Ultramafic Rock Occurrences in the Jurassic Bonanza Arc near Port Renfrew (NTS 092C/09, 10, 15, 16), Southern Vancouver Island[1]

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KEYWORDS: Wrangellia, Vancouver Island, mapping, arc, plutons, ultramafic rocks

INTRODUCTION

Igneous rocks of Jurassic age on Vancouver Island, British Columbia represent an obliquely tilted section of island arc crust called the Bonanza arc. The structural depth of rocks exposed is currently uncertain. Recently, several isolated bodies of ultramafic rock were recognized by G. Pearson, a local prospector, within what are presumed to be the deeper levels of the arc in the area of Port Renfrew. Ultramafic rock outcrops, in many cases, correspond to strong anomalies in the regional aeromagnetic pattern, as well as soil anomalies for nickel and chromium in nearby streams. The extent to which ultramafic rocks are present in the Bonanza arc is potentially very significant, as they may be prospective for nickel and platinum group elements. During the summer of 2006, a field study was conducted as part of the first author's MSc thesis, in order to ascertain the extent of the ultramafic bodies, to determine their relationship to other rocks of the Bonanza arc and to address their economic potential.

FIELD AREA

The field area (Fig 1) is located approximately a two-hour drive northwest of Victoria, BC. The field area is bordered by the San Juan River in the south, Cowichan Lake in the north, Lake Nitinat and the Nitinat River to the west and northwest and the Fleet River to the east. Access to the area is provided by a network of variably maintained logging roads. Many of the roads that once accessed some of the more elevated, remote areas are badly overgrown. Overall, rock exposures are mainly concentrated along active logging roads. Exposure is best in elevated areas that have recently been logged.

REGIONAL GEOLOGY

Most of Vancouver Island is underlain by rocks of Wrangellia as originally defined by Jones *et al.* (1977). The 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 sediments of the Permian Buttle Lake Group (Massey and Friday, 1987). The Sicker Group is interpreted as an island arc that was active from Devonian to Permian time (Greene *et al.*, 2005). Overlying the Sicker Group are the Triassic Karmutsen basalt, a thick (~2500 m) sequence of subaqueous pillow lava, overlain by a few hundred metres of pillow breccia, which are themselves topped by another thick (~3000 m) sequence of subaerial sheet flows (Nixon *et al.*, 1993). The Karmutsen flood basalts may be an emergent ocean island built upon the extinct Sicker island arc (Greene *et al.*, 2005). Conformably overlying the Karmutsen basalt is a thin (<75 m) sequence of micritic limestone called the Quatsino Formation, which is itself conformably overlain by the Parsons Bay Formation, a 35 m thick sequence of thinly bedded argillaceous mudstone, limestone, siltstone and sandstone (Massey and Friday, 1987; Nixon *et al.*, 1995). The Jurassic Bonanza arc intrudes, as well as unconformably overlies, older units of Wrangellia.

Figure 1. Southern Vancouver Island, showing the field area of the present study (as outlined above). The grid outlines NTS sheets 092C, 092F, 092G and 092B (clockwise from lower left).

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

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Wrangellia on Vancouver Island have been recognized as the products of island arc magmatism, based on petrology and geochemistry (Isachsen, 1987; DeBari *et al.*, 1999). From base to top, these units include the West Coast Crystalline Complex, the Island Plutonic suite and the Bonanza Group volcanic rocks. Rocks in the field area have undergone zeolite to locally greenschist facies metamorphism, but the original igneous lithologies are used in their descriptions.

WEST COAST CRYSTALLINE COMPLEX

The West Coast Crystalline Complex has been interpreted as the deepest-preserved level of the Jurassic arc, based on its intrusive relationship with country rock that most often belongs to the Sicker Group (DeBari *et al.*, 1999). Sicker Group rocks, however, were not encountered anywhere in the field area south of Cowichan Lake. Plutonic margins in the West Coast Crystalline Complex tend to be concordant with the country rocks (DeBari *et al.*, 1999).

The complex is dominated by melanocratic to leucocratic quartz diorite and gabbro containing varying amounts of hornblende, biotite, orthopyroxene and clinopyroxene. Grain sizes vary locally from fine grained to pegmatitic. As noted by DeBari *et al.* (1999), West Coast Crystalline Complex diorite commonly contains inclusions of finer-grained mafic rock that range from well-defined, angular shapes to faint, wispy lenticular bodies. As well as sporadic granitoid intrusions, outcrops of diabase are found locally in the West Coast Crystalline Complex in the field area, southwest of the Gordon River. Directly to the north, two distinct bands of light grey marble occur as septa in the diorite. Similar marble outcrops are found in the eastern part of the field area, although these are more irregular in outcrop pattern. Minor magnetite-rich skarn bodies, with variably-developed diopside-garnet assemblages, are found at the contact with the marble. Due to the metamorphosed nature of these carbonate rocks, they are suggested to represent fragments and/or faulted slices of the Buttle Lake Formation, as opposed to recrystallized Quatsino limestone. Most significantly, the West Coast Crystalline Complex contains bodies of ultramafic rock, which are further described below.

Foliations within the West Coast Crystalline Complex, defined by planar fabric of hornblende, biotite or plagioclase, strike northwest and dip 60 to 75° degrees to the southwest. Roughly in the middle of the field area, a large area of Karmutsen basalt is juxtaposed with the West Coast Crystalline Complex along a shear zone with the same attitude as the pervasive foliation in the diorite. Shear zones defined by mylonite horizons within the West Coast Crystalline Complex have a similar orientation in the westernmost parts of the field area. The common orientation and sense of shear (tops to the northeast) for all these shear zones suggest that the West Coast Crystalline Complex is a series of east-verging thrust-faulted panels, the easternmost one of which has been thrust onto the overlying Karmutsen basalt.

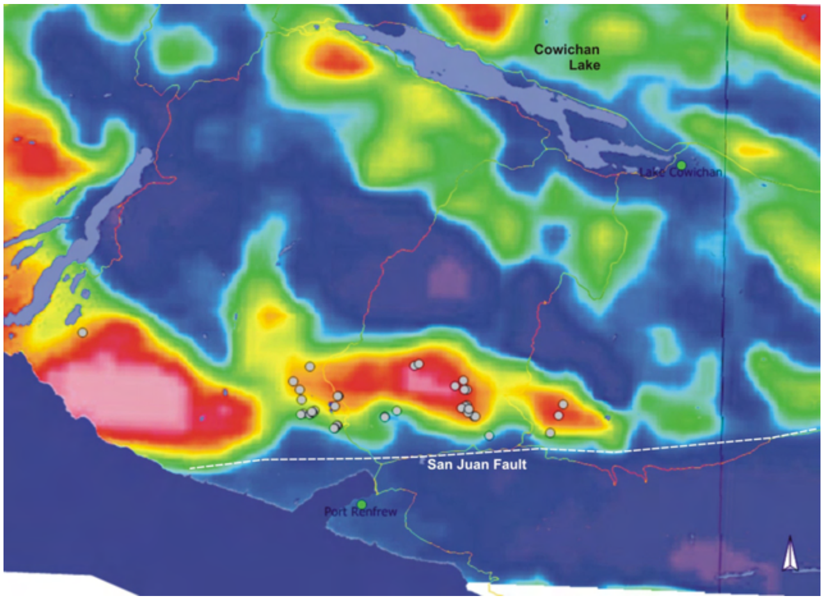

Figure 2. Regional aeromagnetic anomaly map of the field area (BC Geological Survey, 2006). Circles show locations of ultramafic-cumulate gabbro in outcrop.

Regional-scale aeromagnetic data available for southern Vancouver Island (Fig 2) 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 with areas underlain by West Coast Crystalline Complex rocks, but deviations from this general trend exist.

ISLAND PLUTONIC SUITE

The Island Plutonic suite occurs as a roughly northwest-southeast aligned series of plutons ranging from quartz diorite to alkali feldspar granite. As noted by DeBari *et al.* (1999), the Island Plutonic suite most commonly intrudes the Triassic Karmutsen basalt and is distinguished from plutons of similar composition of the West Coast Crystalline Complex by lacking any foliation (Muller *et al.*, 1981). Except where faulted, the contact between the Island Plutonic suite and the West Coast Crystalline Complex 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 West Coast Crystalline Complex to the southwest by intervals of Karmutsen basalt and Quatsino limestone.

BONANZA GROUP VOLCANIC ROCKS

The Bonanza Group volcanic rocks are only very weakly metamorphosed, displaying assemblages indicative of the zeolite facies (Massey and Friday, 1987) and vary from aphanitic basalt, through plagioclase, pyroxene and/or hornblende-phyric andesite to minor dacite. In addition to massive flows, the Jurassic volcanic rocks are also encountered as pillowed flows and flow breccia. Lesser pyroclastic deposits have been noted, with rhythmic banding of aphanitic felsic and mafic ash flows and fall deposits. The lateral extent and continuity of these deposits is obscured by vegetation and overburden. Similar rocks were noted by Nixon *et al.* (1995) in the Quatsino Sound region of northern Vancouver Island.

ULTRAMAFIC ROCKS

Previous Occurrences

Isachsen (1987) reports the occurrence of isolated bodies of gabbro and peridotite, containing up to 35% orthopyroxene and olivine, along Lemmens Inlet on Meares Island, northeast of Tofino. These bodies are associated with Isachsen's Westcoast amphibolite, Westcoast diorite and Westcoast migmatite subunits of the West Coast Crystalline Complex. Their nonfoliated nature and low grade of metamorphism led Isachsen to believe that they were younger than the West Coast Crystalline Complex rocks into which they intruded.

Contact Relationships

Ultramafic rocks occur as discrete bodies within the West Coast Crystalline Complex diorite, ranging in size from 1 m to several tens of metres. Although obscured by overburden, there is some lateral continuity of mineralogically distinct ultramafic bodies over distances of up to 1 km. Contact relationships between the ultramafic bodies and the West Coast Crystalline Complex diorite are quite variable. Smaller bodies, which tend to be more olivine-rich, have either abrupt, undeformed contacts with their host (Fig 3), or are present as sheared pods. Larger bodies, which are generally more gabbroic, grade into the melano and leucocratic diorites of the West Coast Crystalline Complex. In several locations, the association of olivine pyroxenite and pegmatitic hornblende diorite has been noted (Fig 4). Areas of the West Coast Crystalline Complex that host ultramafic rocks appear to correspond with the extreme magnetic highs (*see* Fig 2). The ultramafic bodies were first discovered using an aeromagnetic survey from 1972 (G. Pearson, *pers comm*, 2006). If the regional magnetic signal is controlled by the presence of ultramafic rock, there may be a significant amount of these rocks hidden within the West Coast Crystalline Complex.

Sample Descriptions

In outcrop, the ultramafic bodies are notoriously difficult to recognize, owing to their strongly weathered character. Often, a weathered outcrop containing peridotite can initially be mistaken as dark soil. The majority of the outcrop is commonly in an advanced stage of chemical weathering, with small patches of well-preserved rock dispersed throughout (Fig 5, 6). Peridotite and olivine pyroxenite outcrops weather to dun or chocolate brown and have fresh surfaces that are dark grey to black, often with large oikocrysts of amphibole and pyroxene enclosing subhedral olivine (Fig 7). The gabbroic outcrops weather to a dark brown or dun colour and are better preserved than their olivine-rich counterparts.


Figure 4. Olivine pyroxenite (far right, black) in association with pegmatite diorite (middle) and leucodiorite (left).

In thin section, the peridotite and olivine pyroxenite consist of variably serpentinized cumulus olivine with inclusions of euhedral spinel, poikilitically 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 (Fig 8).

Where present, amphibole appears as the result of reaction with pyroxene, along grain boundaries or along exsolution lamellae. The amphibole is of igneous origin as a deuteric alteration of anhydrous minerals during ad-


Figure 3. Sharp contact between ultramafic body and West Coast Crystalline Complex diorite.


Figure 5. Outcrop of mica peridotite. The majority of the outcrop has weathered to soil.

Figure 6. Peridotite sample with chemically altered outcrop in the background.

vanced crystallization of hydrous magma (*e.g.*, Beard *et al.*, 2005). Moreover, we would not expect the preservation of fresh olivine if these rocks were hydrated (to form amphibole) by metamorphism (*e.g.,* Fig. 9). Igneous phlogopite is also present as a minor phase in some samples.

Cumulate gabbro and gabbronorite display cumulus plagioclase, ±orthopyroxene, clinopyroxene and, in one case, olivine. Much of the postcumulus clinopyroxene has been replaced by amphibole (Fig 10). Plagioclase in these samples is invariably less altered than in the peridotite and olivine pyroxenite samples.

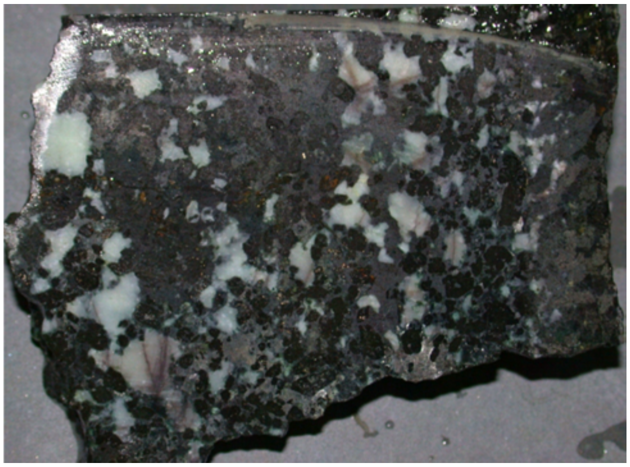

Figure 7. Cut slab of feldspathic olivine pyroxenite. Sample is approximately 10 cm across.

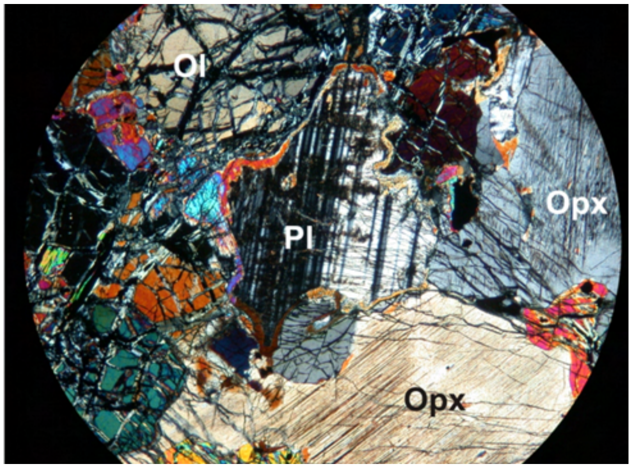

Figure 8. Photomicrograph showing intercumulus plagioclase (Pl) with cumulus olivine (Ol) and orthopyroxene (Opx) oikocrysts. Field of view is 2 mm across.

Magnetite with minor ilmenite exsolution is the dominant opaque phase in the ultramafic samples. It occurs as minor disseminated grains in the peridotite and olivine pyroxenite, and as both a euhedral and intercumulus phase in the gabbroic rocks (Fig 11). A euhedral, dark grey mineral with low reflectivity is present in peridotite and olivine pyroxenite samples, possibly chromite. Minor amounts of chalcopyrite are noted in most samples. Rare inclusions of round, white, high-reflectivity grains in olivine are noted, possibly pentlandite (Fig 12).

DISCUSSION

Ultramafic rocks occur in several different tectonic settings in the Canadian Cordillera, including ophiolite rocks, Alaskan-type intrusions and cumulates associated with calcalkaline intrusions in arc terranes (Nixon, 2003). The hydrous, calcalkaline nature of the parent magma that produced the ultramafic cumulates in the Bonanza arc, as attested to by the presence of primary amphibole, phlogopite and magnetite, is inconsistent with an ophiolite association. Furthermore, there is no spatial association of

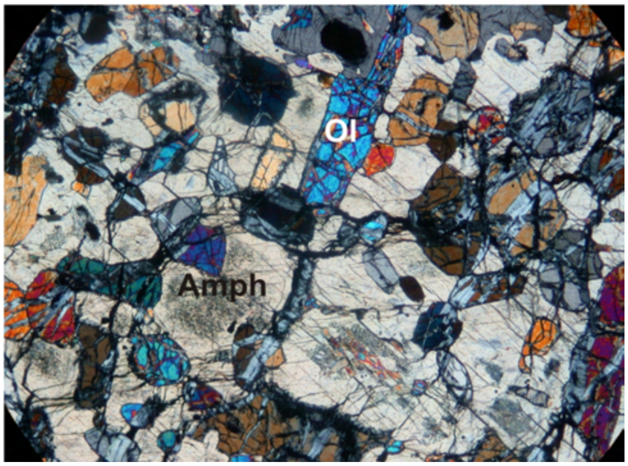

Figure 9. Photomicrograph of fresh cumulus olivine (Ol) enclosed by primary amphibole (Amph). Field of view is approximately 4 mm across.

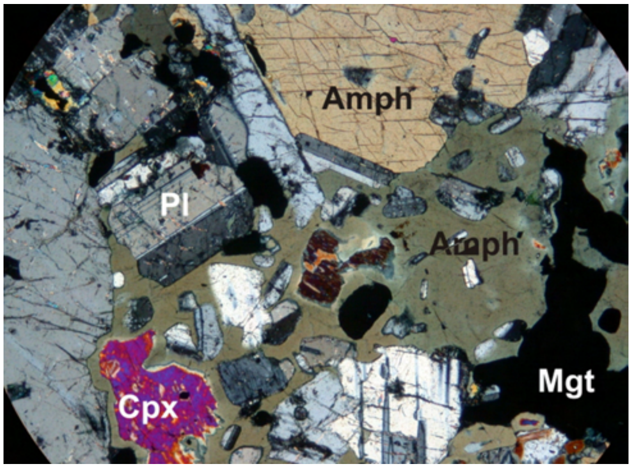

Figure 10. Photomicrograph of cumulate gabbro, with fresh cumulus plagioclase (Pl), amphibole (Amph), relict clinopyroxene (Cpx) and oxides (Mgt). Field of view is approximately 4 mm across.

mantle tectonite, pillow lava or sheeted dikes with the ultramafic bodies or their hostrocks.

Several lines of evidence also show that the ultramafic bodies are not of Alaskan-type affinity. First and foremost, orthopyroxene is a common phase in many samples, an observation that is inconsistent with Alaskan-type ultramafic occurrences (Taylor, 1967). Unlike the Alaskan-type situation, the parent magma from which the ultramafic bodies separated must have been silica saturated. In addition to the mineralogical evidence, field relations also argue against an Alaskan-type origin — the peridotite and olivine pyroxenite bodies lack any concentric zoning and occur as blocks and lozenges in diorite.

Strikingly similar petrography and field relations to the ultramafic rocks of the current study are known from the Giant Mascot deposit of southern BC. Nickel-copper-platinum group element sulphide ores at Giant Mascot are hosted by ultramafic rocks, including peridotite, pyroxenite and feldspathic pyroxenite (Metcalfe *et al.,* 2002). As in the current study, the Giant Mascot rocks contain cumulus spinel and olivine, poikilitically enclosed by orthopyroxene and amphibole (Metcalfe *et al.*, 2002).

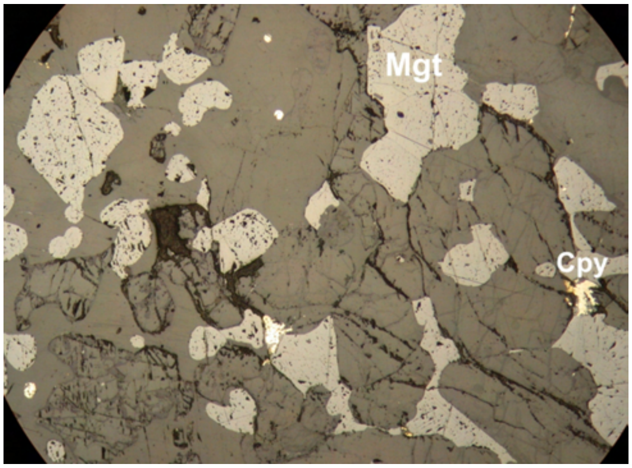

Figure 11. Photomicrograph showing euhedral and intercumulus magnetite (Mgt), with minor chalcopyrite (Cpy) in cumulate gabbro. Field of view is approximately 2 mm across.

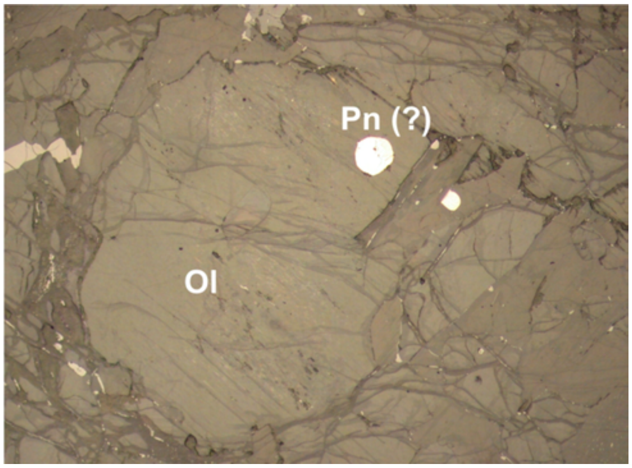

Figure 12. Photomicrograph of pentlandite (?; Pn) inclusion in olivine (Ol). Field of view is approximately 1.5 mm across.

Based on spinel chemistry, the Giant Mascot cumulates have been interpreted as fragments of the root zone to the tholeiitic Karmutsen basalt that were sampled by the Spuzzum diorite (Nixon, 2003). The hydrous nature of the cumulates is explained by Metcalfe *et al.* (2002) as the result of anatexis of metapelitic wallrock, causing dehydration and thereby introducing water into the magma. Although chemical data is pending for the current study, it is difficult to reconcile the presence of primary magnetite and amphibole in the Bonanza ultramafic rocks with the tholeiitic nature or the anatectic processes evident in the Giant Mascot rocks. In the Port Renfrew area, the presence of fresh olivine in amphibole oikocrysts rules out a metasomatic origin for the latter and there is no field evidence for the assimilation of hydrous or pelitic country rock.

Peridotite and pyroxenite are noted to occur in association with gabbronorite towards the middle and base of crust in exhumed island arc terranes in the Cordillera and elsewhere (*e.g.*, Burns, 1985; Takahashi *et al.*, 2006). For example, an oblique section of arc crust exposed in the Kohistan Terrane of northern Pakistan contains peridotite, anorthosite, troctolite and olivine gabbro cumulates, within a larger body of granoblastic diorite and gabbronorite. (Takahashi *et al.,* 2006).

The Bonanza arc and its setting 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). In the Talkeetna arc, ultramafic cumulates are present in large but sporadic occurrences at the base of the arc crust section, in contact with mantle harzburgite and dunite (Burns, 1985; DeBari and Coleman, 1989). The ultramafic cumulates in the Talkeetna arc section are thought to be genetically linked to the more evolved magmatic rocks of the arc (DeBari and Sleep, 1991). In the Tonsina assemblage, a part of the Talkeetna arc, peridotite and pyroxenite bodies occur in association with cumulate garnet-bearing gabbro, which grades into cumulate gabbronorite containing Fe and Ti oxides (DeBari and Coleman, 1989). Plagioclase is present as a late postcumulus phase and never coexists with olivine (DeBari and Coleman, 1989; DeBari and Sleep, 1991). While amphibole is present in the peridotite and pyroxenite primarily in the form of reaction rims on pyroxene, it appears to be a major postcumulus phase in the overlying gabbroic cumulates (DeBari and Coleman, 1989). These petrographic relationships are strikingly similar to ultramafic cumulates from our field area. We suggest that the ultramafic rocks found within the West Coast Crystalline Complex represent cumulates from a primitive (parent?) Bonanza arc magma. There may be a melt-residue relationship between the West Coast Crystalline Complex diorite and the ultramafic cumulates, the latter having been entrained in the former during emplacement.

FUTURE DIRECTIONS AND ECONOMIC POTENTIAL

Whole rock geochemical analysis for major and selected trace elements will further elucidate the origin of the ultramafic and related plutonic rocks in the Port Renfrew area. In addition, geochronological investigations are underway to constrain the age of rocks that host the ultramafic bodies, as well as to constrain the igneous history of this portion of the Bonanza arc. All of the ultramafic samples collected have been sent for assay. In addition, the Ni concentration of olivine will be investigated in peridotite and olivine pyroxenite samples to test if they were in equilibrium with Ni-sulphide. This may shed light on the prospectivity of the ultramafic bodies for Ni-Cu or PGE sulphide, both in the Port Renfrew field area and elsewhere in the West Coast Crystalline Complex.

The majority of the ultramafic bodies are no more than a few tens of metres wide. Although it is discontinuous at the surface, the ultramafic outcrops tend to be distributed in patches throughout the West Coast Crystalline Complex. Geophysical investigations may reveal continuity between these or other ultramafic bodies at depth. No significant concentrations of economic minerals were noted in outcrop, hand sample or thin section, apart from minor Cu and Ni sulphide minerals. Nonetheless, the West Coast Crystalline Complex is exposed along most of western Vancouver Island and the findings of Isachsen (1987) on Meares Island suggest that ultramafic bodies are likely to be present elsewhere throughout the West Coast Crystalline Complex on Vancouver Island, possibly associated with concentrations of Ni-Cu sulphide minerals.

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