southern Vancouver Island, British Columbia.

with their host or are present as sheared pods. Larger bodies, which are mostly olivine gabbro, grade into the diorite of the WCC. In several locations, the association of olivine pyroxenite with pegmatitic hornblende diorite has been noted.

In thin section, peridotite and olivine pyroxenite consist of variably serpentinized cumulus olivine with inclusions of euhedral spinel, poikolitically enclosed by either orthopyroxene, amphibole, or more rarely, clinopyroxene. Orthopyroxene and clinopyroxene coexist in several samples. Weakly to strongly altered plagioclase is present as an intercumulus phase in some samples. In these samples, olivine is never directly in contact with plagioclase, and is always mantled by a corona of pyroxene. Where present, amphibole appears as the result of reaction with pyroxene, along grain boundaries or along exsolution lamellae. Igneous phlogopite is also present as a minor phase in some samples.

Gabbro and gabbronorite display cumulus plagioclase, plus or minus orthopyroxene, clinopyroxene and, in one case, olivine. Much of the postcumulus clinopyroxene has been replaced by amphibole. Plagioclase in these samples is invariably less altered than in the peridotite and olivine pyroxenite samples. Chromite is the dominant opaque phase in the ultramafic samples. Magnetite with minor ilmenite exsolution is both a euhedral and intercumulus phase in the gabbroic rocks. Minor amounts of chalcopyrite are noted in most samples. Rare inclusions of round, white, high-reflectivity grains in olivine (possibly identified as pentlandite) are also noted.

Regional-scale aeromagnetic data available for southern Vancouver Island shows a prominent magnetic high, running parallel to, and extending north from, the San Juan fault. At this resolution, the magnetic anomaly appears to roughly correspond to areas underlain by the WCC (and ultramafic) rocks (Figure 3).

Island Plutonic Suite

The Island Plutonic suite occurs as a roughly southeast aligned series of medium-grained plutons ranging in composition from quartz diorite to alkali feldspar granite. The Island Plutonic suite most commonly intrudes the Triassic Karmutsen basalts, and is distinguished from plutons of similar composition of the WCC by lacking any foliation. The contact between the Island Plutonic suite and the WCC is not well defined. In the field area, rocks of the Island Plutonic suite occur mainly in the northern and eastern parts of the field area, separated from the WCC to the southwest by intervals of Karmutsen basalt and Quatsino limestone, which are in fault contact (to the southwest) with rocks of the WCC.

Bonanza Volcanics

The Bonanza volcanics are only very weakly metamorphosed, displaying assemblages indicative of the zeolite facies and varying from aphanitic basalt through plagioclase-, pyroxene- and/or hornblende-phyric andesite to minor dacite and lesser pyroclastic deposits. The lateral extent and continuity of these deposits is obscured by vegetation and overburden. No contacts between Bonanza volcanics and plutonic rocks were observed.

Geochronology

Geochronological investigations were undertaken to constrain the age of rocks that host the ultramafic bodies. Four samples were obtained in different parts of the map area and were submitted for age dating by the U-Pb zircon method at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at The University of British Columbia. The ages obtained as of this writing are still preliminary but the range in U-Pb ages of zircons is between 194 and 174 Ma (Table 1). In the WCC near Lens Creek in the southeastern part of the map area, melanodiorite is crosscut by a dike of leucodiorite. Both the leuco- and melanodiorite returned ages of 174 Ma. In the southwest, mylonitized diorite near Twin Lakes has an age of 194 Ma. Further west, an undeformed granodiorite pluton near Glad Lake also returned an age of 192 Ma. Thus, magmatism spans an age of at least 20 Ma. All the ages obtained in this study fall within those of the Bonanza Arc elsewhere along strike in the Port Alberni and Bamfield areas (DeBari et al., 1999). Because the diorite hosting ultramafic rocks along both the Granite Creek mainline and on top of Browns mountain is identical to that for which ages were obtained, the ultramafic rocks in the Port Renfrew area are almost certainly Jurassic in age and are related to the Bonanza Arc. A Jurassic age rules out that the ultramafic rocks are cumulate blocks from the older Triassic Karmutsen lavas.

Structural Geology

Foliations within the WCC rocks are defined by a planar fabric of hornblende or biotite, or by a gneissosity of mafic and felsic layers, and generally strike northwest and dip 60–75° to the southwest. Poles to foliations in the WCC between Gordon River and Harris Creek (Figure 1) define a great circle with a pole plunging approximately 50° to the south-southeast (Figure 4). Well-developed minor folds in

Table 1. Uranium-lead zircon ages for samples from the Bonanza Arc in the Port Renfrew region, southern Vancouver Island, British Columbia.

Location	Sample Number	Rock type	U-Pb age (Ma)	
Lens Creek	JL110B	leucodiorite	174.1	0.4
Lens Creek	JL110	melanodiorite	174.8	0.5
Twin Lakes	DC0507	diorite mylonite	193.7	0.5
Glad Mainline	DC0637	granodiorite	192.6	0.4

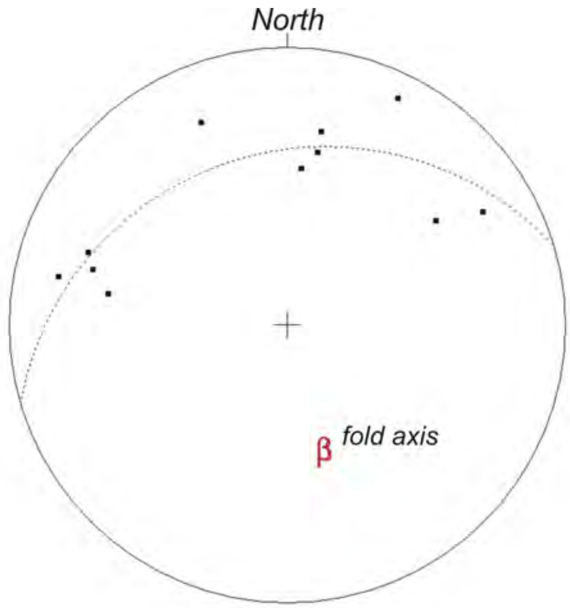

Figure 4. Stereonet projection of poles to foliations for WCC diorite in the area between Gordon River and Harris Creek. Poles to foliations define a girdle having a pole ( ) that defines the regional fold axis (plunging 50° to the south-southeast). Minor folds in diorite on Fairy mountain and near Twin Lakes have nearly identical orientations.

the WCC are evident on Browns mountain and near the Twin Lakes region, and have axes plunging with nearly identical orientations as the major fold axis in Figure 5.

The map pattern of the same rocks northwest of the Gordon River mainline, however, is more consistent with closed folds but plunges northwest rather than southeast. One possible explanation is that the Jurassic units (at least the WCC) are folded along doubly plunging axes (both northwest and southeast) that converge to form a dome structure somewhere between Twin Lakes and Browns mountain. The location where the fold axis changes plunge from northwest to southeast contains the highest concentration of ultramafic rocks. Thus, the WCC, the Island Plutonic suite and the Bonanza Group in the field area are all part of a larger fold structure plunging with fold axes in the northwest and southeast directions, exposing varying structural depth.

Near Harris Creek, a large area of Karmutsen basalt is juxtaposed with the WCC diorite along a 10 m thick shear zone with the same attitude as the pervasive foliation in the diorite. The shear zone is well exposed along the Harris Creek and southern Hemmingsen mainlines. Less obvious shear zones are defined by centimetre- to metre-thick mylonite horizons in the more western parts of the field area, within the WCC diorite near Camper Creek and Twin Lakes. These faults are expressed on topographic and aeromagnetic maps in the southwest portion of the map area.

The common orientation and sense of shear (tops to northeast) in both the mylonite near Twin Lakes and the Harris Creek–Hemmingsen shear zone suggest that the WCC occurs as a series of east-verging thrust-faulted panels. At least two major thrust-faulted panels are recognized: the westernmost panel thrusts the WCC over itself, and the easternmost panel places the WCC onto the Karmutsen basalts and the Quatsino limestone (Figure 1). In this way, it is possible that the WCC is an imbrication of several thrust-faulted panels, but some of the faults are not recognized due to cover.

Downplunge projections of the rock units (along a fold axis plunging 50° to the south-southeast) suggest that at least 15 km of structural depth is exposed in the Jurassic units throughout the entire field area. This is generally consistent with pressures of crystallization obtained by aluminum-in-hornblende geobarometry on granodiorite and diorite plutons in the map area along a line normal to regional strike from Twin Lakes in the west to Cowichan Lake in the east.

Geobarometry

The overall thickness of the entire Bonanza Arc section on Vancouver Island is not known due to a lack of constraints on its structural thickness. This portion of the study addressed this problem by estimating the relative depth of exposure and structural thickness in the Bonanza Arc using aluminum-in-hornblende barometry of its felsic plutons. Coupled with geological data, the structure of exposed arc crust comprising Vancouver Island is assessed.

Felsic rocks were sampled from different parts of the WCC (quartz diorite and granodiorite) and medium- and coarse-grained granodiorite to monzonite were sampled from the Island Plutonic suite. Major and minor elements were determined for amphibole and plagioclase using a CAMECA SX50 electron microprobe at The University of British Columbia. Operating conditions were 15 kV acceleration voltage at a beam current of 20.1 nA and counting times of 20 s on peaks. Standards included natural olivine, diopside, anorthite, albite, orthoclase, kaersutite, rutile and fayalite. In each sample, from four to ten grains each of amphibole and plagioclase were measured, with analyses of both cores and rims on each grain.

The aluminum-in-hornblende barometer (P_{Hbl}) was applied to rocks containing quartz to buffer silica activity and with hornblendes having Mg/Mg+Fe >0.35 (Anderson and Smith, 1995). Where plagioclase was fresh, the hornblende–plagioclase geothermometer (Holland and Blundy, 1994) was applied to estimate temperature. For the samples, a aluminum-in-hornblende barometer formulation is applied that accounts for the effects of temperature T_{HB} on the Al content of hornblende using T_{HB} (Anderson and Smith, 1995).

This study, which was extended for Jurassic plutons across much of Vancouver Island (Canil et al., in press), consistently shows the highest crystallization depths in WCC plutons (10–18 km; Figure 6), supporting the notion that this unit represents the deepest levels of the Bonanza Arc (DeBari et al., 1999). The WCC is well exposed in southernmost Vancouver Island in the Victoria area (Figure 6) and in the Port Renfrew area extending along the west coast of Vancouver Island. If the San Juan fault is considered a strike-slip fault, the restoration of ~80 km of sinistral movement along this fault brings the depths recorded in the WCC in the Victoria area in line with those in Port Renfrew (13 km) and Gold River (12 km), suggesting these plutons were once continuous along strike. If so, the San Juan fault must be younger than the Bonanza Arc (170 Ma) and older than the maximum age of the Nanaimo Group (93 Ma; Mustard, 1994), because sedimentary rocks of the latter are not offset by this fault. Considering any dip-slip component in this fault will reduce the estimate of strike-slip movement.

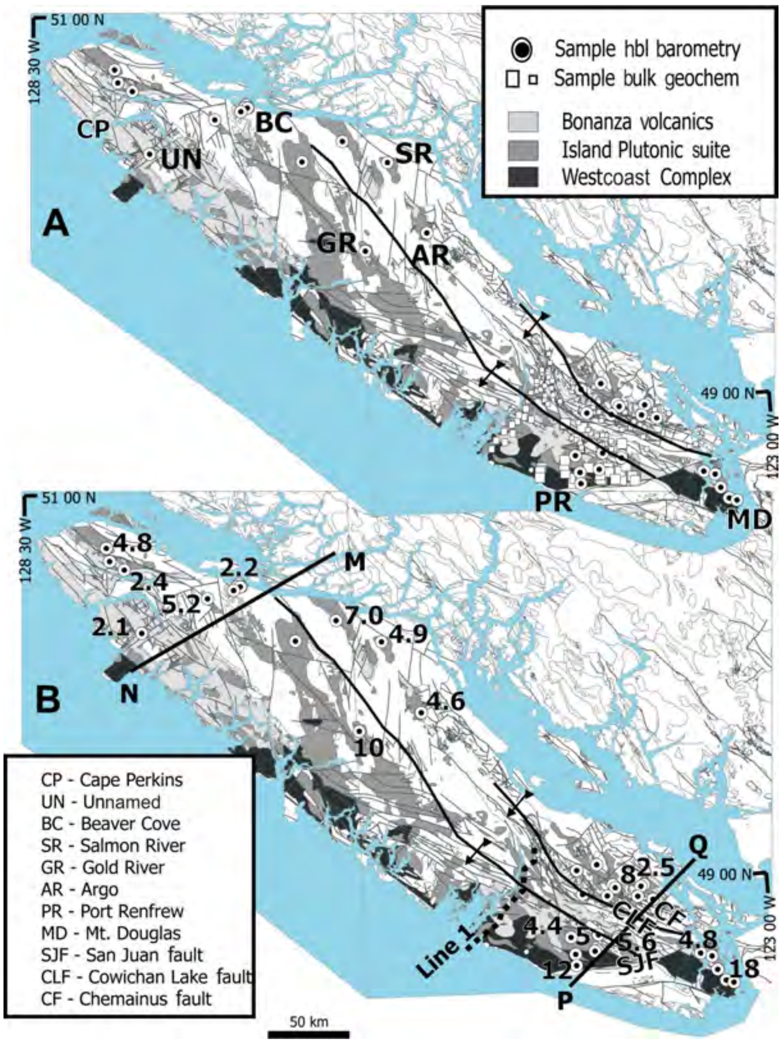

Figure 5. Vancouver Island, British Columbia, showing only the major regional structures and geology of the Jurassic Bonanza Arc, subdivided into Bonanza volcanic rocks, Island Plutonic suite and Westcoast Crystalline Complex: a) Sample locations for hornblende barometry (this study); b) As above but showing depth of crystallization of plutons from aluminum-in-hornblende barometry (assuming 100 MPa = 3 km depth). Not all barometric results are shown for clarity.

On southern Vancouver Island, five samples of the Island Plutonic suite all crystallized at depths of approximately 4–5 km but are too sparsely distributed to reveal any regional structural information along a transect normal to regional strike from Port Renfrew in the west to Ladysmith in the east. The depths of exposure from this study for plutons on southern Vancouver Island suggest this suite must exist as numerous thin, tabular bodies to fit within the stratigraphically measured thicknesses of pre-Jurassic supracrustal rocks on Wrangellia (Figure 6). When comparing P_{Hbl} with stratigraphic sections for Wrangellia, the results are not supportive of previous interpretations (Yorath et al., 1985) that Paleozoic and Mesozoic strata of Wrangellia are 'roof pendants' perched on an underlying Jurassic plutonic complex. To fit the depths from hornblende barometry and map patterns, the Jurassic arc intrusions must be tabular and intrude within the stratigraphy of the older units of Wrangellia, which can be mapped as septa within the intrusions.

There are fewer constraints on the Wrangellia stratigraphy into which the lesser sampled and more mafic WCC intruded. The few depth constraints for crystallization suggest that unlike the more evolved granitic Island Plutonic suite, this mafic-ultramafic unit intruded depths greater than any measured stratigraphic thicknesses of Devonian and Triassic supracrustal rocks, likely in the middle and lower crust below them (Figure 6).

Economic Geology

Assays of the ultramafic rocks returned generally low values of Au, Pt and Pd (1–7 ppb). This is not surprising given the low amounts of sulphide in the samples. Ultramafic rocks occur in several geological settings. The ultramafic cumulates in the WCC around the Port Renfrew area are inconsistent with an ophiolite association or 'Alaskan-type' intrusion (Larocque and Canil, 2007)

Peridotite and pyroxenite bodies with identical petrographic and geological relationships are noted to occur towards the middle and base of crust in exhumed island arc terranes. Such an interpretation for these rocks in the Port

Renfrew area is commensurate with their thermobarometry (Canil et al., in press; Larocque and Canil, 2009). The Bonanza Arc and its setting on Vancouver Island are very similar to the Talkeetna Arc in south-central Alaska, and it has been proposed that the two are of similar age and can be correlated along strike (DeBari et al., 1999).

Future Work

The majority of the ultramafic bodies in the Port Renfrew area are discontinuous and tend to be distributed in patches throughout the WCC. Areas of significant concentration are on Fairy mountain and along the Granite Creek mainline. Areas of the WCC that host ultramafic rocks appear to correspond with magnetic highs in both the regional and detailed aeromagnetic surveys. The aeromagnetic highs may also correspond with laterally discontinuous magnetite skarn, which are strongly magnetic in outcrop. Because neither of the latter rock types is specifically associated with ultramafic rocks, further detailed magnetic surveys in the field area will not be exclusive to the detection of ultramafic rocks.

If the regional magnetic signal is controlled by the presence of ultramafic rocks, there may be a significant amount of these rocks hidden at depth within the WCC. Geophysical investigations (detailed gravity survey) or drilling may reveal the continuity between these or other surface ultramafic bodies at depth beneath the area.

No significant concentrations of chromite, sulphides or platinum-group minerals were noted in the ultramafic rocks in outcrop, hand sample or thin section. Only minor amounts (<2%) of Cu- and Ni-sulphides (chalcopyrite, pentlandite, pyrrhotite) or chromite are seen in thin section. For this reason, and in view of the discontinuous exposure of the ultramafic rocks, heavy-mineral stream sampling is not likely to be an effective method for uncovering further occurrences of these rocks.

Magnetite skarn bodies, if of significant economic interest, may be detected near the surface by magnetic surveys, looking for a contrast of units with weak magnetism (marble) adjacent to strong magnetism (magnetite). Because the marble bodies appear to have some structural continuity (Figures 4, 5), areas for detailed survey are best accomplished along strike of existing magnetite bodies. The Jurassic rock units are folded, however, and it is possible that the magnetite skarn bodies plunge with depth along the regional fold axes, explaining why they are not observed continuously along strike in outcrop at the surface. Further delineation at depth of the existing magnetite bodies might be located by drilling orthogonal to the plunge of regional folds.

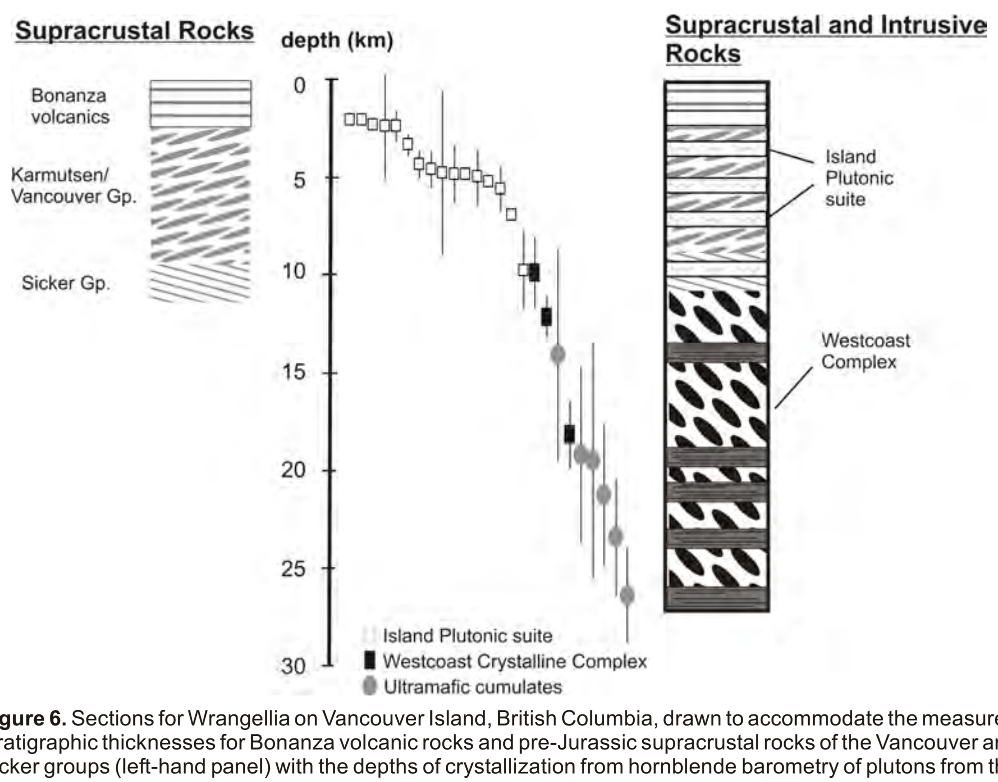

Figure 6. Sections for Wrangellia on Vancouver Island, British Columbia, drawn to accommodate the measured stratigraphic thicknesses for Bonanza volcanic rocks and pre-Jurassic supracrustal rocks of the Vancouver and Sicker groups (left-hand panel) with the depths of crystallization from hornblende barometry of plutons from the Island Plutonic suite and the Westcoast Crystalline Complex (Canil et al., in press) and ultramafic cumulates (Larocque, 2008). The right-hand panel shows how the range of hornblende pressures can be accommodated in the section by having the Island Plutonic suite intrude as several thinner tabular bodies throughout the pre-Jurassic stratigraphy, and with plutons of the Westcoast Crystalline Complex emplaced below both of the latter.

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