A transect of the Pacific Rim – Wrangellia terrane boundary

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Introduction

The aim of this one day field excursion is to examine the boundary between two regionally extensive tectonostratigraphic terranes: Wrangellia and the Pacific Rim. The trip consists of an on-foot traverse from Harling Point (site of the historic Chinese Cemetary) in the east, west along southern coast of Vancouver Island to Holland Point, a straight-line distance of about 5 km, and from there north to the Inner Harbour (Fig. 1).

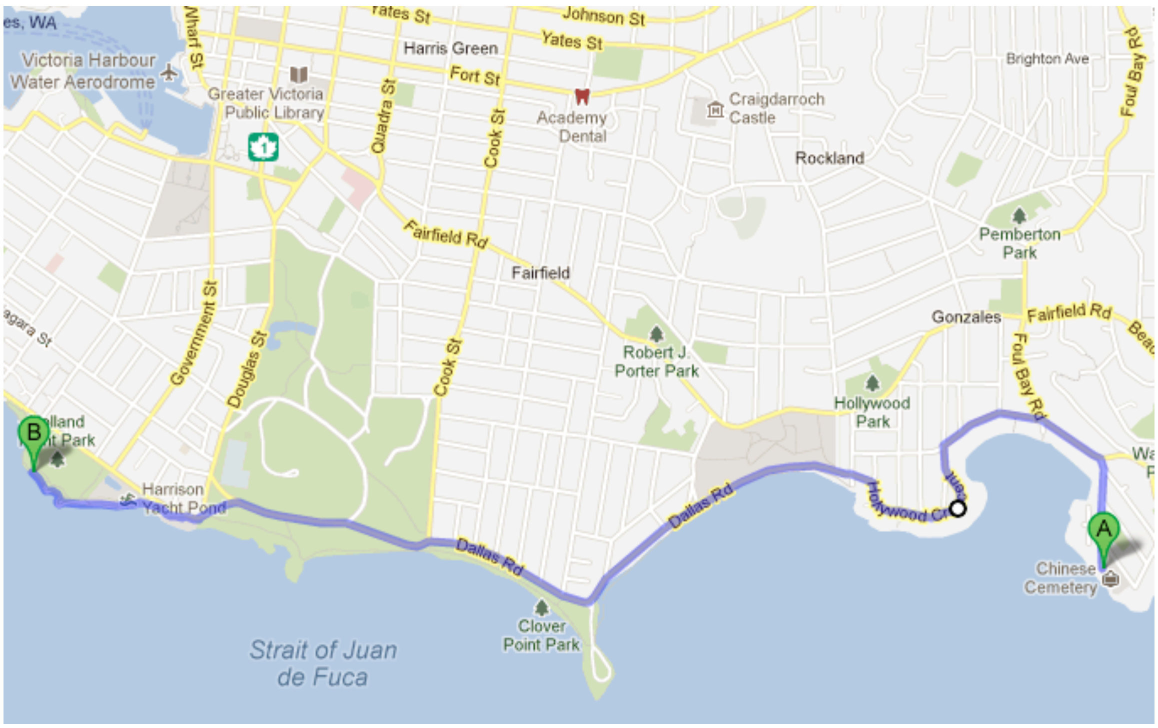

Figure 1- Field Trip route. A – Harling Point (starting location), B – Holland Point. From Holland Point we traverse north along Menzies St. to the Inner Harbour, and then along Wharf Street ending at Swan's Pub on the corner of Pandora and Wharf (Stores) street.

Regional Geology (from Johnston & Acton, 2003; Canil et al., 2012; McEwen, 2013). The North American Cordillera consists of a collage of terranes accreted to one another and to the North American margin between Permian and Miocene time. Vancouver Island is located within the westernmost portion of this orogen, and is divisible into three terranes: Wrangellia, Pacific Rim and Crescent (Figs. 2 and 3). Wrangellia, one of the largest of the accreted terranes within the Cordillera, underlies 90% of Vancouver Island, includes rocks of Devonian to Jurassic age. Post Middle Jurassic - pre-Late Cretaceous

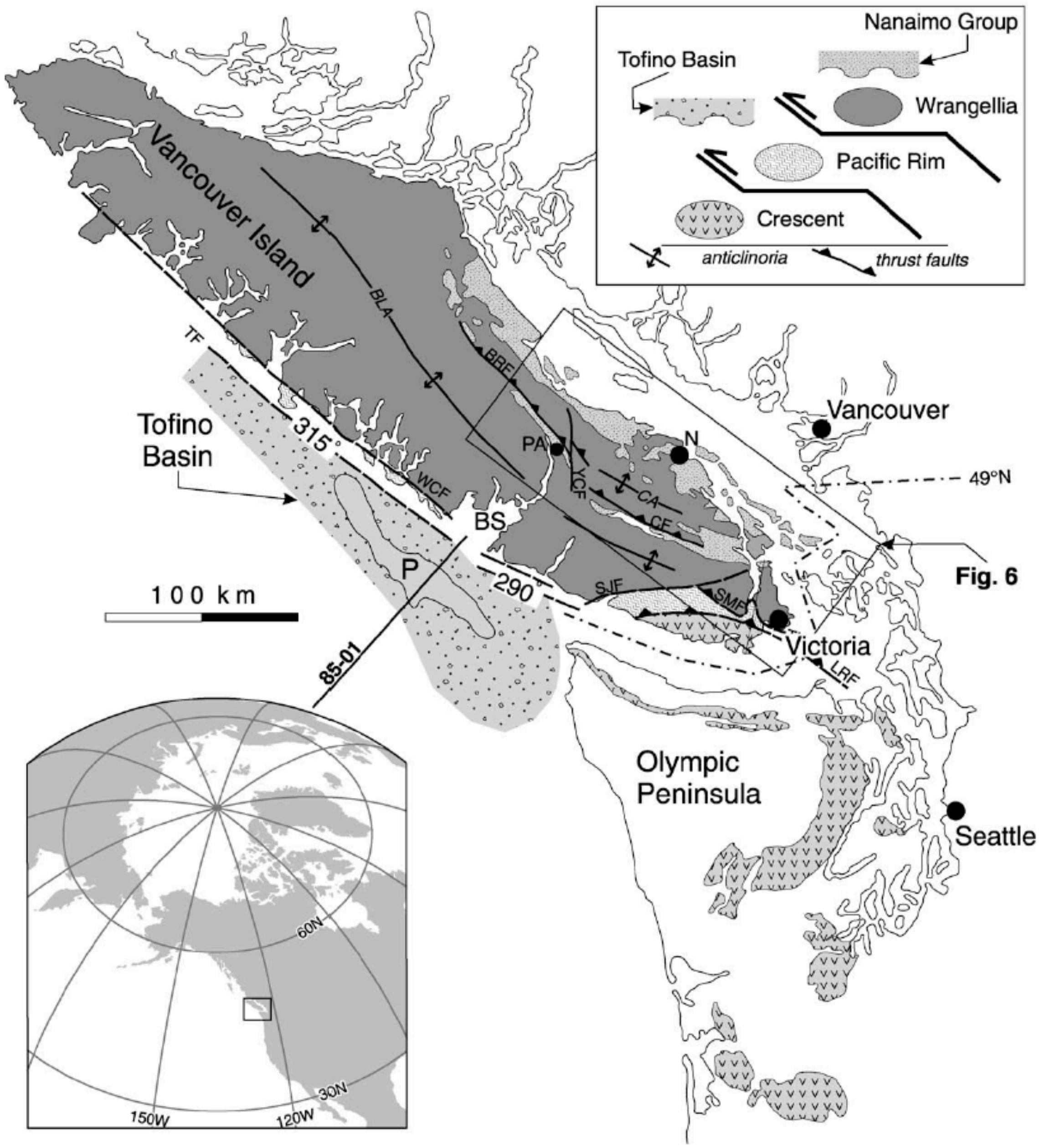

Figure 2 – Regional geology of Vancouver Island. Faults include the West Coast (WCF), Tofino (TF), San Juan (SJF), Survey Mountain (SMF), Trial Island (TIF), Beaufort Range (BRF), Yellows Creek (YCF), Cowichan (CF) and Leech River (LRF). Two anticlinoria, the Buttle Lake (BLA) and Cowichan (CA) are indicated. The Tofino Basin is characterized by the Prometheus (P) magnetic anomaly. Cities indicated include Port Alberti (PA) and Nanaimo (N). A location map is shown at lower left.

deformation, including the development of northwest– southeast trending anticlinoria (Buttle Lake and Cowichan – Fig. 2) provide a record of the mid-Cretaceous accretion of Wrangellia to the autochthon. Marine conglomerate, sandstone and shale of the Nanaimo Group underlie southeastern Vancouver Island and much of the adjacent Gulf Islands, and were deposited unconformably on Wrangellia in the Late Cretaceous (Muller and

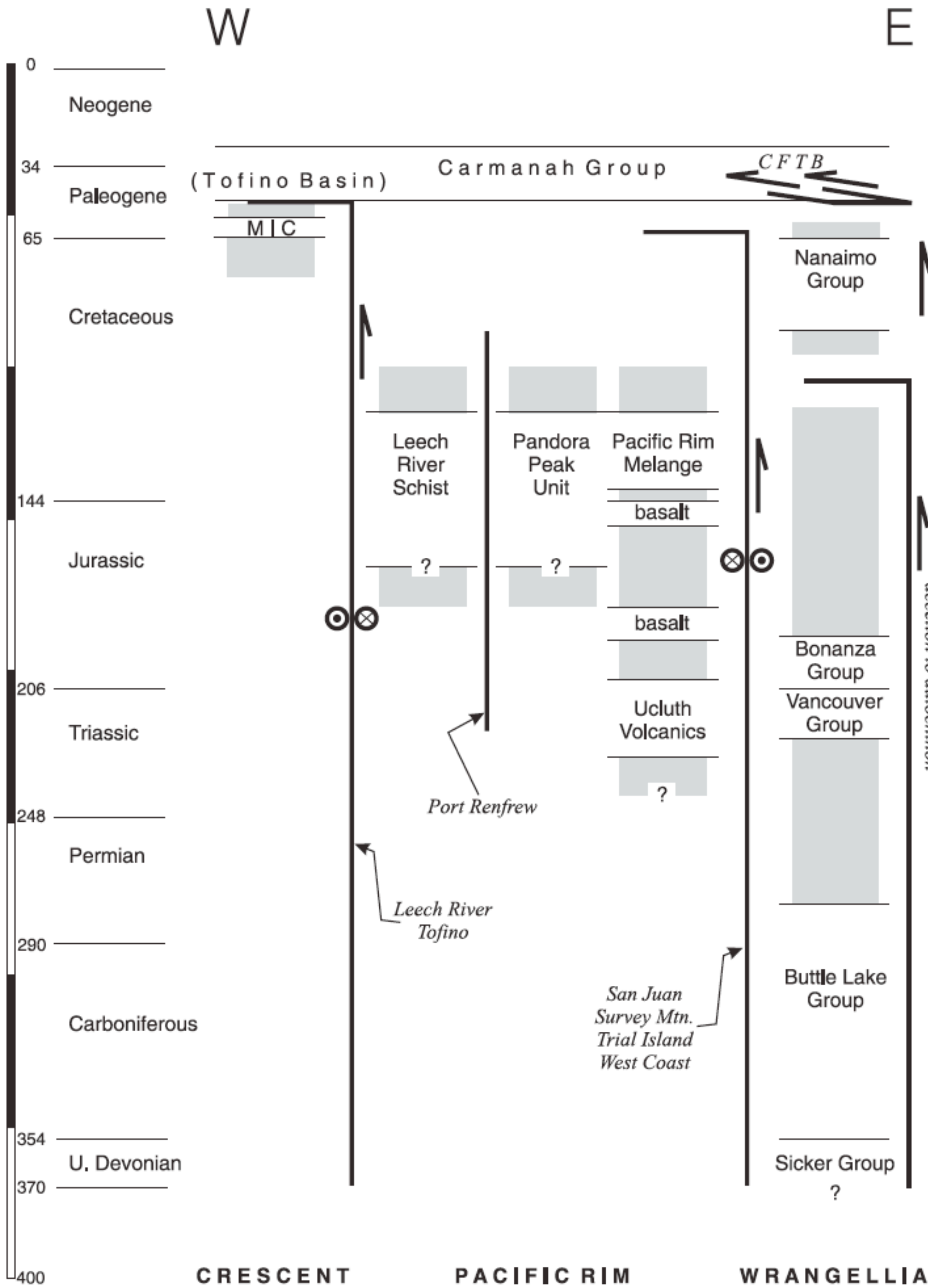

Figure 3 – Stratigraphic columns for Wrangellia, the Pacific Rim and Crescent terranes. Shown schematically are the faults along which the terranes are inferred to have been juxtaposed, and the timing of the accretion events. CFTB – Cowichan fold and thrust belt; MIC – Metchosin Igneous Complex.

Jeletzky, 1970). North northwest-trending, west-verging folds and faults, collectively referred to as the Cowichan fold-andthrust belt (England and Calon, 1991), have shortened and thickened the Nanaimo Group strata and the underlying basement. Normal faults in the Port Alberni region, such as the Yellows Creek fault (Fig. 1) cut Nanaimo Group strata and offset older thrust faults, and are interpreted to be coeval with minor Eocene felsic magmatism (Yorath et al., 1999). Northeast-verging thrusts appear to cut older west-verging thrusts of the Cowichan fold and thrust belt and may be the result of younger Neogene crustal shortening (Journeay and Morrison, 1999).

The southern and southwest-most coastal regions of Vancouver Island are underlain by rocks of the Pacific Rim and Crescent terranes. The Pacific Rim terrane occurs west and south of Wrangellia and consists of Triassic–Jurassic arc volcanics and Jurassic–Cretaceous melange (Brandon, 1989) and, between the Leech River and San Juan faults, marine sedimentary rocks, pillow basalts and amphibolite (C. Yorath, written communication, 2002; Figs. 1 and 2). The Crescent terrane, a Paleocene to Early Eocene oceanic assemblage of basalt flows, breccia, tuff and volcanic sandstones cut by gabbro and diabase intrusions, lies outboard (southwest) of the Pacific Rim terrane (Massey, 1986). Several lines of evidence suggest that the Crescent terrane originated as a series of seamounts formed above a hotspot (Duncan, 1982; Johnston and Thorkelson, 2000). These include the presence of subaerial flows (Massey, 1986), the occurrence in the Olympic peninsula to the south of Vancouver Island of 12–16 km thick sequences of basalt, and geochemical studies indicating derivation in part from an enriched mantle source (Babcock et al., 1992). Accretion of the Crescent terrane pre-dates or is coeval with the deposition of undeformed sandstone and conglomerate of the latest Early Eocene to Oligocene Carmanah Group that unconformably overlies and stitches the Crescent, Pacific Rim and Wrangellia terranes. The Pacific Rim and Crescent terranes have been interpreted as thin east-tapering thrust sheets 7 km thick for the Crescent terrane, and 10 km thick for the Pacific Rim terrane, that were offscraped from a subducting slab and now structurally underplate Wrangellia (Hyndman, 1995; Calvert, 1996; C. Yorath, written communication, 2002). Basaltic rocks that form the floor of the Eocene Tofino basin west of southern Vancouver Island are responsible for the prominent Prometheus magnetic anomaly (Fig. 1) and are correlated with the Crescent terrane (Hyndman, 1995). Accretion must therefore have predated or have been coeval with the Eocene initiation of basin formation.

Our focus is the contact between Wrangellia and the Pacific Rim terranes in Victoria. Two main units, the West Coast Crystalline Complex and the Island Plutonic suite, comprise Wrangellia in the Victoria region. Together these units are interpreted as a intrusive products of the Jurassic 'Bonanza' magmatic arc. The West Coast Crystalline complex (formerly the Wark and Colquitz gneisses) has been interpreted as a part of the middle crust (DeBari et al., 1999a; Larocque and Canil, 2008) and is a heterogeneous mixture of mostly diorite and quartz diorite, with lesser granodiorite crosscut by intrusions of leucotonalite. In the diorite, recent studies have recognized decameter- to rarely kilometer-scale bodies of conformable but discontinuous hornblende gabbro, pyroxenite, olivine hornblendite, and peridotite with cumulate textures (Larocque, 2008; Larocque and Canil, 2007, 2010; Marshall et al., 2007). Intrusive relationships in the

West Coast complex are heterogeneous on all scales, and levels of strain vary within meters in outcrop (Isachsen, 1987). The Island plutonic suite occurs as a series of unfoliated quartz diorite to alkali feldspar granite plutons, with rare diorite and gabbro. The contact between rocks previously mapped as the Island plutonic suite and the West Coast complex is not defined, and to some degree the distinction between these two units is obscure.

Published U-Pb ages for rocks of Bonanza arc vary between 202 and 168 Ma (Nixon and Orr, 2007a) with a weak eastward younging trend on Vancouver Island (DeBari et al., 1999a). There is no information on the age of mafic and ultramafic rocks in the West Coast complex.

Across southern Vancouver Island, the Pacific Rim terrane is divisible into the Leech River Schist and the Pandora Peak unit (Groome et al., 2003; Rusmore and Cowan, 1985). Broadly, the Leech River schist consists of a metamorphosed turbiditic sequence. A maximum depositional age is provided by mid-Cretaceous detrital zircons (Groome et al., 2003). The Pandora Peak unit consists of a mix of argillite, phyllite, weakly to moderately foliated metapelites, meta-sandstone, minor meta-volcanic rocks, chert and conglomerate (Rusmore and Cowan, 1985). Within this classification scheme, the Pacific Rim terrane rocks in Victoria are of uncertain affinity. Muller (1983) interpreted the Harling Point succession as Jurassic volcanic rocks of the Bonanza arc, whereas more recent studies (Rusmore and Cowan, 1985) included them within the Pandora Peak unit. Structurally, the Pacific Rim rocks are inferred from regional studies to lie structurally beneath the West Coast Crystalline complex, however, locally they have been mapped as an isolated block bound by outward-dipping normal faults that have dropped down the adjacent crystalline rocks of Wrangellia (Muller, 1983).

Stop 1 – Harling Point

The Harling Point outcrop is divisible into three distinct units: a strained and altered pillow basalt; an altered, light green, laminated (hyaloclastitic?) basalt; and an argillaceous block-in-matrix sedimentary mélange unit with minor carbonate (Fig. 4). Limestones, greywacke and volcanic rocks inferred to have been derived from the adjacent units occur as olistoliths and in the matrix in the argillite unit. The basaltic units have been metamorphosed to greenschist facies with epidote and chlorite replacing primary plagioclase and pyroxene.

This tripartite package is multiply folded. The oldest folds (F_1), best seen along the southern portion of the NW region, are isoclinal and recumbent, and are sub-horizontal to locally shallowly east-plunging. At the northwest end of the outcrop, F_1 closes to the south with pillow basalt eclosing the hyaloclastite. To the southeast end of the exposure the hyaloclastite encloses the sedimentary unit. Thus, the stratigraphic sequence is inverted with the youngest unit, the mélange, at the deepest structural level. The implication is that Harling Point rocks are in the overturned limb of a north-verging thrust nappe (Figs. 5, 6).

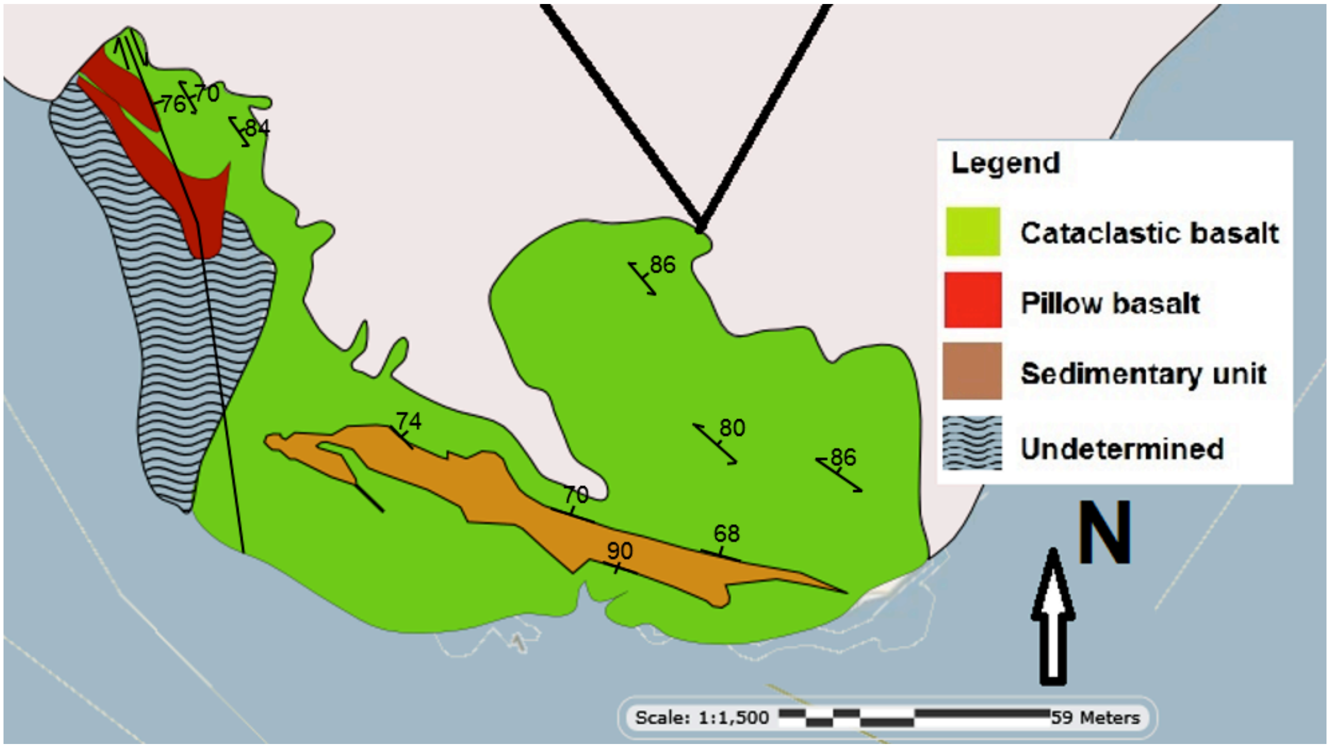

Figure 4 – A geological map of the Harling Point exposure of the Pacific Rim Terrane.

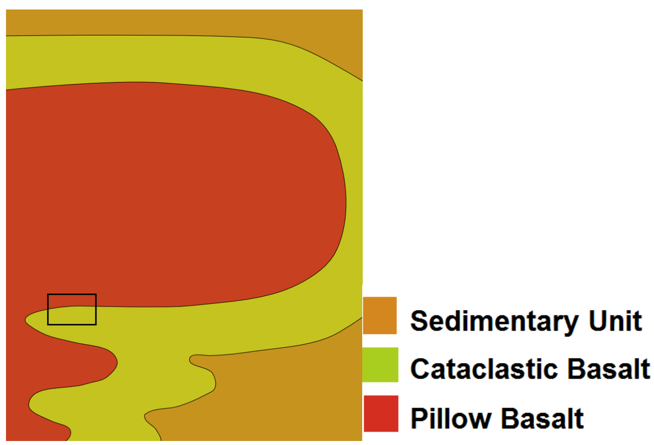

Figure 5 – A schematic cross-section shown looking to the west showing the inferred geometry of the F1 nappe prior to subsequent folding. The rectangle indicates the approximate location of the west end of the Harling Point exposure where the pillow basalt unit encloses the hyaloclastitic basalt unit. The geometry of the nappe implies that it was emplaced to the north (to the right).

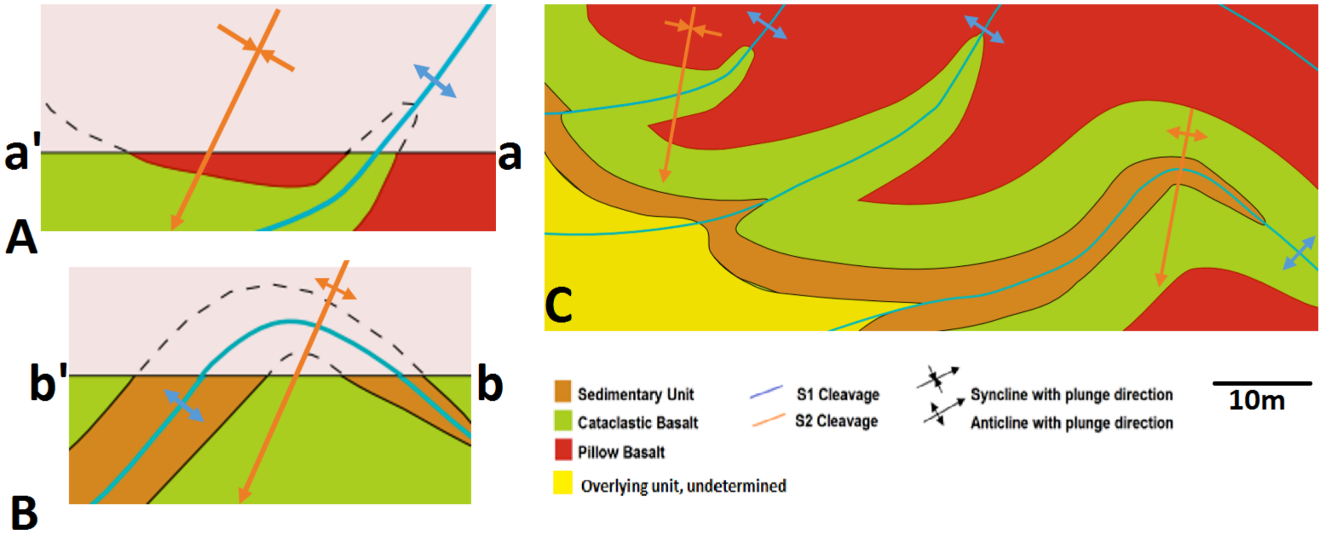

Figure 6 – Downplunge projection (looking east) of: (A) the syncline at the west end of Harling Point and (B) the anticline at east end; looking southeast showing orientations of refolded S_1 cleavage planes. S_2 cleavage (orange line) strikes E-W and dips 70-80^0 toward the north. (C) Suggested fold pattern linking the east and west segments showing S_1 cleavage (blue lines), refolded into south verging asymmetric open folds. Overlying unit (yellow) is not in outcrop at Harling Point but is included here to maintain consistent layer thickness in the Sedimentary Unit.

A second phase of folding (F_2) is indicated by folding of the axial surfaces (S_1) of the F_1 folds. The F_2 folds are south-verging and asymmetric with a long, shallowly north-dipping limb and a short, steeply south-dipping limb. S2 cleavage plane are characterized by dextral kinematic indicators; either F2 folding was transpressional or the S2 cleavage was subsequently reactivated during dextral shearing. The F1 and F_2 axes are roughly coaxial despite F1 being characterized by top to the north vergence, while F2 yields top to the south vergence. Change in the orientation of the S_2 cleavage from NNW-striking in the northwest, to WNW-striking in the southeast implies late open folding about a steeply-plunging F_3 fold axis, possibly a reflection of oroclinal buckling of southern Vancouver Island (Johnston and Acton, 2003).

Stop 2 – Gonzalez Bay

From Harling Point we proceed on foot 1 km north and then northwest along Crescent road, turning left at Foul Bay Road where we descend a steep staircase down to Gonzalez Bay. Immediately to left (to the east) is an exposure of the argillaceous block in matrix mélange characterized by an S2 cleavage striking ~300 and dipping steeply to the NNE. Resistant, high standing bluffs of the laminated hyaloclastitic basaltic unit are exposed along Crescent Road to the north indicating that the argillite mélange dips north beneath the hyaloclastite. We interpret this relationship as the an overturned limb along an asymmetric, south-verging F2 fold along the upright lower limb of the F1 nappe observed at stop 1.

Follow the beach along to the west. Melange and laminated hyaloclastite crop out along the west side of the bay and are faulted against amphibolite along a steeply-dipping east-west striking brittle fault. Access to the fault is limited by the tides and may not be accessible due to a high tide.

Stop 3 – Hollywood Point East

Return to the Gonzalez Bay beach and climb the stairs at the west end of the beach to Ross Street where toilet facilities can be found. From there we continue west along Ross Street, then south on Robertson, bearing left on Hollytwood Crescent. Watch for the beach access on your left. Descend down the stairs to the coast, and then left around the point abutting the west entrance to Gonzalez Bay.

Flagging, flat-lying to east to north-east dipping, foliated to finely laminated meta-volcanic and meta-clastic (?) sequence of rocks characterized by intrusive (?) lenses of hornblende diorite and by sheath-folds. These rocks are mapped as part of the West Coast Crystalline Complex and are inferred to have been downdropped against the Pacific Rim Rocks of Gonzalez bay along a normal fault (Mueller, 1983). However, this sequence is structurally coherent with and plunges east beneath the Pacific Rim rocks to the east, and is lithologically similar to parts of the Pacific Rim terrane observed in Gonzalez Bay and Harling Point. The most obvious problem with interpreting these rocks as a structurally coherent continuation of the Pacific Rim terrane lies in the metamorphic grade: little metamorphosed argillite exposed in Gonzalez bay is difficult to reconcile with the ductile deformation and metamorphic grade of these rocks. None the less, we interpret these rocks as metamorphosed equivalents of the sequence observed at Harling Point.

Stop 4 – Hollywood Point

Return to Hollywood Crescent and continue west to the next public access point where we will descend back down onto the coastal exposure.

Meta-clastic rocks exhibit ductile deformation and include boudins of amphibolitic gneiss. Note the continued overall northeast-dip indicating that as we traverse to the west we continue to descend to deeper structural levels. Can the increase in metamorphic grade be explained as a result of the descent to deeper structural levels? Regardless, the inferred structural stack of little metamorphosed Pacific Rim terrane beneath the crystalline rocks of Wrangellia is inconsistent with the east to northeast dip of this metamorphic sequence beneath the Harling Point rocks to the east.

Continue along the coast to the west, rounding the point abutting the east end of Ross Bay. Note the abundant marble and meta-limestone interfoliated with the meta-clastic rocks. Limestones are bound by calc-silicate mantles consistent with metamorphism of a carbonate bearing volcano-sedimentary sequence, and distinguishing these rocks from the West Coast Crystalline Complex.

Stop 5 – Clover Point

Return to Hollywood Crescent / Dallas Road and continue west 1.5 km to Clover Point. Rocks exposed along the east side of the point are the flaggy, limestone / calc-silicate bearing metamorphic sequence. Cross the point at the boat house. Rocks along the west side of the point are flaggy mylonites characterized by a locally well-developed north-plunging mineral- and rodding lineation. The mylonites are buckled about shallowly east-plunging axes into asymmetric, south-verging folds inferred to be a continuation of the F2 folds observed at Harling Point. F2 axes are perpendicular to the L1 lineation implying that the two are kinematically linked. Protoliths are massive felsic to mafic granitoids and are interpreted as the strained equivalents of the massive and little deformed intrusive rocks of Wrangellia exposed to the west. Pope interpreted these mylonites as a basal thrust fault along which the overlying metamorphic sequence, which he included in the Pacific Rim terrane, was emplaced above the crystalline rocks of Wrangellia (Fig. 7). Subsequent F2 folding explains the distribution of the mylonites and the overlying metamorphic complex.

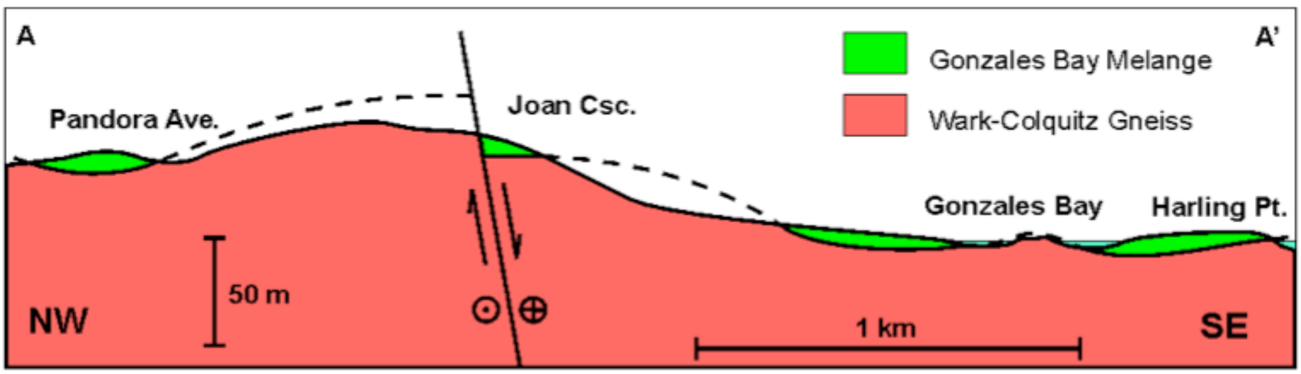

Figure 7 – Cross-section looking east showing the mélange / metamorphic unit cropping out above the West Coast Crystalline complex. The contact is characterized by a package of mylonitized granitoids as is well illustrated at Clover Point. The mylonite descends irregularly to the south as a result of asymmetric south-verging F2 folds which are characterized by long, shallowly-dipping north limbs and steep to locally overturned south-dipping southern limbs. From Matt Pope.

Stop 6 – Finlayson Point

Follow the coastal path west from Clover Point along the top of the south-facing bluff. Dog lovers – enjoy Victoria's largest off-leash area. Dog haters – WATCH OUT! Continue 1.25 km along path to Finlayson Point. Descend stair-case to beach and continue 50 m to the west. Intrusive complex mapped by Muller as part of the Wark-Colquitz complex. Mafic, finely crystalline biotite-horblende diorite and more coarsely crystalline biotite granodiorite. Agmatic textures are common, as a range of compositions. Continue west along the coast. Watch for bimodal dykes that intrude intermediate granitoids. This intrusive complex is now interpreted as the intrusive root of the Early Jurassic Bonanza arc.

Stop 7 – Holland Point

Continue to the west, around a sharp bay and then ascend the green stair case back up to the bluff-top path. Continue west and then back down the stairs across from Paddon Ave to Holland Point.

The Holland Point exposure was previously interpreted as belonging to the Devonian Saltspring Intrusive suite. To the north along the Malahat a similar intrusion has been dated by U-Pb methods at 400 to 370 Ma and was considered to be the oldest rock exposed on Vancouver Island. Subsequent geochronological studies have, however, shown that the Devonian age determinations are attributable to inheritance and the entire suite is now considered to be Early Jurassic. The outcrop at Holland Point is a good example of mafic-felsic magma intermingling shown by "pillows" of amphibolite set in quartz diorite selvages. Similar fabrics are recognized in many felsic-mafic magma complexes and show "way up" indicators (Weibe). Younger igneous events are represented by hornblende and plagioclase-phyric dikes which crosscut the Holland Point leucogranite. Note the locally well-developed layering that dips steeply to the west. Interpretation of the layering as originally vertical dyke-like structures implies that the crust here is tilted to the east, consistent with the over-all east plunge of the entire section.

Stop 8 – Swan's

Climb the stairs back up to the coastal path and follow it along to Dallas road. Cross Dallas road and head north on Menzies Street to the inner harbor. Round the harbor and proceed along Wharf street to Pandora. Enter Swan's Pub and order a pint of Extra IPA.

Note from STJ: This is an informal field guide. It is not fully referenced, has not been adequately proof-read, is published without having been approved by my co-authors, and is meant as a working document. In addition, large parts of this guide were liberally plagiarized from my publications and those of my co-authors and students.