INTRODUCTION

Rocks and structures of the San Juan Islands of northwest Washington record a long and complex history related to Cordilleran convergent margin tectonism. The area is underlain by the San Juan Islands–northwest Cascades thrust system, made up of nappes a few kilometers or less thick and up to 100 km in breadth (Figs. 1, 2), thrust onto the continental margin during mid-Cretaceous time (e.g., Misch, 1966; Brown, 1987; Brandon et al., 1988). The nappes have an oceanic history, indicating accretion to the edge of the North American continent, but they also bear clear evidence of interaction with the continental margin long preceding their emplacement in Washington. Their mid-Cretaceous arrival in Washington as thrust sheets was likely the consequence of some type of post-accretionary fragmentation and dispersal. The timing and mechanisms of the accretion, dispersal and final emplacement of terranes of the San Juan Islands–northwest Cascades thrust system are poorly known and have been the focus of our recent work.

Many aspects of the lithology, structure, and metamorphism are similar to the Mesozoic evolution of other parts of the Cordillera; other aspects may be unique to the San Juan Islands. The east-west transect across the San Juan Islands during this field trip will highlight the different terranes juxtaposed by the thrust system, and structures formed before, during and after high-pressure–low-temperature (HP-LT) metamorphism. The trip builds on earlier work that identified the main terranes and structures in the San Juan thrust system (e.g., McClellan, 1927; Danner, 1966; Vance, 1975; Whetten et al., 1978; Brandon et al., 1988). Our recent results on structure, metamorphism, geochronology, and paleomagnetism will provide a forum for discussions that bear on the tectonic history and correlation with other Cordilleran terranes. We will compare and contrast units from the external, unmetamorphosed parts of the thrust system to the more internal...
units that experienced subduction and HP-LT metamorphism. In particular, we would like to consider how the geology of the area relates to various hypotheses regarding the origin and paleogeography of the terranes, and the evolution of deformation before, during, and after emplacement in their current location.

TECTONIC SETTING

The San Juan Islands—northwest Cascades thrust system lies at the south end of the 1500 km long Coast Plutonic Complex, a belt of continental arc plutons and metamorphic country rock that formed from Late Jurassic to Early Cenozoic (Figs. 1, 2). Outboard of the Coast Plutonic Complex and intruded by it is the Insular superterrane composed of the co-joined Wrangellia and Alexander terranes. Inboard of the Coast Plutonic Complex are rocks of the Early Cretaceous continental margin, including the Methow stratigraphic sequence in Washington. Detritus, current indicators and stratigraphy in the Methow sequence indicate absence of an outboard sediment source until ca. 110 Ma (Tennyson and Cole, 1978; Haugerud et al., 2002), thus we view the locale of the Washington Cascades and San Juan Islands as an ocean basin until that time. Major orogenic activity characterizes the region from ca. 110–80 Ma, during which nappes of the San Juan Islands—northwest Cascades thrust system were emplaced, the Coast Plutonic Complex was intruded by voluminous arc plutons, and country rock of the complex was locally buried to depths of up to 35 km (in the “Cascade crystalline core”; Figs. 2 and 3) and was deformed by orogen-normal and orogen-parallel displacements. Overlapping the waning stages of this orogenic pulse was development of the Nanaimo stratigraphic sequence, bearing detritus from the San Juan Islands—northwest Cascades thrust system as well as from the Coast Plutonic Complex, in an elongate basin extending north from the San Juan Islands. In Eocene time the orogen was cut obliquely and displaced ~170 km (estimates range from 90 to 190 km; e.g., Vance, 1985; Misch, 1977) by the N-S dextral, strike-slip Straight Creek–Fraser River fault system. Restoration of the fault shows the San Juan Islands—northwest Cascades thrust system to have lain along the southern margin of Wrangellia and the Coast Plutonic Complex (Fig. 3)
Figure 2 (on this and following page). San Juan Islands–northwest Cascades thrust system and surroundings. Based on compilation by Brown and Dragovich (2003) and references therein. Abbreviations given in Table 1. (A) Map. B.C.—British Columbia; WA—Washington.
in Late Cretaceous time. South of this orogenic complex is the Columbia Embayment, an area covered primarily by Cenozoic volcanic rocks, thought to be underlain by primitive crust, and considered in some models to be a possible homeland for the thrust system nappes (e.g., Davis et al., 1978; Vance et al., 1980). East and south of the Columbia Embayment are accreted terranes of the Blue Mountains, and Klamath Mountains respectively (Fig. 1), the latter especially bearing similarities to units of the San Juan Islands–northwest Cascades thrust system.

**STRUCTURAL STRATIGRAPHY**

The nappe pile of the San Juan Islands–northwest Cascades thrust system (Fig. 2) is characterized by mid to late Paleozoic terranes overlain by Mesozoic terranes. The structurally lowest component of the nappe complex is the East Sound Group in the San Juan Islands and correlative Chilliwack Group in the Cascades. These are island arc derived sedimentary and volcanic rocks of Devonian–Permian age (Danner, 1966; Vance, 1975; Misch, 1966; Tabor et al., 2003). Calc-alkaline Devonian plutonic rocks presumed to be related to this arc are the Turtleback and Yellow Aster Complexes of the San Juan Islands and Cascades, respectively (Mattinson, 1972; Whetten, et al., 1978; Brandon et al., 1988; Tabor et al., 2003). This assemblage is likely related to arc rocks that extend from California to northern British Columbia and mark mid-late Paleozoic convergence along the continental margin (McCloud belt of Miller, 1987).

Higher in the nappe pile, in both the San Juan Islands and Cascades, is a disrupted section including Permian to Jurassic ribbon chert, Permian HP-LT schist, ocean island basalt, Permian limestone bearing Tethyan fusulinids (exotic to North America), and other materials (Fig. 2, Table 1). This assemblage is likely related to arc rocks that extend from California to northern British Columbia and mark mid-late Paleozoic convergence along the continental margin (McCloud belt of Miller, 1987).

The highest nappes in the San Juan Islands–northwest Cascades thrust system are Late Jurassic rocks that include ophiolitic plutonic rocks, mid-oceanic-ridge basalt, ribbon chert, and arc-derived mudstone-sandstone. Units of these upper nappes that we will examine include rocks in the Lopez fault zone, the Constitution Formation, Fidalgo Ophiolite and Easton Metamorphic Suite. These units are closely similar to terranes in the western Jurassic belt, Franciscan Complex and Coast Range Ophiolite of the Klamath Mountains and California Coast Range (e.g., Brown and Blake, 1987; Garver, 1988; Blake and Engebretson, 1994; J.S. Miller et al., 2003).
TABLE 1. KEY TO UNITS

<table>
<thead>
<tr>
<th><strong>Thrust system units</strong></th>
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</tr>
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<tbody>
<tr>
<td>EASTON METAMORPHIC SUITE (EA)</td>
<td>Late Jurassic ocean floor and trench deposits, well-recrystallized Early Cretaceous blueschist.</td>
</tr>
<tr>
<td>FIDALGO COMPLEX (FC)</td>
<td>Late Jurassic arc-related ophiolite, minimal fabric, incipient prehnite-pumpellyite metamorphism.</td>
</tr>
<tr>
<td>CONSTITUTION FORMATION (CO)</td>
<td>Late Jurassic trench deposits, minimal fabric, incipient blueschist metamorphism.</td>
</tr>
<tr>
<td>LUMMI FORMATION (LM)</td>
<td>Late Jurassic ocean floor and trench deposits, penetrative fabric, incipient blueschist metamorphism.</td>
</tr>
<tr>
<td>LOPEZ STRUCTURAL COMPLEX (LS)</td>
<td>Jurassic to Early Cretaceous ocean floor and trench deposits, incipient blueschist metamorphism.</td>
</tr>
<tr>
<td>TWIN SISTERS DUNITE (TS)</td>
<td>Mantle-derived ultramafic tectonite.</td>
</tr>
<tr>
<td>TURTLEBACK COMPLEX (TB) and correlative YELLOW ASTER COMPLEX (YA)</td>
<td>Early to middle Paleozoic gabbro/tonalite, and paragneiss in YA, minimal fabric, amphibolite, greenschist and prehnite-pumpellyite facies metamorphism.</td>
</tr>
<tr>
<td>GARRISON SCHIST (GA) and correlative VEDDER COMPLEX (VC)</td>
<td>Ocean floor deposits, Permian epidote-amphibolite and blueschist metamorphism.</td>
</tr>
<tr>
<td>ORCAS CHERT including DEADMAN BAY VOLCANICS (OC) and correlative BELL PASS MELANGE (BP)</td>
<td>Triassic-Jurassic chert, lesser oceanic-island basalt in OC and BP; exotic blocks of Early Cretaceous sandstone-argillite, Twin Sisters Dunite, Yellow Aster Complex, and Vedder Complex in BP; Garrison Schist and limestone with Permian Tethyan fusulinids in OC.</td>
</tr>
<tr>
<td>EAST SOUND GROUP (ES) and correlative CHILLIWACK GROUP including Cultus Formation (CH)</td>
<td>Silurian to Jurassic island arc, McCloud fauna, minimal fabric, incipient blueschist metamorphism.</td>
</tr>
<tr>
<td>NOOKSACK FORMATION (NK)</td>
<td>Jurassic to Early Cretaceous island arc possibly formed contiguous with Wrangellia. Slaty fabric, incipient prehnite-pumpellyite metamorphism.</td>
</tr>
<tr>
<td>INGALLS TECTONIC COMPLEX (ING)</td>
<td>Early to Late Jurassic ocean floor and forearc or backarc-related ophiolite, prehnite-pumpellyite metamorphism and thermal aureole. Occurs east of the Straight Creek–Fraser River fault, but is correlative with the higher nappes in the thrust system.</td>
</tr>
<tr>
<td><strong>Mélange belts</strong></td>
<td></td>
</tr>
<tr>
<td>HELENA-HAYSTACK MELANGE (HH)</td>
<td>Serpentinite matrix, blocks of graywacke, mudstone, chert, basalt-ryolite and 150–170 Ma gabbro-tonalite.</td>
</tr>
<tr>
<td>WESTERN MELANGE BELT (WM)</td>
<td>Scaly argillite matrix, blocks are mostly Late Jurassic–earliest Cretaceous lithic sandstone/siltstone, some 150–160 Ma gabbro-tonalite blocks.</td>
</tr>
<tr>
<td>EASTERN MELANGE BELT (EM)</td>
<td>Mostly meta-chert and greenstone, Devonian-Jurassic fossils, 165–190 Ma tonalite-gabbro, Permian Tethyan fusulinids.</td>
</tr>
<tr>
<td><strong>Footwall units to the San Juan Island thrust system</strong></td>
<td></td>
</tr>
<tr>
<td>HARO FORMATION and SPIEDEN GROUP (HS)</td>
<td>Triassic to Early Cretaceous arc-derived sedimentary rocks, zeolite facies metamorphism.</td>
</tr>
<tr>
<td>WRANGELLIA (WR)</td>
<td>Paleozoic arc and Triassic ocean plateau complex, microcontinent, zeolite facies metamorphism.</td>
</tr>
<tr>
<td><strong>Cascade crystalline core, part of the Coast Plutonic Complex</strong></td>
<td></td>
</tr>
<tr>
<td>TONGA FORMATION (TG)</td>
<td>Early Cretaceous trench deposits and arc volcaniclastic rock, greenschist and amphibolite facies.</td>
</tr>
<tr>
<td>CHIWAUKUM SCHIST (CW)</td>
<td>Early Cretaceous accretionary complex, Barrovian amphibolite facies metamorphism.</td>
</tr>
<tr>
<td><strong>Overlap units</strong></td>
<td></td>
</tr>
<tr>
<td>NANAIMO GP. (NA)</td>
<td>Late Cretaceous epicontinental marine sedimentary rock, zeolite facies.</td>
</tr>
<tr>
<td>CHUCKANUT FORMATION and related units (CN)</td>
<td>Eocene fluviatile sedimentary rock, virtually unmetamorphosed.</td>
</tr>
</tbody>
</table>
to be approximately at the same level and laterally contiguous. This is based in part on correlations of terranes between the two regions (as shown in Fig. 2 and Table 1). The structural model also assumes a simple in-sequence assembly of the nappe pile. Because the stratigraphy is not exposed under the broad nappe of Easton Suite between the Cascades and San Juan Islands, out-of-sequence thrust models relating nappes in these two areas could be viable. Cowan and Bruhn (1992) proposed that Cascades nappes lie at a higher structural level than those in the San Juan Islands. McGroder (1991) favors a break in continuity of nappes in the hidden zone between the Cascades and San Juan Islands caused by out-of-sequence thrusting and folding of the nappe pile.

Peripheral to the San Juan Islands nappe pile along its northwest flank are the arc-derived Late Triassic Haro Formation, the Late Jurassic–Early Cretaceous Spieden Group, and the Late Cretaceous Nanaimo Group bearing detritus from the thrust system. These units lack evidence of HP-LT metamorphism and penetrative tectonite fabric, and thus are considered to be “external” to the thrust system (Brandon et al., 1988). Owing to the different tectonic and metamorphic histories, a fault is assumed to separate the nappe pile from the external units. This fault, named the Haro fault, cannot be directly observed, but is inferred to dip under the nappe pile based on regional dips and a gravity survey (Johnson et al., 1986; Palumbo and Brandon, 1990). The Haro fault may have been reactivated during south-vergent thrusting in the Cowichan fold and thrust belt (England and Calon, 1991).

The ultimate foothold to nappes of the San Juan Islands–northwest Cascades thrust system is problematic in the San Juan Islands, but clearer in the Cascades. Based on arguments given above that external units underlie the San Juan Island nappes and observation that Wrangellia underlies Nanaimo Group units on Vancouver Island, one could infer that Wrangellia is basement to the San Juan Island nappes (e.g., Cowan and Bruhn, 1992). In the Cascades, evidence indicates that nappes are thrust over the southern end of the Coast Plutonic Complex. In the central Cascades, the Inglalls Complex, a component of the San Juan Islands–northwest Cascades thrust system, is thrust over Chiwaukum Schist and Mount Stuart batholith along the Windy Pass Thrust (Figs. 2, 3; Miller, 1985). In the northwest Cascades, the relatively undeformed Jurassic-Cretaceous Nooksack Group which underlies the nappe pile (e.g., Misch, 1966) appears to be a southern extension of the Harrison Lake stratigraphic sequence in the southern British Columbia Coast Plutonic Complex (Fig. 3; Monger and Journeay, 1994). Along its western flank, the Coast Plutonic Complex is intrusive into Wrangellia. Thus, one interpretation for the regional structure is that Wrangellia and the Coast Plutonic Complex constituted a structural block in mid-Cretaceous time that served as footwall to the San Juan Islands–northwest Cascades thrust system in both the San Juan Islands and Cascades (e.g., Brown, 1987; McGroder, 1991; Monger and Brown, 2008). Other interpretations place nappes of the San Juan Islands–northwest Cascades thrust system within, and as part of, the country rock of the Coast Plutonic Complex (Monger and Journeay, 1994; Cowan and Brandon, 1994).

AGE OF THRUSTING

The age of assembly of the nappes is uncertain because observed structures could potentially have formed during one of many tectonic events, including initial accretion going back to the Paleozoic for the older terranes, post-accretionary terrane translation at least hundreds of kilometers, emplacement of nappes into the regional geologic setting of northwest Washington, and deformation related to the Eocene and younger fold and thrust belt affecting the Nanaimo Group and Chuckanut Formation (England and Calon, 1991). Certainly some metamorphic fabric and possibly some fault boundaries are inherited from events pre-dating assembly of nappes in their present setting (Brown et al., 2005). However, there is good evidence for major mid-Cretaceous assembly. This deformation is referred here to as the thrusting event. Nappes of the thrust system were emplaced and unroofed in the San Juan Islands vicinity by the time of deposition of the Nanaimo Group (Vance, 1975); the oldest part of the Nanaimo known to bear detritus from the thrust system is ca. 85 Ma (latest Campanian-earliest Santonian; Brandon et al., 1988). A maximum age for thrusting in the San Juan Islands is given by fault juxtaposition of Late Aptian (112–115 Ma) fossiliferous rock with 124 Ma HP-LT metamorphic rock on Lopez Island (one of our field trip stops). In the Cascades, a population of detrital zircons in the Nooksack Formation (footwall to the nappes) gives a maximum depositional age of 114 Ma, and a large sandstone raft in the Bell Pass Mélange bears 119 Ma detrital zircons (Brown and Gehrels, 2007).

More precise ages of thrusting are known for two localities: K-Ar whole rock ages of 87 and 93 ± 3 Ma were obtained for two mylonite samples from the west flank of the Twin Sisters Dunite (Armstrong in Brown, 1987). Movement on the Windy Pass thrust is dated at ca. 94 Ma by relationships with U-Pb zircon-dated plutos that predate, postdate and are involved in thrusting (R.B. Miller et al., 2003). Thus, major displacement is broadly bracketed between ca. 115 and 85 Ma based on youngest terranes involved and the age of rocks bearing detritus of the nappes, and a more limited time frame is suggested to be ca. 90–95 Ma from dated rocks in two fault zones.

METAMORPHISM

Most units in the San Juan Islands–northwest Cascades nappe pile show effects of Cretaceous HP-LT metamorphism. The degree of recrystallization and metamorphic fabric development varies greatly, even within the same units. In the Cascades, evidence of HP-LT metamorphism is found virtually in all thrust system units of Jurassic or older age. The blueschist facies Easton Metamorphic Suite in the Cascades bears synkinematic metamorphic minerals dated at 120–130 Ma by K-Ar and Rb-Sr (Brown et al., 1982; Armstrong and Misch, 1987). Rock units younger than 120 Ma (Nooksack Formation and sandstone in the Bell Pass Mélange) lack definitive
evidence of high-pressure metamorphism. In the San Juan Islands, aragonite (Fig. 4) and lawsonite are widely developed in Jurassic and older rocks that are otherwise relatively unaltered (Vance, 1968; Glassley et al., 1976). This incipient HP-LT metamorphism has been considered to be related to mid-Cretaceous thrusting (Brandon et al., 1988; Maekawa and Brown, 1991) but so far the only isotopic ages available, Ar-Ar muscovite, indicate metamorphism at 124 Ma (Brown et al., 2005) and ca. 137–154 Ma (Lamb, 2000), older than the emplacement phase of thrusting.

The age of blueschist metamorphism relative to thrusting is critical to understanding the tectonics of the thrust system. If aragonite was formed during thrusting, burial on the order of 20 km is required at the ~200 °C temperature estimated for metamorphism (Brandon et al., 1988), indicating a great thickness of overlying nappes. An alternative concept that blueschist metamorphism in the thrust system is inherited from an event predating nappe emplacement may be possible for the older terranes. However, Schermer et al. (2007) showed that HP-LT metamorphism lasted during several phases of brittle deformation that followed juxtaposition of the internal San Juan Island nappes, including the late Aptian Richardson rocks. If all of the HP-LT metamorphism in the San Juan Islands is related to the same subduction zone, the time span of deformation and metamorphism in that subduction zone could be several tens of millions of years (at least from 124 Ma to some time after 112 Ma, but likely beginning earlier). The subduction zone model requires emplacement in the San Juan Islands vicinity after HP-LT conditions ended, and on structures that are not exposed in the internal nappe pile (Schermer et al., 2007). Figure 5 summarizes various interpretations of the age of metamorphism relative to deformation.

**TECTONIC EVOLUTION**

A number of features and arguments point to primary accretion and residence of terranes of the San Juan Islands–northwest Cascades thrust system along the continental margin prior to mid-Cretaceous assembly in the present nappe pile. As Brandon et al. (1988) note, the presence of detritus in sandstones from diverse sources, including metamorphic rock, chert, and silicic arc volcanic rock (e.g., Constitution Formation) suggests proximity to a “continent-like” landmass. They also note that elsewhere in the Cordillera correlatives of Paleozoic terranes of the San Juan Islands–northwest Cascades thrust system (e.g., East Sound Group) accreted long before the mid-Cretaceous. Additional arguments and evidence are provided by the: (1) the Yellow Aster Complex (Figs. 2 and 6; Table 1), a pre-Devonian terrane with links to the continent indicated by beds of quartz arenite and a suite of detrital zircons that match those of the miogeoclinal (Brown and Gehrels, 2007); and (2) Permian blueschist metamorphism in some units (Garrison Schist, Vedder Complex; Armstrong et al., 1983), indicating that these rocks were involved in convergent margin tectonics long before thrusting in the San Juan Islands–northwest Cascades system.

Although terranes of the thrust system are similar to other outboard units of the Cordillera, especially those in the Klamath Mountains with which they have been correlated (see below), some aspects of the thrust system are unique. The stacking sequence of the San Juan Islands–northwest Cascades thrust system is older on the bottom, younger on top, approximately reversed from that generally understood for primary accretion, as in the Klamath Mountains where the oldest rocks are on top (Irwin, 1981). The duration of assembly of the terranes is a few tens of millions of years at most,

**Figure 4. Aragonite in the San Juan Islands.** (A) Coarse aragonite from marble in the Orcas Chert unit, McGraw-Kittinger quarry, Orcas Island (Vance, 1977, p. 194). The sample shown is a single crystal exhibiting twin lamellae on a cleavage surface that extends across the entire specimen. (B) Aragonite veins crossing foliation in the Constitution Formation, South Beach, San Juan Island.
much briefer than the ~300 m.y. period of accretion that built the Klamath complex (Irwin, 1981). Cretaceous blueschist metamorphism in the San Juan Islands–northwest Cascades thrust system affects not only Jurassic-Cretaceous Franciscan type rocks as in the Klamath Mountains, but also apparently all the Paleozoic rocks. We are not aware of anywhere else along the Cordillera that Paleozoic rocks are affected by Cretaceous blueschist metamorphism. Thus, the building process of the San Juan Island nappe pile is different than that understood for other parts of the Cordilleran margin.

Brown et al., 1981

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Figure 6. Detrital zircon age distributions in terranes of the San Juan Islands–northwest Cascades thrust system (Spieden Group from Housen and Fanning, unpublished; other units from Brown and Gehrels, 2007).
Notwithstanding the important contributions of many previous studies of the San Juan Islands–northwest Cascades thrust system, the homeland of the nappes and the tectonic process of their transport and emplacement remain unresolved issues. Three published interpretations (Fig. 7) are:

1. An orogen-normal contractional model in which the nappes formed as continental borderland terranes that were caught in a collision zone between the offshore Wrangellian microcontinent and North America (Brandon and Cowan, 1985; Brandon et al., 1988; Rubin et al., 1990; McGroder, 1991; Burchfiel et al., 1992b; Cowan and Brandon, 1994; Monger and Journeay, 1994).

2. A transcurrent-transpressional model in which the nappe terranes originally accreted or were deposited south (or north?) along the margin from their present location and then moved coastwise, finally stacking up in a reentrant of the continental margin formed by the south end of Wrangellia (Brown, 1987; Maekawa and Brown, 1991; Brown and Dragovich, 2003; Monger and Brown, 2008).

3. A two-phase model in which terranes were first juxtaposed by orogen-normal thrusting along the continental margin south of Wrangellia, and then underwent orogen-parallel thrusting and strike-slip faulting (Bergh, 2002).

Resolution of the emplacement history of the San Juan Islands–northwest Cascades thrust system is central to our understanding of mid-Cretaceous orogeny in the Pacific Northwest, including: the cause of crustal thickening and Barrovian metamorphism in the crystalline core, the origin of the Nanaimo basin, and the configuration of terranes along the North American margin in the Early Cretaceous. On a broader regional scale, the San Juan Islands–northwest Cascades thrust system is relevant to understanding evolution of the 1500-km-long Coast Plutonic Complex which extends from northwest Washington to Alaska. Based on their interpretation as orogen-normal contractional features, thrusts of the San Juan Islands and northwest Cascades have been correlated with thrusts in northern British Columbia and Alaska and cited as evidence for a west-vergent thrust system that extends virtually the entire length of the Coast Plutonic Complex and has accommodated many hundreds of kilometers of mid-Cretaceous shortening between the Insular superterrane and North America (Rubin et al., 1990).

**Kinematics of Outcrop Scale Structures**

One approach to understanding displacement of nappes in the San Juan Islands–northwest Cascades thrust system is kinematic analysis of outcrop scale structures. Such studies to date yield somewhat disparate results (Fig. 5). Brown (1987), working in the Cascades, reported a set of orogen-normal stretching lineations in the Easton Suite coeval with 120–130 Ma blueschist minerals (see above). Younger orogen-parallel lineations were found in mylonite zones separating Cascades nappes (ca. 90 Ma, see above). Smith (1988), and Maekawa and Brown (1991) mapped orogen-parallel stretching lineations in the Cascades and San Juan Islands, respectively, that they interpreted to indicate northwest-directed thrusting. Brandon et al. (1993) disputed this conclusion for the San Juan Islands, suggesting that lineations mapped by Maekawa and Brown (1991) are the product of differential solution-mass-transfer, not thrusting. Cowan and Brandon (1994) described folds and Riedel shears in the Lopez and Rosario fault zones that they interpret to indicate southwest transport of the nappes (orogen-normal). In the eastern San Juan Islands, Lamb (2000) reported northeast vergent (orogen-normal) isoclinal folds dated by synkinematic mica at ca. 137–154 Ma (see above) in rocks inferred to be related to the Easton Suite. Bergh (2002) observed folds, stretching lineations, and shear zones in the Lopez and Rosario fault zones supporting both orogen-normal and orogen-parallel displacement and conceived the two-stage model described above and shown in Figures 5 and 7. Burmester et al. (2000) found that many of the rocks in question have been reoriented after acquiring their magnetization, which developed during or after the fabric was formed; therefore they suggested that the orientation of the fabrics cannot be used to determine direction of transport in the present frame of reference. Brown et al. (2005) determined that fabric in blueschist tectonite of the Lopez fault zone predates thrusting and they suggested that much of the kinematic analysis in the San Juan Islands has been carried out on similar pre-thrust fabric and therefore may not be useful in understanding emplacement of the nappes. Gillaspy (2004) and Schermer et al. (2007) found that faults and extension veins indicate a protracted period of orogen-normal shortening coupled with orogen-parallel extension during argonite metamorphism that postdates thrusting, juxtaposition of the terranes, and penetrative fabric formation. The different interpretations are summarized in Figure 5. To more effectively make use of these structural observations, the challenge for future workers is to understand the age of outcrop-scale structures relative to the age of emplacement of the nappes.

**Regional Considerations**

Another strategy for establishing nappe displacements is consideration of regional geology. Because units of the San Juan Islands–northwest Cascades thrust system bear evidence of residence along the continental margin prior to emplacement in the present day setting, direct accretion of these rocks from the west, the Pacific basin, seems improbable. Derivation of the nappes from the northeast is envisaged in the contractional model described above and shown in Figures 5 and 7. Burmester et al. (2000) reported northeast vergent (orogen-normal) isoclinal folds that postdate thrusting, juxtaposition of the terranes, and penetrative fabric formation. The different interpretations are summarized in Figure 5. To more effectively make use of these structural observations, the challenge for future workers is to understand the age of outcrop-scale structures relative to the age of emplacement of the nappes.
Figure 7. Schematic drawings of three published models for tectonic evolution of the San Juan Islands–northwest Cascades thrust system (NWCS). (A) Contractional model of McGroder (1991). Terranes of the thrust system were formed in a basin between Wrangellia and the continental margin. Convergence between these masses thrust the intervening terranes as nappes over the Cascade crystalline core (including the Skagit migmatite complex) and onto the eastern edge of Wrangellia, achieving orogen-normal shortening of some 400-500 km. (B) Transcurrent model of Brown (1987). Terranes of the San Juan Islands–northwest Cascades thrust system are interpreted to have accreted 100s of km south of their present site and south of Wrangellia. Blueschist metamorphism and orogen-normal fabrics were recorded in the Easton Suite. Post-accretionary displacement moved the terranes northward along the coast as a fore arc sliver, driven by dextral-oblique Farallon–North America convergence, until they collided with a reentrant in the continental margin formed by the south end of Wrangellia. (C) Two-phase model of Bergh (2002). Terranes of the San Juan Islands–northwest Cascades thrust system lay south of Wrangellia and developed orogen-normal contractional structures during the D1 phase in response to high-angle Farallon–North America convergence. D2 structures include NW and SE coastwise displacements as low-angle wedge extrusions caused by sinistral-oblique Farallon convergence. CPC—Coast Plutonic Complex; F—Farallon plate. Other abbreviations as in Fig. 1 and Table 1.
basin caused by emplacement of San Juan Islands–northwest Cascades nappes. However, several aspects of regional geology pose problems for this interpretation.

(1) The contractional model invokes transit of nappes of the San Juan Islands–northwest Cascades thrust system over the Cascade crystalline core (Fig. 3) at precisely the time of great magmatic arc activity in that region. No rocks related to this arc activity are found in the San Juan Islands or Cascades, except where nappes lap onto the southern edge of the Cascade core in the vicinity of the Windy Pass thrust (Figs. 2 and 3).

(2) Nappes of the San Juan Islands–northwest Cascades thrust system carry metamorphic aragonite acquired prior to (as well as after) thrusting. Aragonite has been shown experimentally to invert quickly to calcite outside its stability field at elevated temperature except under conditions of abnormally low T/P, less than 10 °C/km (Carlson and Rosenfeld, 1981). Transit of the thrust system nappes over the active arc would place them in a region of abnormally high T/P, precluding preservation of aragonite.

(3) The elongate, orogen-parallel Nanaimo basin is flanked not by terranes of the San Juan Islands–northwest Cascades thrust system, but by plutonic rocks of the Coast Mountains. Thrust system terranes occur south along strike from the Nanaimo (Figs. 2 and 3), and thus the basin is not likely a consequence of nappe loading.

Many workers have envisaged a southerly origin of some or all of the terranes of the San Juan Islands–northwest Cascades thrust system, in the Columbia embayment, Klamath Mountains, or California Coast Range (e.g., Davis et al., 1978; Vance et al., 1980; Brown and Blake, 1987; Garver, 1988; Burchfiel et al., 1992b). Davis et al. (1978) and Vance et al. (1980) proposed that the Mesozoic ophiolitic terranes of the San Juan Islands–northwest Cascades system formed in a “pull-apart gap” in southeastern Oregon and subsequently moved northward and were obducted onto the continent. Geologic features cited in support of the model are: (1) thrust emplacement of the Ingalls ophiolite over the south edge of the Cascade core, (2) absence from eastern Oregon and western Idaho of some continental margin terranes that are part of the Mesozoic assemblage to the north and south along the Cordillera, and (3) Sr isotope ratios and seismic velocities indicating primitive crust underlying the Columbia embayment. More recent geophysical evidence for a deep crustal rift in the Columbia embayment is a linear break in the gravity field running along the southern margin of the embayment (Riddihough et al., 1986).

Paleomagnetic and Other Constraints of Paleogeography

Paleomagnetic studies of the rocks in the San Juan Islands have had mixed success in constraining their tectonic history, with the main complication being an extensive remagnetization that has affected all of the “internal” units that have experienced high P-T metamorphism. Burmester et al. (2000) found that these rocks had all been remagnetized during or after folding, and that the predominantly normal polarity of the remagnetized directions indicated to them that this remagnetization occurred during the Cretaceous Long-Normal Chron (116–83.5 Ma). The remagnetized directions from the San Juan Islands are scattered, however, indicating that a significant amount of rotation and/or tilt occurred after this remagnetization event.

Paleomagnetic studies of the unmetamorphosed “external” units of the San Juan Islands have more promising results. The exception is the Haro Formation; Hults and Housen (2000) have found that these rocks were also remagnetized prior to folding, despite their lack of any significant metamorphism.

The rocks of the Spieden Group have complex magnetizations, with the majority of these clastic rocks having poorly resolved magnetizations. Dean (2002) found three magnetic components in most of the Late Jurassic Spieden Bluff Formation samples, which yielded an inconclusive paleomagnetic fold test. The Early Cretaceous Sentinel Island Formation has a simpler, two-component magnetization in some of the rocks. Dean (2002) found that the second-removed component from the Sentinel Island Formation passes the inclination-only paleomagnetic fold test, with the best-clustered inclinations occurring at 100% untilting. The mean inclination of 64°, α95 = 7.8°, suggests an Early Cretaceous paleolatitude of 46° N. Comparing this direction with that expected for the present-day location of Spieden Island calculated from a stable North America reference pole (Housen et al., 2003), a latitudinal translation of 1500 ± 1000 km is estimated for these rocks.

The Nanaimo Group has been the subject of extensive paleomagnetic study, primarily from outcrops in the Canadian Gulf Islands (Ward et al., 1997; Enkin et al., 2001; Kim and Kodama, 2004), with limited work from Orcas Island (Housen et al., 1998). All of these studies have found that most Nanaimo Group rocks have poorly defined magnetizations (~60% “failure rate” reported for most sample collections). However, a significant number of samples in all of these studies (a few 100 out of ~1000 samples collected) have well-defined magnetizations that pass a reversals or fold test. Studies of inclination error, notably Kim and Kodama (2004), suggest that inclination error in these sediments is moderate (8–10°), and that when corrected for the paleomagnetic inclinations in these rocks place the Nanaimo Basin at a paleolatitude of 41° N during Campanian-Maastrichtian time. Using a Late Cretaceous North American reference pole for comparison, a translation of 1600 ± 900 km is indicated for these rocks since ca. 75 Ma.

Related constraints on the Late Cretaceous paleogeography of the San Juan Islands also come from paleofaunal data from the Nanaimo Group rocks. Kodama and Ward (2001) argued that the lack of rudist bivalves in the otherwise well-preserved paleofauna of the Nanaimo Group can be used to constrain the paleolatitude of these rocks. Rudists are tropical to subtropical reef forming bivalves, and are common in a number of Late Cretaceous marginal basin rocks from Baja California to Central California. Using estimated locations of rudist-bearing basins, and the locations of anoxic black shales (Marca Shale) that mark
the presence of a cold-water upwelling zone along the ancient California margin, Kodama and Ward (2001) suggested that the Nanaimo Group rocks were located at or north of the location of the Moreno Basin (central California, 42° N reconstructed paleolatitude) at 75 Ma. Some additional support for this constraint comes from the recognition of a marine reptile fauna from Nanaimo Group rocks on Vancouver Island, which share some provinciality with the marine reptile fauna of the Moreno Formation from central California (Nicholls and Meckert, 2002).

Another set of data, detrital zircon age distributions, has also been used to test paleogeographic constraints on the location of the Nanaimo Group rocks. Mahoney et al. (1999) used the presence of several Archean-aged zircons to indicate that the Nanaimo Group rocks had been located no more than 500 km south of its present-day location, during Late Cretaceous time. Using the same set of data, Housen and Beck (1999) compared variations in the detrital zircon age distributions as a function of stratigraphic position within the Nanaimo Group. They argued that variations in Proterozoic-aged zircons support a source of detrital zircons from the Mazatzal and Yavapai orogens in southwest North America, and that northward migration of the Nanaimo Basin during its deposition was consistent with other paleomagnetic evidence, and plate motion estimates. The analyses of Kodama and Ward (2001), and Kim and Kodama (2004) also supported the conclusion of Housen and Beck (1999), that the Nanaimo Group reached the “moderate” paleolatitude of −43° N at 75 Ma, consistent with the so-called “Baja-BC” (Baja–British Columbia) hypothesis.

Taken together, these paleogeographic data would be most consistent with the “Klamath origin” models discussed above. Complicating this correlation, however, are the proposed ties between the San Juan Islands rocks and Wrangellian or North Cascades basement, as abundant paleomagnetic data from stratified rocks of Wrangellia/Insular affinity (Wynne et al., 1995, Enkin et al., 2003), or barometrically corrected plutonic rocks (Housen et al., 2003) both indicate more southerly paleolatitudes (36 N, and 300 ± 700 km of translation) for these units during mid-Cretaceous time (93–88 Ma).

Modern Analogues?

Modern tectonic regimes along the western North American margin (Fig. 8) that serve as possible analogues for emplacement of the San Juan Islands–northwest Cascades thrust system via coastwise movement are collision zones formed by northward displacement of: (1) Siletzia against the south end of Wrangellia (e.g., Wells et al., 1998), and (2) the Yakutat terrane against the southeast corner of Alaska in the Saint Elias orogen (Plafker et al., 1994). Siletzia lies in the Cascade forearc, driven by a combination of oblique plate convergence and Basin and Range extension (Wells et al., 1998). Seismic reflection allows identification of Siletzian rocks under Wrangellia to depths of 15–20 km along shallow to moderately north-dipping faults (Clowes et al., 1987). Total northward displacement is not known, but Beck (1984) suggested paleomagnetic discordance indicates as much as 300–
400 km. The current rate of arc-parallel transport is 6–8 mm/yr at the northern end of the terrane (Wells and Simpson, 2001).

The Yakutat terrane is moving north along the Fairweather–Queen Charlotte transform fault at 45–50 mm/yr relative to North America (Plafker et al., 1994; Bruhn et al., 2004). At the corner area in southern Alaska where plate interaction changes from transform to convergent, the Yakutat terrane is colliding with the continent (Fig. 8). A north-dipping Benioff zone and the Wrangell magmatic arc in this region both testify to significant subduction of the Yakutat terrane (and probably other materials). The convergent zone is marked by a thin-skinned accretionary complex of Cretaceous and younger rocks displaced northward on gently to moderately dipping thrust faults (Bruhn et al., 2004). Displacements are strongly partitioned between strike-slip faults and thrusts. Both analogues are characterized by low-dip thrusts accommodating margin-parallel displacement indicating that such structure, as possibly fits the San Juan Islands–northwest Cascades thrust system, is not a tectonic anomaly.

FIELD TRIP GUIDE

The field trip guide begins at Friday Harbor, San Juan Island (Fig. 9). Before departing, be certain that you have brought along warm clothes, raingear, and good field boots.

Please do not use rock hammers or collect specimens anywhere on this trip unless specifically advised.

DAY 1

Day 1 is spent primarily on the terranes “external” to the San Juan Islands thrust system. These units are the Haro Formation, Spieden Group, and Nanaimo Group. They broadly overlap in age with rocks in the nappe pile but are distinguished by their absence of, or very low-grade (zeolite facies), metamorphism, and, in the case of the Spieden and Nanaimo Groups, an absence of penetrative tectonite fabric. These units are important to understanding the younger portion of the tectonic history of the San Juan Islands. The field trip will begin with a drive from Friday Harbor across San Juan Island to picturesque Roche Harbor, on the northern end of San Juan Island. We will depart from the boat ramp at Roche Harbor, taking a chartered craft to Stuart and Spieden Islands. We will be landing on public access beach areas, but please note that only the intertidal zone in these areas is considered to be public property, and that the uplands are privately owned. Access to Spieden Island in particular is restricted by its owner.

Directions and Other Instructions

Before departing on the Humpback Hauling vessel, be certain that you have brought warm clothes and your lunch. Even if the weather appears to be sunny, raingear is recommended. A lifejacket (provided on the vessel) is required at all times, and please do not forget yours on the beach. If you are prone to seasickness, please take appropriate precautions. The vessel has a landing-craft type ramp, so we will be able to disembark on relatively dry land. However, caution must be exercised to avoid a nasty fall on the slick seaweed-covered rocks that may be present. Please pay attention to the field trip guides as the departure time draws near, to ensure you are on the vessel, and the trip can run in a safe and timely fashion. After we have finished the Stuart Island stop, participants will re-embark for a ~45 min trip to Spieden Island.

Stop 1-1. Fossil Cove, Stuart Island, Nanaimo Group (Fig. 10)

The Nanaimo Group comprises a set of 11 formations, ranging from Turonian to Maastrichtian in age, composed of clastic marine and deltaic sedimentary deposits (Fig. 10). The ages of these rocks are constrained by biostratigraphy (e.g., Haggart, 1994), and magnetostratigraphy (Enkin et al., 2001). These rocks were deposited in a large marginal basin, extending ~175 km from its southernmost extent in the San Juan Islands to its northernmost extent on Vancouver Island. The Nanaimo Group contains several elements that are of tectonic interest. Structurally, the Nanaimo Group rocks (along with the Paleocene-Eocene Chuckanut Formation) are folded as part of the Cowichan fold and thrust belt (England and Calon, 1991; see also Mustoe et al., this volume, and Blake and Engebretson, this volume). One of the primary constraints on the age of uplift and thrusting of the metamorphosed “interior” domain of the San Juan Islands is the presence of metamorphosed sandstone clasts interpreted as being derived from the Constitution Formation that are found in conglomerates of the Extension Formation of the Nanaimo Group on Orcas and Stuart Islands (Brandon et al., 1988). On a larger scale, age distributions of detrital zircons (Housen and Beck, 1999; Mahoney et al., 1999), paleomagnetism (Ward et al., 1997; Housen et al., 1998; Enkin et al., 2001; Kim and Kodama, 2004), and fossil assemblages (Kodama and Ward, 2001) have been used to evaluate possible large-scale displacements of the Nanaimo Group rocks.

On Stuart Island, the turbidites and sandstones of the Haslam Formation, the conglomerates of the Extension Formation, and the sandstones and siltstones of the Pender Formation can be found (Fig. 10). A stop at Fossil Cove, on the NW end of Stuart Island (a boat trip of ~45 minutes), allows for examination of the bedding and sedimentary structures in these rocks, as well as the many fossils (primarily Inoceramus). Time permitting, we may stop at a beach where the Extension Formation crops out, in order to examine the conglomerate clasts of this interesting unit.

Stop 1-2. North Shore Spieden Island, Spieden Group (Fig. 11)

Spieden Island is one of the largest (perhaps the largest) privately owned island in the San Juan archipelago. It has a colorful history, most notably as “Safari Island,” when in the 1970s a group of investors purchased the island with the bright idea of transforming it into a private exotic game hunting reserve. The island was stocked with many species of exotic game animals (mostly Asian and African deer, goat, sheep, and antelope
Figure 9. Map of San Juan Island and vicinity. Solid circles locate field trip stops. Sources are Brandon et al. (1988) and Burmester et al. (2000).
species). Needless to say, the concept of hunting exotic game in the midst of an ecological paradise did not work out; the island reverted to Spieden Island, and the descendants of the surviving creatures can be seen cavorting around the island today.

Geologically, Spieden Island, and nearby Sentinel Island, are the only known occurrences of the late Jurassic–early Cretaceous Spieden Group. The Spieden Group is composed of two formations, the Oxfordian-Kimmeridgian Spieden Bluff Formation, and the uppermost Valanginian Sentinel Island Formation (Fig. 11). The ages of these units are constrained by biostratigraphy (McClellan, 1927, Haggart, 2000), primarily via fossils of Buchia. The rocks of both formations are clastic sediments, with finer-grained turbidite deposits characterizing the Spieden Bluff Formation, and volcaniclastic-rich sandstone, mudstone, and conglomerates characterizing the Sentinel Island Formation. The rocks also display some soft-sediment deformation features; some have a very weak anastomosing scaly cleavage, and have been folded.

Our field trip stop will be located on a wave-cut bench, exposed at low tide, on the north shore of Spieden Island. Here we will see outcrops of both formations, and localities that display the locally abundant macrofossils. We will have ~30 min at this location; please follow the instructions of the trip leaders closely. After we re-embark, the vessel will take us on a ~40 min trip back to the Roche Harbor boat ramp, where the seaborne portion of this trip will end.

After leaving the Roche Harbor boat ramp, we will drive to Davidson Head, parking on the shoulder of the road at the “neck” of the head. We will then walk northwest along the beach, examining the exposures of the Haro Formation in the intertidal zone. Fans of fresh oysters will be certain to notice the abundant (likely seeded) oysters present on the Haro Formation outcrops.

**Directions to Stop 1-3**

From Roche Harbor waterfront, drive southwest on Reuben Memorial Drive.

- 0.2 mi  Go left on Roche Harbor Road.
- 0.9 mi  Go left (NW) on Afterglow Drive.
- 1.8 mi  Neck of Davidson Head; park on gravel shoulder on right side of road.

**Stop 1-3. Davidson Head, San Juan Island, Haro Formation**

The north shore of San Juan Island is home to one of the most geographically restricted units in the San Juan Islands—the Late Triassic (Norian) Haro Formation. This unit crops out on Davidson Head, and is a 700-m-thick mixed volcaniclastic unit.
The Haro Formation has only experienced zeolite facies metamorphism, and thus the contact between the Haro Formation and the high-P, low-T metamorphic rocks immediately to the south of Davidson Head represents a fundamental structural boundary in the San Juan Islands. This contact is nowhere exposed, but is inferred to be a thrust fault (the Haro Thrust), based primarily on the large-scale structural architecture of the San Juan–north Cascades nappes (e.g., Brandon et al., 1988).

**Directions to Stop 1-4**

0.0 Return on Afterglow drive to Roche Harbor Road; reset odometer and go left (east-southeast).

1.3 Go right (south) on West Valley Road.

2.8 Go right (west) on Mitchell Bay Road.

5.6 Go left (south) on Westside Road.

9.7 Turn in at entrance to Lime Kiln Point Park and follow trail to coast.
Figure 11. Geology of Spieden and Sentinel Islands, after Johnson (1981) and Dean (2002). (A) Geologic map. (B) Schematic section of the Spieden Group.
Stop 1-4. Lime Kiln Point State Park, San Juan Island  
(Fig. 12)

Lime Kiln Point is a famous venue for orca whale spotting. For geologists, the locality is important for its exposures of limestone that bears Permian Tethyan Fusulinids, known to have grown at a tropical latitude and suggesting large displacements of the terrane (Danner, 1966, 1976; Monger and Ross, 1971). The limestone occurs as layers and irregular masses within a sequence of ocean island pillow basalt flows and breccias, named the Deadman Bay Volcanics (Brandon et al., 1988). The age of the unit as a whole ranges from Early Permian to Late Triassic based on fusulinids, conodonts and radiolarians. The Tethyan fusulinids link this unit to the “Cache Creek belt” of mélange oceanic rock extending along the Cordilleran margin from California to northern British Columbia (Miller, 1987). The limestone is largely recrystallized to aragonite marble (Vance, 1968).

The Deadman Bay Volcanics are separated from the overlying Orcas Chert unit by an east-dipping thrust fault; however these two units are regarded by Brandon et al. (1988) as parts of a single terrane based on their mutual similarity of age, lithology, and chemical signature of ocean island basalts.

Return to Friday Harbor via West Side Road and Bailer Hill Road (Fig. 9).

Figure 12. Geology of Lime Kiln Point, reproduced from part of Fig. 9 in Brandon et al. (1988).
DAY 2

On day 2, we will examine the Rosario and Lopez fault zones on San Juan and Lopez Islands, two of the major structures in the San Juan Islands thrust system.

Directions to Stop 2-1
0.0 Intersection of Argyle Ave and Spring Street in Friday Harbor; head south on Argyle Ave.
1.0 mi Beginning of Cattle Point Road.
7.1 Turn right (south) on Pickett’s Lane in American Camp Park.
7.6 Go right (west) on Salmon Banks Road (dirt road).
7.9 End of road; park.

Stop 2-1. South Beach, American Camp National Park, San Juan Island (Fig. 13)

Americans and British disputed the boundary between their respective territories in the early 1800s and set up military camps on San Juan Island, which both sides claimed. War nearly broke out in 1859 when an American settler shot a pig belonging to the British Camp. The international boundary dispute was finally resolved by arbitration in 1872, in favor of the Americans.

This part of the Rosario thrust, well exposed at the water’s edge, has been a key locality for interpretations of San Juan Islands structural evolution (summarized in Figs. 5 and 7). Maekawa and Brown (1991) observed shear zones with fault drag and northwest trending lineations at this locality and suggested dominantly northwest thrusting (Fig. 14A). Cowan and Brandon (1994) applied a “symmetry based statistical analysis” of asymmetric folds and Riedel shears, concluding that the structures formed by southwest thrusting. Bergh (2002) divided structures into an early set of folds, foliation and lineations related to southwest contraction (D1), and a later set of lineations and shears (D2) formed by northwest displacement as exhibited at this locality (Fig. 14B).

The Rosario thrust at this locality dips northeast. Footwall to the thrust is the Triassic-Jurassic Orcas Chert which is dominantly composed of ribbon chert with lesser pillow basalt, mudstone, and limestone (Vance, 1975). In the hanging wall is the Late Jurassic Constitution Formation, mostly composed of volcanic-rich graywacke sandstone. The fault at this locality (mapped in detail by Brandon et al., 1988) is marked by an imbricate zone ~100 m wide bearing lenses and rafts of ribbon chert, sandstone, mudstone, greenstone, and most significantly HP-LT greenschist-amphibolite of the Permian Garrison Schist unit.

Amount and timing of displacement on the Rosario thrust are difficult questions. Vance (1975) noted that the overlying Constitution Formation bears detritus that appears to be derived from the underlying Orcas Chert, Garrison Schist, and Deadman Bay Volcanics and proposed that the contact is an unconformity. The imbricate structure and inclusion of the Garrison Schist in the deformation zone, however, suggested a fault of large displacement to Maekawa and Brown (1993) and Cowan and Brandon (1994).

Directions to Stop 2-2
8.7 mi Retrace route to Cattle Point Road. Turn right (east) and drive to Cattle Point.
10.8 Parking for Cattle Point.

Figure 13. Bedrock geology of the South Beach area, American Camp, reproduced from Brandon et al. (1988). Legend as in Fig.12.
Figure 14. Structural analysis of fabrics in the Rosario Thrust at South Beach, San Juan Island by (A) Maekawa and Brown (1991), and (B) Bergh (2002). These interpretations are in mutual agreement, indicating northwest thrusting. Cowan and Brandon (1994) interpret these structures to be part of a pattern of Riedel shears that together with fold orientations statistically indicate southwest-vergent thrusting (i.e., toward the viewer with respect to Fig. 14B).
Lopez Structural Complex

At Cattle Point and subsequent stops on Lopez Island, we will see rocks and structures of the Lopez Structural Complex (Fig. 15), one of the major fault zones in the San Juan thrust system (Brandon et al., 1988). The Lopez Structural Complex is an ~2.5 km wide imbricate zone composed of northwest-elongated, relatively coherent lenses separated by sheared mudstone-rich fault zones. The large lenses are predominantly ocean floor clastic and volcanic rocks and Constitution terrane sandstone; smaller lenses include Turtleback terrane and exotic material not found elsewhere in the region. The magnitude of offset along the Lopez Structural Complex is unknown, but the inclusion of exotic material such as the Early Cretaceous Richardson complex (stop 2-3) suggests tens of kilometers of movement similar to other terrane bounding faults in the San Juan Islands (Brandon et al., 1988; Cowan and Brandon, 1994). Foliation and fault contacts in the Lopez Structural Complex dip moderately to steeply northeast (Maekawa and Brown, 1991; Cowan and Brandon 1994; Bergh, 2002) (Fig. 15). These structures are subparallel to the northern boundary of the Lopez Structural Complex, the Lopez fault, where most of the offset is thought to have occurred (Brandon et al., 1988).

Recent structural analysis of the Lopez Structural Complex (Gillaspy, 2004; Schermer et al., 2007), reveals a sequence of events that provide insight into accretionary wedge mechanics and regional tectonics. After formation of regional ductile flattening and shear-related fabrics (the thrusts and strike slip faults illustrated in Fig. 5), the area was crosscut by brittle structures including: (1) southwest-vergent thrusts, (2) extension veins and normal faults related to northwest-southeast extension, and (3) conjugate strike-slip structures recording northwest-southeast extension and northeast-southwest shortening. Aragonite-bearing veins are associated with thrust and normal faults, but only rarely with strike-slip faults (Fig. 16). High-pressure low-temperature (HP-LT) minerals constrain brittle deformation to have occurred at $\geq 20$ km and $\sim 200–300$°C. The presence of similar structures elsewhere indicates the brittle structural sequence is typical of the

Ocean Floor Complex
- Clastic sequences
- Volcanic rocks and associated sedimentary rocks

Constitution Terrane
- Sandstone with chert and volcanic rocks
- Mudstone-rich assemblages

"Exotic" and Other slices
- Richardson Basalt Complex
- Turtleback Complex
- Imbricate Zones

Approximate fault contact
Major terrane boundary
Strike and dip of foliation

Figure 15. Generalized geology and terrane map of the Lopez Structural Complex. Open circles show locations of field trip stops 2-2 (Cattle Point), 2-3 (Richardson) and 2-4 (Iceberg Point). Modified from Brandon et al. (1988), Burmester et al. (2000), and M.C. Blake (2000, written commun.). Eastern extension of Lopez thrust (from Brandon et al. 1988) may not coincide with a terrane boundary (from Schermer et al., 2007).
San Juan Island nappes, at least for the Constitution and structurally higher terranes. Sustained HP-LT conditions are possible only if structures formed in an accretionary prism during active subduction, suggesting brittle structures record internal wedge deformation at depth and early during uplift of the San Juan Island nappes. The structures are consistent with orogen-normal shortening and vertical thickening followed by vertical thinning and along-strike extension. The change in vein mineralogy indicates exhumation occurred prior to the strike-slip event. The P-T conditions, and spatial and temporal extent of small faults associated with fluid flow suggests a link between these structures and the silent earthquake process.

Given that these latest identified structures likely formed in an accretionary wedge setting, we are faced with the dilemma of not having found the Late Cretaceous structures related to emplacement in northwest Washington. These emplacement structures, if they formed by any of the models illustrated in Figure 7, would be unlikely to have associated HP-LT metamorphism or along-strike (NW-SE) extension. It is possible that the unexposed Haro fault (stop 1-3) is one of the main emplacement related structures, but the timing and kinematics of this fault are poorly understood.

Stop 2-2. Cattle Point Park, San Juan Island (Figs. 9, 15)

At Cattle Point, highly sheared mudstones with disrupted and elongated sandstone beds and clasts form a NW-striking, steeply dipping shear zone adjacent to less-deformed coarse grained sandstones and chert-pebble conglomerates. We will examine early ductile and late brittle deformation. In the sheared mudstone, which is interpreted by Bergh (2002) to contain a composite S1-S2 fabric, there is evidence of NW-SE shearing, interpreted as top to the NW thrusting by Maekawa and Brown (1991) and sinistral reactivation of SW-vergent thrusts by Bergh...
(2002). Strain in the early thrusting event(s) is strongly partitioned into the mudstone-rich units, as seen here and throughout the Lopez structural complex. Foliation in the sandstone unit is dominated by pressure solution and volume loss (Feehan and Brandon 1999). The later brittle structures studied by Gillaspy (2004) and Schermer et al. (2007) are present in both sandstone and mudstone units, but best observed in the sandstone, where several generations of faults and extension veins cross cut the dominant foliation. These structures include rare SW-vergent thrusts subparallel to foliation, followed by extension veins and normal faults, then conjugate strike slip faults. Analysis of these structures in outcrops throughout the Lopez structural complex and eastern San Juan Islands indicates a prolonged episode of brittle deformation at the base of the accretionary wedge that resulted in N-S to NW-SE extension (Figs. 5 and 17).

Directions to Stop 2-3

Return to Friday Harbor and take the ferry to Lopez Island.

0.0 Ferry terminal on Lopez Island, drive south on Ferry Road.

2.1 mi Turn left (east) on Fisherman Bay Road.
2.3 Go right (south) on Center Road.
7.7 Turn right (west) on Lopez Sound Road.
7.9 Turn left (south) on Richardson Road continue south to coast.
9.6 End of road at fuel terminal; park here.

Stop 2-3. Richardson, Lopez Island

Geologic relations at Richardson on Lopez Island (Figs. 18 and 19) have played an important role in understanding San Juan Island evolution since the discovery there of Cretaceous microfossils by Ted Danner of the University of British Columbia (Danner, 1966), establishing a maximum age limit on thrusting. Until recently the accepted age for these rocks was late Albian (ca. 100 Ma), determined by Bill Sliter of the U.S. Geological Survey (in Brandon et al., 1988) based on microfossils in a mudstone collected by John Whetten, University of Washington, in 1977. Map relations displayed at this site show a layered sequence of pillow basalts, pillow breccias, tuff and mudstone (Fig. 19). All these rocks were considered to represent a coherent mid-Cretaceous stratigraphic assemblage (Brandon et al., 1988). However, recent Ar-Ar analysis of blueschist facies phengitic mica in the pillow breccias (Fig. 20) yielded an age of 124.43 ± 0.72 Ma (Brown et al., 2005). Revisitation of the fossil ages in the Whetten sample indicates a late Aptian age (112–115 Ma) (Fig. 21). Remapping the structural features demonstrates that the fossiliferous mudstones (Fig. 21) are faulted into the sequence. These findings broaden the age brackets for thrusting, and suggested to Brown et al. (2005) that San Juan Islands blueschist metamorphism is older than thrusting. But, a recent finding of aragonite veins in the late Aptian mudstones by Schermer et al. (2007) indicates that the blueschist metamorphism continued to at least that time and was apparently coeval with and outlasted thrusting, as interpreted by earlier workers (Brandon et al., 1988; Maekawa and Brown, 1991).

Figure 17. Generalized map of the eastern San Juan Islands with paleomagnetic results of Burmester et al (2000) and kinematics of late brittle deformation from Schermer et al. (2007), Gillaspy (2004), and Lamb (2000). Small grey arrows indicate direction of magnetic vector from Burmester et al (2000); inclination values omitted; small arrowheads indicate upward inclination. K-is and K-bj show expected directions for in situ and Baja-BC terrane models of the Cretaceous location of San Juan terranes. Other arrows indicate kinematic directions of brittle structures as defined in key. If no arrow is shown for brittle structures at a site, data are too few to conclude kinematic significance. Circles indicate subhorizontal extension in several directions during normal faulting or extension veining. Foliation symbols show average foliation direction and are located at reconnaissance study sites: at all sites, the same sequence of faulting is observed, but not all sites have enough data to conclude kinematic significance of all phases of faulting. A—San Juan Island; B—N. Lopez Island; C—Watmough Head; D—Guemes Island; E—Jack Island; F—Lummi Island; G—Eliza Island; H—Samish Island.
The fault that juxtaposes the mudstone and volcanic rocks bears slickenlines trending N30° W and plunging 20°, seen below the road at this locality. This lineation is part of the data set used by Maekawa and Brown (1991) as a basis for their inference of dominantly orogen-parallel transport of the San Juan Island nappes.

Directions to Stop 2-4

9.6 mi Drive north from end of Richardson Road.
9.9 Vista Road. Turn right (east).
11.4 Mud Bay Road. Go right (south).
12.5 MacKaye Harbor Road. Turn right (west).
14.6 End of road.

There is no parking at the end of the road; note a sign indicating “private road” at the end of the public road. There are two areas at a county park picnic site with parking for 2 or 3 cars each, available on the left (south) side of the road ~50 m before the end. After parking, walk to the end of the public road, go straight through the open wooden gate onto the private road, take the right-hand fork through private land, pass through a metal gate and follow the path ~15 min to Bureau of Land Management land at Iceberg Point. Please respect private property.

Stop 2-4. Iceberg Point, Lopez Island

At Iceberg point, we will examine interbedded sandstones and mudstones with several generations of brittle structures. If time and tide permits, we will also examine a shear zone between these rocks (of ocean-floor affinity) and a fault slice of Consti-
tution terrane to the north. Late brittle structures include SW-vergent thrusts subparallel to foliation, abundant extension veins and normal faults showing predominantly NW-SE extension, and conjugate strike slip faults. Because the late brittle structures are broadly distributed across the Lopez Structural Complex, we may not be able to see all generations of structures and cross-cutting relations between them.

**Directions to Overnight Lodging**

Return to ferry landing and take the ferry to Anacortes. Drive on Washington State Highway 20 spur to the intersection with the main route of highway 20, at Sharps Corner.

**DAY 3**

Day 3 is mostly devoted to the Fidalgo Complex on Fidalgo Island. On the last stop of the day we observe outcrops of the Easton Metamorphic Suite exposed at the south end of Chuckanut Mountain.

**Fidalgo Complex**

The Fidalgo Complex (Fig. 22) consists of a stratigraphic sequence distinctive of ophiolite. From the base upward in the section are: ultramafic tectonite, cumulate gabbro, a sheeted
intrusive complex of mostly plagiogranite (diorite, tonalite, trondjemite, albite granite) and hypabyssal equivalents, a volcanic sequence of mainly dacitic to andesitic breccias and interlayered tuffaceous argillite, coarse sedimentary breccia that bears clasts of all the underlying units, pelagic argillite, and volcanic-rich graywacke at the top of the section. U-Pb zircon ages of the plagiogranites on Fidalgo Island are 167 ± 5 Ma, and elsewhere are 160 ± 3 Ma on Lummi Island and 170 ± 3 on Blakely Island (Whetten et al., 1978, 1980). Radiolaria in the pelagic argillite are late Kimmeridgian–early Tithonian ca. 150 Ma (Gusey, 1978; Brandon et al., 1988). The U-Pb age pattern of detrital zircons from a sample of the graywacke unit bears a single prominent peak at 148 Ma, considered to represent a nearby volcanic provenance (Brown and Gehrels, 2007). All these rocks are affected by prehnite-pumpellyte metamorphism.

The plutonic part of the Fidalgo Complex is interpreted to be a remnant arc. An arc origin of the ophiolite is indicated by the abundance of intermediate to felsic igneous rocks (Brown, 1977; Gusey and Brown, 1987; Burmester et al., 2000). The coarse breccia and overlying radiolarian argillite stratigraphically above the igneous rocks indicate that the 160–170 Ma arc was rifted and terminated as a volcanic center prior to deposition of the sedimentary part of the section. Thus the arc was faulted and shifted off its magmatic axis before attaining much crustal thickness or subaerial exposure. The old eroded arc was then buried at ca. 148 Ma by younger clastic arc detritus from an adjacent volcanic axis. This evolution is similar to that of modern remnant arcs (e.g., Karig, 1972).

The Fidalgo complex is similar in age and lithology to the California Coast Range ophiolite with which it has been correlated (Garver, 1988; Blake and Engebretson, 1994). This unit also bears some affinity to the Ingalls Complex in the central Cascades (described by Miller, 1985, and Metzger et al., 2002).

Directions to Stop 3-1

Drive into Anacortes on Washington 20 Spur and follow signs toward the ferry terminal. Continue past the turnoff to the ferries on Sunset Ave. to Washington Park.

0.0 Entrance to Washington Park
0.2 mi Begin one-way loop drive.
0.7 Park on left, cement stairs to beach on right.

Stop 3-1. Washington Park, Fidalgo Island

Ultramafic rock here is interpreted to be basement to the Fidalgo ophiolite (Fig. 22) based on its position structurally beneath the other parts of the ophiolite; however, the contact is covered by Quaternary materials. Minerals are serpentinite (after olivine), relict pyroxene, and chromite. Protolith rock ranges from dunite to peridotite. Rock that was originally peridotite is marked by significant amounts of relict pyroxene, together with serpentine, whereas the original dunite is virtually free of pyroxene. The meta-peridotite and meta-dunite are thus distinguishable and can be seen as irregular layers through this exposure. Pyroxenite veins exhibiting comb structure cross the other lithologies. We will speculate about the origin of these layers and veins and what information they might provide about mantle deformation and basalt genesis.

Directions to Stop 3-2

Continue around the “loop road”; exit Park back to Sunset Ave.

3.1 mi Turn right on Anacos Beach Road and continue on to merge with Marine Drive.

Stop 3-2. Private Property along Marine Drive, Fidalgo Island (Fig. 22)

Cumulate gabbro displays layering formed by differential settling of pyroxene and plagioclase crystals in the melt (Fig. 23). Dikes of plagiogranite and keratophyre occur locally in the gabbro, and exclusively as a sheeted complex higher in the section. The orientation of bedding in the gabbro and direction of grading are consistent with its mapped structural position low in the ophiolite stratigraphy, but above the ultramafic rock.

Directions to Stop 3-3

Continue south on Marine Drive

5.8 mi Turn right (south) on Havekost to the intersection with Rosario Road.

6.8 Rosario Road: turn right (east).

7.8 Heart Lake Road: turn left (north).

9.0 Go right (east) on Ray Auld Drive.
9.1 Turn right (south) on Erie Mountain Drive.
9.3 Park in pull-out on right; cross the highway to see outcrops.

Stop 3-3. Roadcut along Erie Mountain Drive, Anacortes City Park, Fidalgo Island (Fig. 22)

Observe green volcanic breccia. The lithology here is keratophyre (= meta-dacite). The volcanic section of the ophiolite ranges from 48 to 74 wt% SiO₂ (Brown et al., 1979). K₂O is typically <1.0% through the suite, anomalously low for calc-alkaline rocks. Primary textures are well preserved, as in this exposure, and do not support a hypothesis of postmagmatic chemical alteration. Igneous minerals observable in thin-section are plagioclase, epidote, pumpellyite, prehnite, albite, and quartz. Metamorphic minerals, in veins and incipiently developed in the igneous matrix, are chlorite, epidote, pumpellyite, prehnite, albite, and quartz. Identification of aragonite at one locality (Gusey, 1978) has not been confirmed by X-ray analysis of many other carbonate samples from the Fidalgo ophiolite (M.C. Blake, 2006, personal commun.).
Figure 22. Map and schematic stratigraphic section of northern Fidalgo Island. Rocks of Fidalgo Island are interpreted to represent an ophiolite sequence based on the stratigraphy shown here. The abundance of felsic igneous rock and absence of mid-oceanic-ridge basalts precludes origin of the ophiolite as sea floor crust, and indicates an affinity with island arc magmatism (from Brown et al. 1979). Ages are from igneous zircons in plagiogranite, radiolaria in pelagic sediment, and detrital zircons in clastic sediments at the top of the section. All are mutually consistent considering their relative position in the stratigraphy, and indicate a Late Jurassic age. References: Whetten et al. (1978); Gusey (1978); Brown and Gehrels (2007). Q—Quaternary deposits.
Fifty meters down the road, and structurally below the volcanic rock, is dark brown, manganese-rich, radiolarian argillite. This rock unit, termed “pelagic argillite,” is as much as 500 m thick and forms the second sedimentary layer up in the ophiolite section (Figs. 22 and 24). An unexposed thrust fault separates these rocks. This structure as well as other shear zones in the Fidalgo ophiolite have not been analyzed but have potential for addressing the kinematics of the San Juan Islands thrust system.

**Directions to Stop 3–4**
Continue up Erie Mountain Drive.
10.7 mi Summit of Mount Erie.

**Stop 3-4, Mount Erie Summit, Anacortes City Park, Fidalgo Island (Fig. 22)**

Massive diorite of the sheeted zone is intruded by fine-grained green dike rock (keratophyre and spilite). See views of the Olympic Mountains Tertiary subduction complex, Admiralty Inlet to Puget Sound, glacial drift from the Puget lobe, Eastern and Western Mélange belts in the Cascade foothills.

Directions to Stop 3–5
Retrace route down the Erie Mountain Drive.
12.3 Go south on Heart Lake Road.
13.5 Turn right (west) on Rosario Road.
14.4 Turn right (north) on Havekost Road, past intersection with Marine Drive.
16.2 Entranceway to the Lakeside Industries quarry is on the right.

Obtain permission at the office. Hard hats and vests are required. Avoid quarry slopes, which are unstable and dangerous.

**Stop 3-5, Lakeside Industries Quarry, Fidalgo Island (Fig. 22)**

Here we observe non-faulted stratigraphic contacts between the plagiogranite and sedimentary breccia, and between the breccia and overlying pelagic argillite. The coarse breccia consists of clasts of all lithologies of the underlying plutonic section including ultramafic rock, and therefore indicates uplift and exposure of the deeper levels of the section, presumably by faulting. The breccia represents slide and/or talus deposition. Presence of radiolaria (Fig. 24) and high manganese content of the overlying argillite indicates a marine environment enriched by alteration of volcanic materials and isolated from continent-derived sediment. The argillite is a chloritic mudstone with minor tuffaceous layers and thin sandstone beds with ultramafic detritus (Gusey, 1978). Volcanic-rich graywacke overlies these sedimentary rocks and bears detrital zircons with a 148 Ma age peak, younger than the breccia detritus which is derived from the 160–170 Ma underlying arc (Fig. 22). The Fidalgo ophiolite is interpreted to be a remnant arc, and the overlying graywacke to have been deposited in either a fore-arc or backarc basin.
Directions to Stop 3-6 (See Also Fig. 25)

Return to highway 20 spur by the following route:
- Turn right out of the Lakeside Industries driveway to go north on Havekost Road.
- 41st Street: Go right (east) on 41st St.
- O avenue: Jog north one block then east one block.
- Commercial Avenue: Go north.
- Highway 20 spur: Drive east on highway 20

0.0 Sharps Corner, main highway 20, reset odometer; continue east.
6.8 mi Highway 237 (Farm to Market Road); go north to the village of Edison.
14.6 Bow Hill Road; go right (east).
15.6 Chuckanut Drive; go left (north).
19.6 Cross Oyster Creek (at hairpin turn).
19.7 On the left is Oyster Creek Inn and the road to Taylor shellfish farm (sign). Head down this one-lane road, across Oyster Creek at the bottom of the hill, continue for ~100 m, and park on the right near the railroad tracks. Hike across the tracks and north along the tide flats to the mouth of Oyster Creek.

Easton Metamorphic Suite

The Easton Metamorphic Suite (formerly known as the Shuksan Metamorphic Suite; Misch, 1966) is a mostly well-recrystallized blueschist terrane with close similarities to the Pickett Peak terrane of the Franciscan Complex (Brown and Blake, 1987). A variety of lithologic components are found in this unit (Fig. 25): (1) blueschist and greenschist derived from mid-oceanic-ridge basalt (Dungan et al., 1983) known as the Shuksan Greenschist (Misch, 1966); (2) quartzose carbonaceous phyllite, derived from mudstone, named the Darrington Phyllite; (3) metagraywacke semischist derived from sandstone with abundant chert and dacitic-andesitic clasts; (4) local pods of metamorphosed plutonic rock of tonalitic to gabbroic composition; and (5) a local zone of high-pressure amphibolite and eclogite. The suite as a whole defines the “Shuksan Nappe” of Tabor et al. (2003), a sheet some 100 km in length and breadth exposed across much of the northwest Cascades and breached in an anticlinal structure known as the “Mt Baker window” (Misch, 1966) where underlying nappes can be observed.

Figure 25. Regional map of the Easton Metamorphic Suite; isotopic ages from Brown et al. (1982), Armstrong and Misch (1987), Gallagher et al. (1988), Dragovich et al. (1988, 1999). Cz—Cenozoic rocks and surficial deposits; abbreviations of other units given in Table 1.
An ocean floor stratigraphy is evident where the Shuksan Greenschist is stratigraphically overlain by a thin zone of metaliferous quartzose rock which is in turn overlain by Darrington Phyllite (Haugerud et al. 1981). The metagraywacke unit is interlayered with Darrington Phyllite in the western part of the Shuksan Nappe and represents volcanic arc and flysch detritus. Based on the above relations, Gallagher et al. (1988) proposed a back arc setting for the Easton Metamorphic Suite.

Protolith ages are indicated by U-Pb zircon ages of the tonalite and gabbro bodies at 163–164 Ma (Fig. 25; Walker in Gallagher et al. 1988, Dragovich et al. 1998, 1999) and detrital zircons in a sample of the graywacke yielding a prominent age peak at 155 Ma (Brown and Gehrels, 2007). The gabbro-tonalite bodies occur within the graywacke stratigraphy and bear the same metamorphic mineralogy and tectonite fabric as the graywacke. These relations and the older age of the gabbro-tonalite bodies imply that they were faulted or slid into the graywacke depositional basin.

Metamorphic ages known from Rb-Sr and K-Ar ages of muscovite and amphibole (Armstrong in Brown et al. 1982; Armstrong and Misch, 1987) date regional blueschist metamorphism at 120–130 Ma and the higher grade localized amphibolite-eclogite metamorphism at 144–160 Ma.

Stop 3-6. Semischist and Gabbro of the Easton Suite at the Mouth of Oyster Creek, Private Land (Fig. 26)

This outcrop is near the western margin of exposure of the Easton Suite, which comprises the “Shuksan Nappe.” Metamorphic mineralogy and structure point to continuation of the Shuksan Nappe somewhat beyond this point into small islands of the eastern San Juan archipelago (Lamb, 2000). Some workers have considered that the Shuksan Nappe possibly extended as a structurally high unit across the San Juan Islands contributing to the 20-km-thick burial required for aragonite metamorphism (Brandon et al., 1988).

The semischist exposed here is chert rich (Fig. 27) and is interbedded with carbonaceous phyllite. Stretched chert clasts mark a northeast trending shallow lineation of similar orientation to that found regionally in the Easton Suite and interpreted to represent orogen-normal displacement during Early Cretaceous subduction zone metamorphism (Brown, 1987).

A short distance along the tidelands to the north is a body of metagabbro (Fig. 26) similar to others in the Easton Suite dated to be 163–164 Ma (Fig. 25). The contact of the gabbro and semischist along the beach is covered by colluvium, but in roadcuts along the highway above, serpentinite is seen to intervene between the units. The origin of the gabbro bodies in the Easton is an interesting problem. They have apparently either slid or been faulted into the graywacke section (see above). The gabbro ages are similar to plutonic rocks in the Fidalgo Complex and the Ingalls Complex (Fig. 2A), which therefore could conceivably have been a source for these materials.

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