Geology of the San Juan-Cascade Nappes, Northwestern Cascade Range and San Juan Islands

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INTRODUCTION

The San Juan-Cascade nappes (Fig. 1) lie in a northwest-trending belt which is bounded by the Skagit metamorphic core (Haugerud, this volume) to the northeast and Wrangellia to the southwest. Wrangellia is a large coherent terrane that underlies much of Vancouver Island. At present, the nappe sequence has a cross-strike width of at least 150 km, extending from the westernmost thrust in the San Juan Islands (labeled Late Cretaceous suture in Fig. 1) to the Ingalls ophiolite in the Mount Stuart area (shown as Decatur terrane on Fig. 1). A common interpretation is that the San Juan-Cascade nappes represent a long-lived accretionary system that formed by successive arrival of far-traveled terranes (for example, Whetten and others, 1978). This view is certainly consistent with the varied assortment of Mesozoic and Paleozoic terranes in the nappes. More recent work (Brandon and others, 1988), however, has shown that large parts of the nappe sequence were assembled during a short-lived orogenic event, bracketed between 100 and 84 Ma. Brandon and Cowan (1985) argue that this orogenic event was associated with the collision of Wrangellia. The San Juan-Cascade nappes are considered to be a system of Late Cretaceous thrust sheets that were driven to the southwest over Wrangellia. Many parts of the nappe sequence were also affected by a synchronous high-pressure metamorphic event (characteristic assemblage: prehnite-lawsonite-aragonite) caused by rapid structural burial and subsequent uplift within an advancing thrust wedge (Brandon and others, 1988).

The discussion section of this paper provides an overview for field stops in the San Juan-Cascade nappes, which are Stops 2-7 to 2-11 in the western Cascades (Haugerud, this volume) and Stops 3-1 to 3-8 in the San Juan Islands (described below). The discussion focuses on the following three topics: (1) pre-Late Cretaceous terranes within the nappe sequence, (2) continental accretion of these terranes prior to the Late Jurassic, and (3) the tectonic setting associated with Late Cretaceous thrusting.

DISCUSSION

Pre-Late Cretaceous Terranes in the San Juan-Cascade Nappes

The San Juan-Cascade nappes are commonly identified as a composite terrane (for example, Jones and others, 1983) because of the pervasive effects of Late Cretaceous thrusting. In the extreme, each nappe or fault slice might be considered a separate terrane, and the Late Cretaceous faults viewed as fundamental terrane boundaries. A more conventional approach is to use geologic relations within each nappe to piece together the larger tectonostratigraphic units that existed prior to the Late Cretaceous. An example of this approach is the analysis of Brandon and others (1988), which employs stratigraphic relations, paleontological ages, isotopic dates, and chemical analyses to identify and characterize pre-Late Cretaceous terranes in the San Juan Islands. The results of this analysis are extended here to all parts of the San Juan-Cascade nappes (Table 1, Figs. 1 and 2). This analysis should be viewed as preliminary considering that the internal stratigraphy and age of many of the Cascade nappes are just starting to be resolved.

Seven pre-Late Cretaceous tectonostratigraphic units are identified in Table 1 (shown as major headings). Each of these contains one or more affiliated rock units (listed below the major headings). Three types of tec-

From: Joseph, N. L., and others, editors, 1989, Geologic guidebook for Washington and adjacent areas: Washington Division of Geology and Earth Resources Information Circular 86.

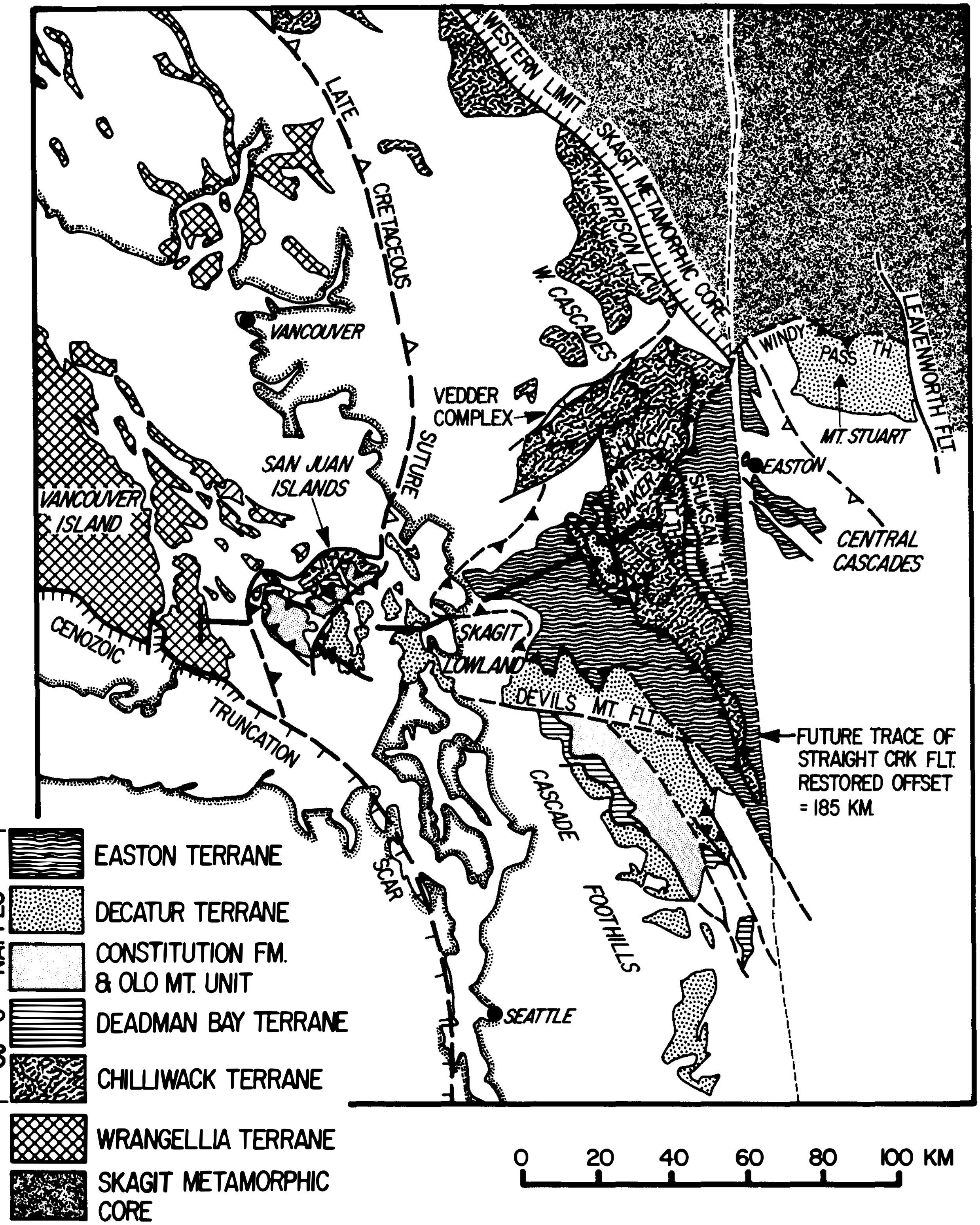

Figure 1. Generalized map of tectonostratigraphic units in the San Juan-Cascade nappes. The Straight Creek fault is restored based on the interpretation of Misch (1977b), which matches metamorphic units in the Skagit Core (Chiwaukum and Settler Schists). The Vedder terrane, Richardson basalts, and Lopez Structural Complex are too small to show here. One exception is a large outcrop of Vedder terrane at Vedder Mountain (labeled "Vedder Complex"). The east-west line across the San Juan Islands and Mount Baker locates the cross-section in Figure 4. The fault labeled "Late Cretaceous suture" marks the western limit of the San Juan-Cascade nappes. The fault labeled "Cenozoic truncation scar" marks the location of an inferred early Cenozoic fault that truncated the southwest side of the Cascade orogen (Brandon, 1985).

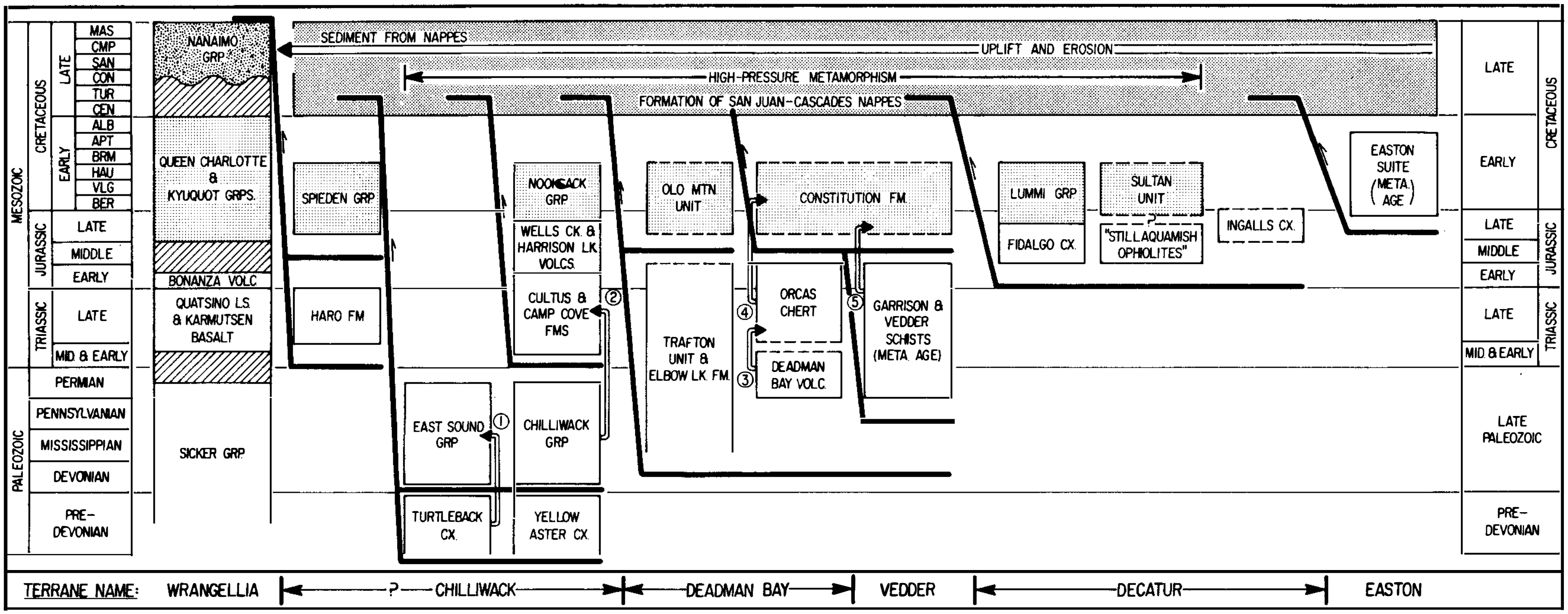

Figure 2. Pre-Late Cretaceous terranes in the San Juan-Cascade nappes (modified from Brandon and others, 1988; see Table 1 for further details). Each column represents a separate terrane with its name appearing below. The continuous portion of a column shows rock units that are connected by demonstrable stratigraphic contacts. Breaks in a column indicate that stratigraphic contacts are not preserved. Stratigraphic hiatuses are hachured, and dashed horizontal lines indicate that the age range of the unit is not known. Arrows with numbers indicate other types of geologic ties between rock units within a terrane. The numbers refer to the following comments: (1) dikes related to the East Sound Group are found in the Turtleback Complex, and a poorly preserved unconformity between the two units is locally present (Brandon and others, 1988); (2) cobbles of Chilliwack Group limestone are found in the Camp Cove Formation (Monger, 1986; Monger and Berg, 1987); (3) similarities in chert ages and basalt chemistry (Brandon and others, 1988); (4) Tethyan fusulinid-bearing limestone cobbles in the Constitution Formation (Brandon and others, 1988); and (5) Garrison schist cobbles and detritus in the Constitution Formation (Brandon and others, 1988). Stippled units are Jurassic and Cretaceous clastic linking sequences, which are inferred to postdate accretion of the pre-Late Cretaceous terranes to continental America. The timing of Late Cretaceous thrusting and regional high-pressure metamorphism is shown at the top of the diagram. Heavy lines are meant to schematically represent thrust faults within the San Juan-Cascade nappes. The lower flats of these faults underlie the units that they involve, and the upper flats marks the time of movement of the fault. The Nanaimo Group is a synorogenic unit that was deposited on Wrangellia and received detritus from the San Juan-Cascade nappes.

Table 1. Pre-Late Cretaceous units in the San Juan-Cascade nappes. Tectonostratigraphic headings are listed in an order that approximates their relative positions, from top to bottom, in the nappe sequence.

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EASTON TERRANE (METAMORPHIC)

Easton Metamorphic Suite (= Shuksan Suite of Misch, 1966) [WC & CC; 2, 12, 14]: Metamorphism is primarily Early Cretaceous (120-130 Ma). A coherent high-pressure metamorphic unit composed of basalt (ocean-floor chemistry), graphitic quartzose phyllite, minor sandstone, and rare metalliferous sediments. Locally includes minor Late Jurassic barroisite schist. Isotopic dating suggests a Jurassic depositional age for the clastic sediments.

DECATUR AND RELATED TERRANES (COHERENT)

Middle and Late Jurassic ophiolite and arc-volcanic complex; also includes overlying Jura-Cretaceous clastic strata.

Fidalgo Igneous Complex [SJ; 1]: Middle and Late Jurassic. Ultramafite, gabbro, and low-potassium basalt, andesite and dacite. In the San Juan Islands, the associated volcanic sequence contains interbedded radiolarian argillite and chert, and breccia with clasts derived from the underlying plutonic and volcanic sequence.

Miscellaneous ophiolitic units in the Cascades Foothills [CF; 9, 11]: Middle and Late Jurassic. A group of ophiolitic units which based on age and lithology are broadly correlative to the Fidalgo Complex. Includes the Twin Sisters dunite, the Haystack unit [9, 10], the Stillaguamish ophiolite [11], volcanic and plutonic rocks of the Western Melange [8], and the Deer Creek volcanics [2].

Ingalls Complex [CC; 3,4]: Late Jurassic. A complexly faulted assemblage of ultramafite, gabbro, mafic and silicic volcanics, ribbon chert, and sandstone.

Lummi Group [SJ; 1, 13]: Latest Jurassic and Early Cretaceous. Marine clastic strata overlying the Fidalgo Complex.

Clastic units associated with ophiolitic rocks of the Cascades Foothills [CF]: Late Jurassic and Early Cretaceous. Consists of poorly exposed and variably disrupted mudstone, turbidite, conglomerate and minor chert. Includes the Sultan unit [7] and units pTwa and pTwak in the Western Melange [8].

PILLOW BASALTS OF RICHARDSON (EXOTIC FAULT SLICE)

Basalts of Richardson [SJ; 1]: Middle Cretaceous (latest Albian, 100 Ma). A small fault-bounded pillow basalt unit found in the Lopez Structural Complex, a Late Cretaceous imbricate fault zone in the San Juan Islands. Another slice of this unit may be present on northern Cypress Island [13]. High-Ti basalt chemistry suggests an ocean-island affinity. The age of this unit provides a lower bound for thrusting and regional high-pressure metamorphism in the San Juan Islands.

CONSTITUTION FORMATION (FAULT-BOUNDED LINKING SEQUENCE)

Constitution Formation [SJ; 1]: Jurassic or Early Cretaceous. Stratified sequence of volcaniclastic sandstone, mudstone, ribbon chert and green tuff with slide blocks of pillowed basalt and dacite. Contains clasts and cobbles derived from the Garrison Schist and a fusulinid-bearing limestone cobble from the Deadman Bay Volcanics.

Possibly correlative units in the Cascade Foothills [CF; 9]: Late Jurassic and Early Cretaceous. Poorly exposed and variably disrupted assemblage of mudstone, sandstone, chert, basalt and green tuff. Includes the Olo Mountain unit [7, 9] and units pTws and pTwsv in the Western Melange [8].

VEDDER AND RELATED TERRANES (METAMORPHIC)

Vedder Complex [WC; 2] and Garrison Schist [SJ; 1]: Permian and Triassic metamorphic ages. Metabasaltic schist with minor metachert; grade ranges from greenschist to albite-epidote amphibolite and blueschist. In the San Juan Islands, the Garrison occurs as isolated fault slices along the Rosario thrust.

Table 1. Pre-Late Cretaceous units in the San Juan-Cascade nappes (continued).

DEADMAN BAY AND RELATED TERRANES (COHERENT)

Upper Paleozoic and Lower Mesozoic high-Ti pillow basalts, chert and limestone with Tethyan fusulinid fauna.

Deadman Bay Volcanics and Orcas Chert [SJ; 1]: Early Permian to Early Jurassic. A disrupted stratigraphic sequence composed of chert, mudstone, pillow basalt, and limestone. Basalt chemistry indicates an oceanic-island affinity. Limestones contain Tethyan fauna.

Elbow Lake Formation [WC; 2]: Poorly dated (Pennsylvanian?, Jurassic?). Ribbon chert and mudstone with minor green tuff, limestone and high-Ti basalt.

Trafton unit [CF; 7, 9]: Mississippian to Jurassic. Ribbon chert, mudstone, green tuff, basalt and limestone. Limestones contain Tethyan fusulinid fauna.

CHILLIWACK AND RELATED TERRANES (COHERENT)

Paleozoic to Middle Jurassic arc-volcanic rocks with McCloud-type fusulinid fauna; includes overlying Jura-Cretaceous clastic sequence.

Yellow Aster [WC; 2] and Turtleback [SJ; 1] Igneous Complexes: Mostly Early Paleozoic, possibly a Precambrian component as well. A plutonic complex composed of tonalite and subordinate gabbro. Relationships in the San Juan Islands suggest that these units are basement for the Chilliwack-East Sound volcanics [1].

Chilliwack [WC; 2] and East Sound [SJ; 1] Groups: Early Devonian to Early Permian. An arc-volcanic sequence with minor interbedded limestone. Limestones contain McCloud-type fauna.

Cultus [WC; 2], Camp Cove [HL; 5] and Haro [SJ; 1] Formations: Triassic and Early Jurassic. Volcaniclastic and pyroclastic sediments, radiolarian-bearing siliceous argillite, shelly interbeds and subordinate silicic volcanic rocks. The Camp Cove contains fossiliferous limestone cobbles derived from the Chilliwack [6].

Wells Creek [WC; 2] and Harrison Lake [HL; 5] Volcanics: Early and Middle Jurassic. Andesitic and dacitic volcanic flows and pyroclastic rocks.

Nooksack [WC & HL; 2, 5] and Spieden [SJ; 1] Groups: Late Jurassic and Early Cretaceous. Well bedded marine clastic strata derived primarily from an arc-volcanic source.

NOTE: Brackets enclose locations and references. Locations are: **WC** western Cascades, **SJ** San Juan Islands, **HL** west side of Harrison Lake, **CF** Cascade foothills south of Devils Mountain fault, and **CC** central Cascades (Mount Stuart area).

REFERENCES: [1] Brandon and others, 1988; [2] Brown and others, 1987; [3] Southwick, 1974; [4] Miller, 1985; [5] Arthur, 1986; [6] Monger and Berg, 1987; [7] Danner, 1957, 1966; [8] Frizzel and others, 1987; [9] Whetten and others, 1988; [10] Whetten and others, 1980; [11] Vance and others, 1980; [12] Frizzel and others, 1984; [13] Garver, 1988a; [14] Armstrong and Misch, 1987.

tonostratigraphic units have been recognized (terms in parentheses following major headings in Table 1):

(1) *coherent terrane*, which comprises a stratigraphically related sequence of units with an associated crustal basement;

(2) *metamorphic terrane*, which refers to a package of rocks that have been so thoroughly reconstituted that they are best characterized by their metamorphic history; and

(3) *linking sequence*, defined as an epiclastic unit that demonstrates, by virtue of provenance or stratigraphic overlap, the juxtaposition of two disparate terranes or the incorporation of an oceanic terrane into a continental margin setting.

Some parts of the San Juan-Cascade nappes are better characterized by their Late Cretaceous structural history than by their pre-Late Cretaceous history. They constitute a fourth type of tectonostratigraphic unit, called a *structural complex*, which is a heterogeneous and highly faulted assemblage of rock units. At present, there is only one designated structural complex in the San Juan-Cascade nappes (Lopez Structural Complex in the San Juan

Islands; Brandon and others, 1988), although some of the highly imbricated zones in the western Cascades are likely candidates. An important aspect of these structural complexes is the common occurrence of small slices of exotic rock units which are stratigraphically unrelated to units outside of the complex (for example, the Richardson pillow basalts in the Lopez Complex; see Table 1). The presence of these exotic elements suggests that these zones have accommodated large displacements.

Some of the linking relations that are used to tie various rock units to specific terranes are shown in Figure 2. Some of these assignments are tentative (for example, Haro Formation and Spieden Group in the Chilliwack terrane), but in most cases they can be well supported (references given in Table 1). Five pre-Late Cretaceous terranes are recognized: three coherent terranes, the Chilliwack, Deadman Bay, and Decatur; and two metamorphic terranes, the Easton and Vedder.

The oldest terrane is the Chilliwack (Monger and Berg, 1987), which records intermittent arc-magmatism from at least the Cambrian to Middle Jurassic. This terrane is synonymous with the Grandy Ridge terrane of Haugerud (this volume) and the Turtleback terrane of Brandon and others (1988). The Chilliwack terrane contains an early Paleozoic, and possibly Precambrian igneous basement (Turtleback and Yellow Aster Complexes) and a Lower Devonian to Middle Jurassic sequence of volcanic rocks with subordinate limestone and epiclastic sediments. Units within this terrane are examined at Stops 2-7 and 2-8 (Haugerud, this volume). The Chilliwack terrane is commonly correlated with arc-volcanic rocks in the eastern Klamath Mountains and eastern Sierra Nevada of northern California, and with the Quesnellia terrane of British Columbia (Davis and others, 1978; Saleeby, 1983). These terranes are considered to be remnants of a late Paleozoic and early Mesozoic magmatic arc that fringed the western margin of North America. Permian limestones in this belt are distinguished by the McCloud fusulinid fauna, a provincial fauna of western North America (Monger and Ross, 1971; Saleeby, 1983).

Two other terranes include Paleozoic rocks: the Deadman Bay and Vedder terranes. They overlap in age with the Chilliwack terrane but are otherwise distinct. The Deadman Bay terrane (Stop 3-7) comprises a Lower Permian to Lower Jurassic stratigraphic sequence of oceanic-island pillow basalt, limestone, and ribbon chert. In addition to obvious lithological contrasts with the Chilliwack, Permian limestones in the Deadman Bay terrane contain a Tethyan fusulinid fauna considered to be exotic to North America. The Deadman Bay is probably equivalent to parts of the Cache Creek terrane of British Columbia and the North Fork-Hayfork terrane of the Klamath Mountains (Davis and others, 1978; Saleeby, 1983).

The Vedder terrane (Stop 3-6) consists chiefly of fine-grained metabasaltic schist ranging in grade from greenschist to albite-epidote amphibolite and blueschist (Brown and others, 1987; synonymous with the Garrison terrane of Brandon and others, 1988). The largest outcrop is at Vedder Mountain in the western Cascades (labeled Vedder Complex in Fig. 1). All other occurrences are less than several hundred meters across and are too small to show in Figure 1. Isotopic dates cluster between 286 and 219 Ma (Armstrong and Misch, 1987), indicating Permian or Triassic metamorphism. Thus, metamorphism of the Vedder coincided with volcanism and chert deposition in the Chilliwack and Deadman Bay terranes. The Vedder may be related to other Permian and Triassic metamorphic units in the western Cordillera, such as the Pinchi Lake blueschist of British Columbia (Paterson and Harakal, 1974) and the Fort Jones blueschists of the Klamath Mountains (Davis and others, 1978; Irwin, 1981). A common feature of these Permian and Triassic metamorphic rocks is that they are typically associated with Deadman Bay-like units composed of upper Paleozoic and lower Mesozoic chert, basalt, and limestone. An inference is that the Vedder and Deadman terranes formed in a common tectonic setting, possibly at a late Paleozoic-early Mesozoic subduction zone (Davis and others, 1978). In the San Juan-Cascade nappes, Late Cretaceous faulting has obscured any obvious evidence of an early connection between these two terranes.

The youngest terranes in the San Juan-Cascade nappes are the Decatur and Easton terranes. The Decatur terrane (Stops 3-1 and 3-2) is floored by a Middle to Upper Jurassic ophiolite and contains a superimposed Upper Jurassic arc-volcanic complex. The ophiolitic basement of the Decatur allows this terrane to be clearly distinguished from older San Juan-Cascade terranes. The Decatur terrane is strikingly similar in age and stratigraphy to the Coast Range ophiolite of California (Hopson and others, 1981; Shervais and Kimbrough, 1985; Garver, 1988b).

The Easton terrane (Stop 2-11 in Haugerud, this volume) comprises a suite of Early Cretaceous metamorphic rocks, metamorphosed under blueschist conditions (P = 800-900 Mpa [8-9 kb], T = 300°-400° C; Brown and Blake, 1987). Its distinctive metamorphic history distinguishes the Easton from the other terranes listed above. The Easton appears to be of the same age, lithology, and degree of metamorphism as metamorphic rocks in northern California and southern Oregon (Brown and Blake, 1987). These rocks are located in the eastern part of the Franciscan Complex (South Fork Mountain and Colebrook schists) and in a thrust window in the Klamath Mountains (Condrey Mountain schist) and apparently were formed during an early stage in the development of the Franciscan subduction complex.

Another potential tectonostratigraphic unit is the middle Cretaceous pillow basalts of Richardson. This unit appears to be restricted to two small fault slices in the San Juan Islands (approximate dimensions: 2.5 km x 250 m-500 m). The main slice (Stop 3-4) is in the Lopez Structural Complex at the town of Richardson, southern Lopez Island (labeled "R" in Fig. 3). Garver (1988a) has tentatively identified a second slice on northern Cypress Island (labeled "R?" in Fig. 3), but paleontological ages from this locality are poorly resolved. The Richardson basalts are important to San Juan geology because they are the youngest rocks affected by Late Cretaceous thrusting and high-pressure metamorphism. Foraminifera from interbedded shale at the Richardson locality have been identified as latest Albian (100 Ma) (Brandon and others, 1988).

An important question is whether to designate the Richardson basalts as a terrane. Arguing in favor is the fact that this unit is in some respects similar to the exotic limestone-basalt terranes in the Franciscan Complex (for example, Laytonville), which are interpreted as accreted fragments of seamounts. An important difference is that the middle Cretaceous Franciscan terranes contain pelagic limestone and chert, indicating an open-ocean setting (Sliter, 1984), whereas sediments in the Richardson basalts are limited to interbeds of hemipelagic shale with minor sand-sized grains of volcanic quartz. I feel that tectonostratigraphic classification is not warranted at this time. The main problem is that there are no coeval units to compare with the Richardson basalts. The tentative discovery of these basalts in the middle of the Decatur terrane ("R?" in Fig. 3) raises the possibility that they are a younger part of the Decatur terrane. If correct, the Richardson slice in the Lopez Complex ("R" in Fig. 3) could be explained as a fault slice derived from the adjacent Decatur terrane.

To the west and northwest of the San Juan-Cascade nappes lies Wrangellia (Jones and others, 1977) (Fig. 1), a coherent and regionally extensive terrane that underlies most of Vancouver Island. Wrangellia comprises a stratified sequence of Paleozoic arc-volcanic rocks, Triassic flood basalts, and Lower Jurassic arc-volcanic rocks (Muller, 1977). The oldest rocks are pre-Devonian, and probably Silurian (Brandon and others, 1986). This terrane is distinguished from adjacent terranes by its distinctive Triassic stratigraphy and also by the presence of a Boreal fusulinid fauna in Permian limestones (Monger and Ross, 1971). Wrangellia of Vancouver Island was not significantly affected by Late Cretaceous thrust faulting and shows no evidence of high-pressure metamorphism. It must have been near the nappes during the Late Cretaceous because it is overlain by synorogenic deposits of the Upper Cretaceous Nanaimo Group, which were derived, at least in part, from erosion of the San Juan-Cascade nappes (Brandon and others, 1988).

Timing of Continental Accretion

Most of the structural boundaries that separate terranes within the San Juan-Cascade nappes and also separate the nappes from Wrangellia are probably Late Cretaceous faults. There is evidence, however, that these terranes were accreted to continental America long before the Late Cretaceous. This conclusion is based on stratigraphic distinctions between terranes, which are pronounced during the Permian and Triassic and become almost insignificant during the Late Jurassic and Early Cretaceous.

This point is illustrated in Figure 2. All Upper Jurassic and Lower Cretaceous units (stippled units in Fig. 2) are composed almost entirely of marine epiclastic strata. In some places, these epiclastic units are in stratigraphic contact with older terranes (Kyuquot Group for Wrangellia; Lummi Group for Decatur terrane; Nooksack Group for Chilliwack terrane). In other places, these units are fault-bounded but can be tied to older terranes by a provenance link (for example, Constitution Formation contains clasts derived from Deadman Bay and Vedder terranes; Brandon and others, 1988).

All of these Jurassic and Cretaceous units are composed mainly of volcaniclastic sediments (p. 77 in Sutherland Brown, 1968; p. 36-39 in Muller and others, 1974; p. 25-31 in Muller and others, 1981; Brown and others, 1987; Brandon and others, 1988; Garver, 1988a), indicating that their source regions were dominated by intermediate to silicic arc-volcanic rocks. K-Ar dates of volcanic cobbles in the Spieden Group indicate that at least some of these volcanic rocks are Late Jurassic in age. The volcanic material cannot have been derived from San Juan-Cascade terranes or from Wrangellia because at that time these terranes were covered by Jurassic and Cretaceous marine strata.

The volume of sediment represented by these epiclastic units and other coeval epiclastic units to the north and south requires subaerially exposed source regions with continent-scale dimensions (Brandon and others, 1988). Thus, these epiclastic units are considered to be linking sequences that tie the San Juan-Cascade terranes and Wrangellia to a large continent-like mass, presumably the American continent, by the Late Jurassic. It is important to note that these linking sequences provide no information about the relative latitudinal position of each of the terranes along the Late Jurassic margin and do not preclude the possibility of younger coastwise translation.

Pre-Late Jurassic accretion is consistent with the accretionary history of similar terranes in the southern part of the Cordillera. In California, terranes similar to the

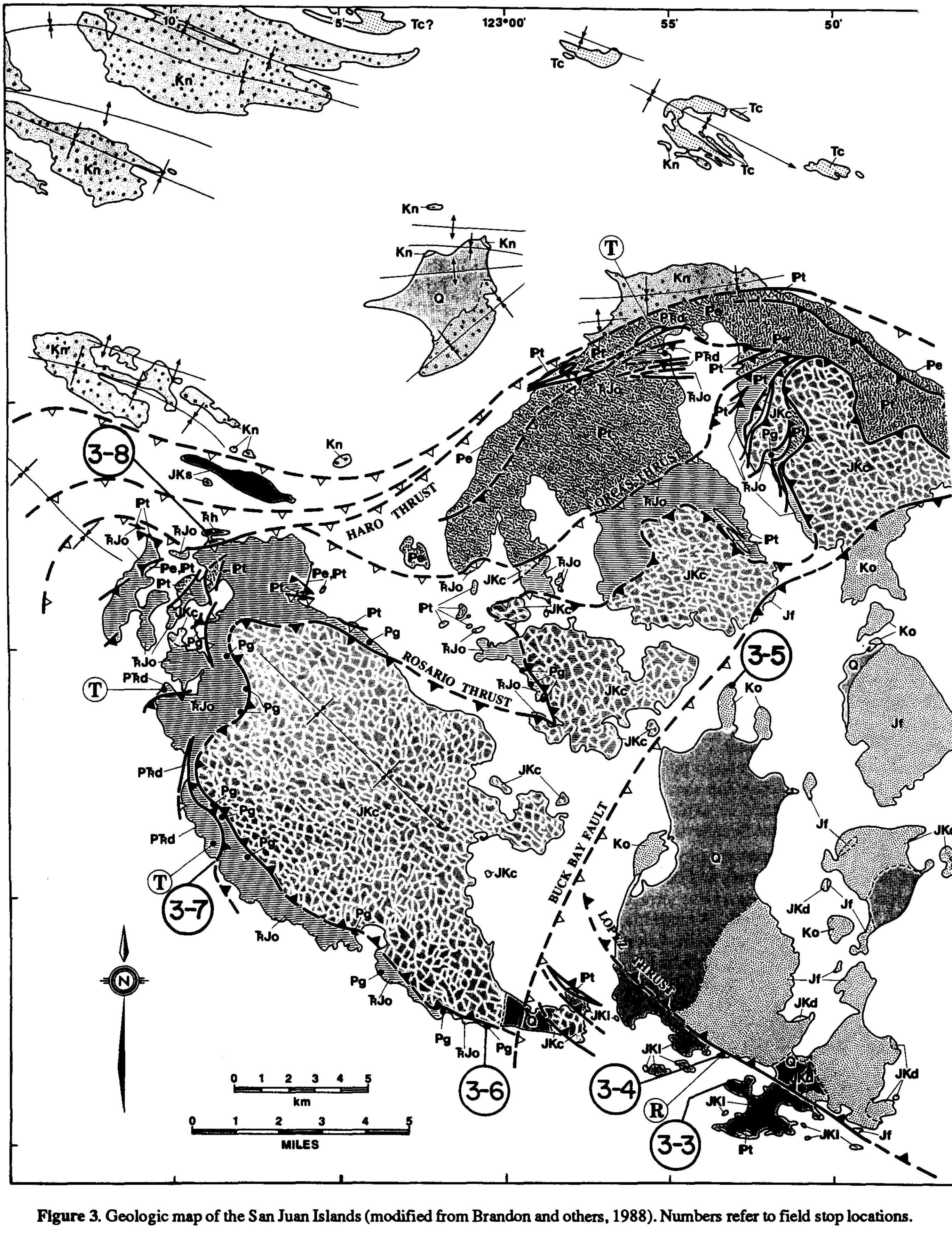

Figure 3. Geologic map of the San Juan Islands (modified from Brandon and others, 1988). Numbers refer to field stop locations.

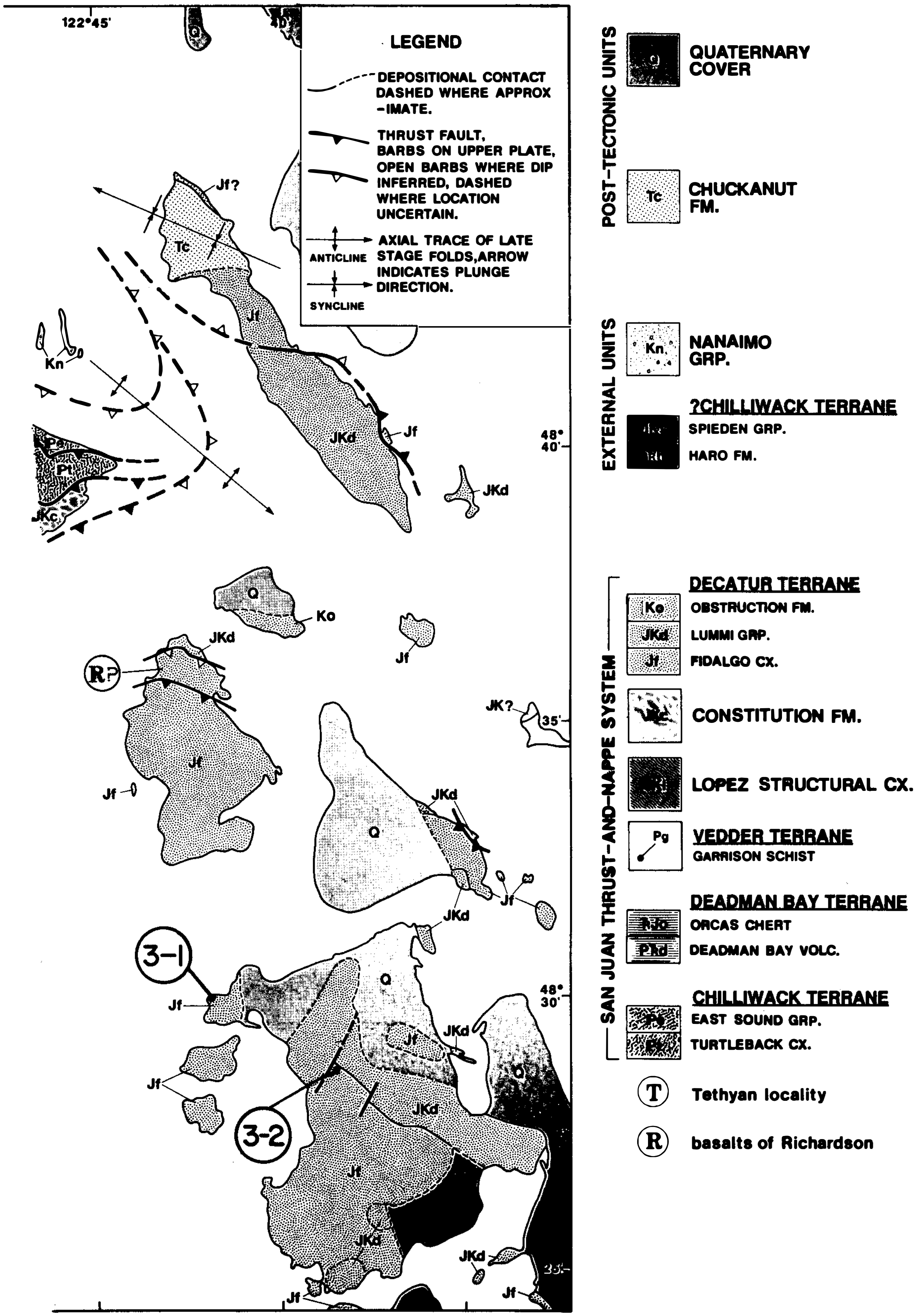

Figure 3. Geologic map of the San Juan Islands, continued.

Chilliwack, Deadman Bay, Vedder, and Decatur were accreted to continental North America by the Middle and Late Jurassic. The nature of this accretionary event remains uncertain: Did it involve the collisional arrival of an oceanic island arc (Schweickert, 1981) or non-collisional shortening of an in-situ arc system (Saleeby, 1981)? Regardless of the interpretation, this Middle to Late Jurassic event marks an important stratigraphic transition to widespread epiclastic sedimentation during the Late Jurassic and Early Cretaceous, as recorded by the Great Valley Group and Franciscan Complex. The Great Valley Group was deposited in a forearc setting with older accreted terranes forming the basement beneath the arc and forearc. The San Juan-Cascade terranes, and perhaps Wrangellia as well, may have been situated in a similar tectonic setting somewhere else along the Jurasic and Cretaceous Cordilleran margin. One readily identifiable remnant of this convergent margin setting is the Easton terrane.

Tectonic Setting of Late Cretaceous Orogeny

The formation and stacking of the San Juan-Cascade nappes is considered to be the hallmark of the Late Cretaceous Cascade orogeny (for example, Misch, 1966; Vance, 1977). The internal structure of the thrust belt is best preserved in the Mount Baker area and in the San Juan Islands (Fig. 1) where the superimposed effects of Tertiary deformation are minor. The east-west cross-section in Figure 4 provides a schematic view of the regional-scale structure of the thrust system. Though greatly simplified, this section shows that a regular stacking order is present at a regional scale. Misch (1966, 1977a) was first to recognize the broad aspects of this stacking order in the Mount Baker area. Further work in the Mount Baker area (Brown and others, 1987) and in the San Juan Islands (Vance, 1975, 1977; Whetten and others, 1978; Brandon and others, 1988) has substantiated and extended Misch's interpretation.

Misch (1966, 1977a, 1988) recognized three structural divisions in the Mount Baker area, from top to bottom: the Shuksan plate, the Church Mountain plate, and the "autochthon". The Shuksan plate forms the highest recognized nappe in the San Juan-Cascade system. It is composed solely of a fairly coherent section of Easton terrane and has a structural thickness that may approach 10 km. This plate is floored by the Shuksan thrust, which shows little imbrication with rocks of the underlying

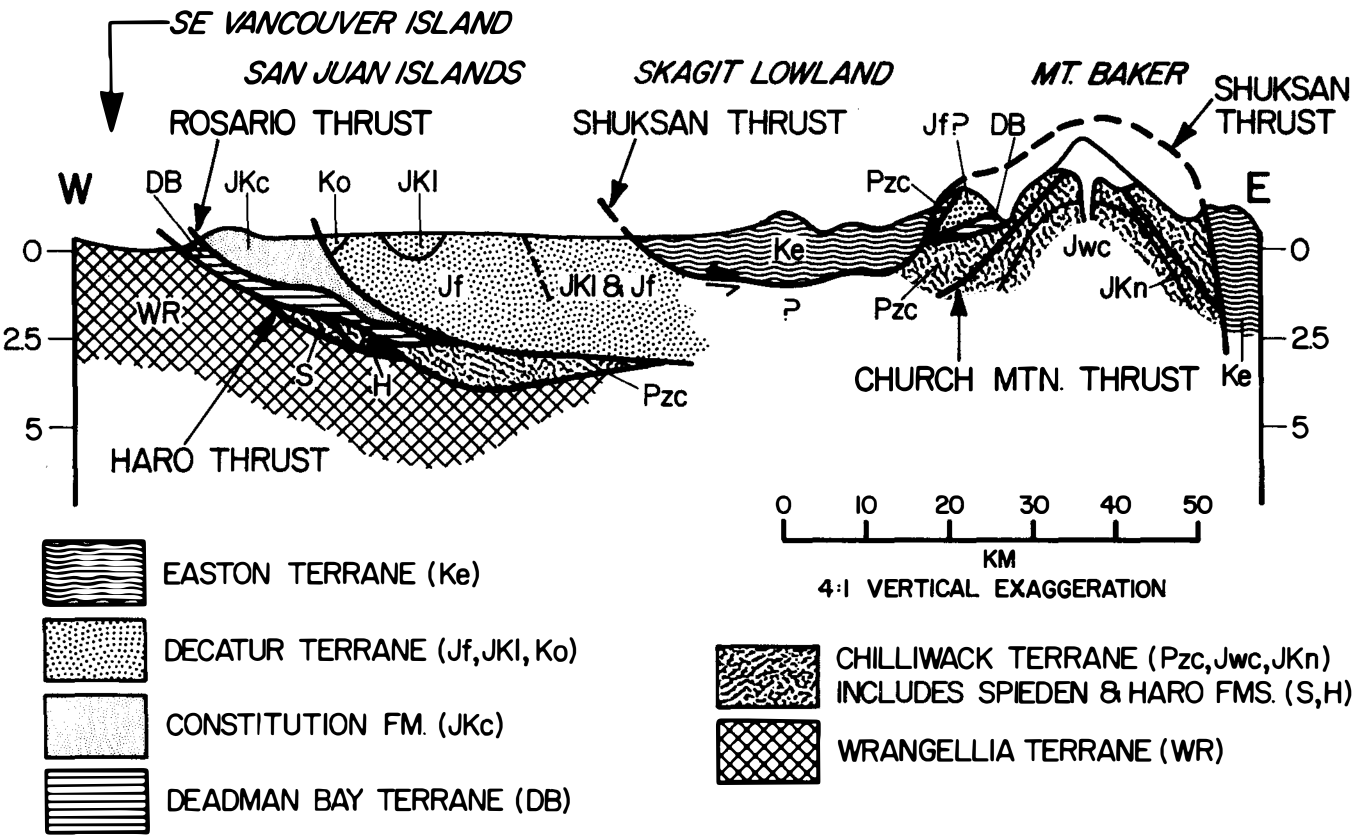

Figure 4. A schematic east-west cross section across the western Cascades and San Juan Islands (modified from Brandon and others, 1984). The location of the section is shown in Figure 1. Subsurface geology is projected in from the northwest using an average structural plunge of 12° to the southeast. Tectonostratigraphic units are defined in Table 1. The Vedder terrane, the Richardson basalts, and the Lopez Structural Complex are too small to portray here.

Church Mountain plate. The Church Mountain plate consists of a highly imbricated and heterogeneous assemblage derived mainly from the Chilliwack terrane and to a lesser degree from the Deadman Bay, Decatur, and Vedder terranes. The Church Mountain plate, which might be best represented as a structural complex, does occupy a specific structural level within the San Juan-Cascade nappes. Beneath the Church Mountain plate, which is floored by the Church Mountain thrust, lies the "autochthon" which consists of a relatively coherent section of Jurassic and Lower Cretaceous rocks of the Chilliwack terrane (Wells Creek Volcanics and Nooksack Group). Misch recognized that an unexposed thrust may underlie his "autochthon", and thus used this term merely as a label.

The extension of Misch's structural divisions west into the San Juan Islands is complicated by poor exposure in the intervening Skagit lowland (Fig. 1). The highest nappe found in the San Juans is the Decatur terrane. The Shuksan plate may have extended over the San Juan nappes (discussed below), but at present its western erosional limit is restricted to the Skagit lowland. The structural sequence in the San Juans, from top to bottom, consists of: Decatur terrane, Lopez Structural Complex, Constitution Formation, Vedder terrane, Deadman Bay terrane, and the Chilliwack terrane. (The Lopez Complex and Vedder terrane are too small to show in Fig. 4.) This sequence may represent a western extension of Misch's Church Mountain plate. Parts of the San Juan nappe sequence are highly imbricated; for example, see descriptions of the Orcas, Rosario, and Lopez faults in Brandon and others (1988). However, the San Juan sequence does not seem to be as pervasively faulted as the Church Mountain plate. Lying beneath the San Juan nappes are some small fault slices of Triassic and Jurassic and Cretaceous rocks (Haro Formation and Spieden Group, labeled "H" and "S" in Fig. 4) that may be equivalent to Misch's "autochthon". The presence of low-pressure zeolite assemblages in these rocks indicates that they were not subjected to the high-pressure metamorphic history that characterizes the rest of the San Juan-Cascade nappes.

In Figure 1, the San Juan-Cascade nappes are shown extending to the south and east of the Mount Baker area. This conclusion is based largely on the fact that almost all units in these areas can be correlated with units in the San Juan Islands and Mount Baker area. In some areas, particularly in the region south of the Devils Mountain fault (Fig. 1), Late Cretaceous structures are difficult to identify because of subsequent early Tertiary faulting and plutonism. However, these rocks do contain the same high-pressure metamorphic assemblage found in nappes of the San Juan Islands and Mount Baker area, suggesting a common tectonic history (discussed below).

A distinctive aspect of the San Juan-Cascade nappes is their metamorphic history. Much of the nappe sequence shows some evidence of a very low temperature, high-pressure metamorphism characterized by the formation of minor amounts of prehnite, lawsonite, and aragonite (McMillan, 1966; Monger, 1966; Vance, 1968; Misch, 1971; Beaty, 1974; Glassley and others, 1976; Brown and others, 1981). The details of this metamorphic event are best resolved in the San Juan Islands where Brandon and others (1988) have demonstrated that high-pressure metamorphism was caused by rapid structural burial during Late Cretaceous thrusting. Stratigraphic ages constrain this metamorphic event to the interval 100 to 84 Ma: (1) the youngest rocks involved in thrusting and metamorphism are the uppermost Albian (100 Ma) Richardson basalts; and (2) sandstone cobbles with lawsonite-prehnite assemblages are found in lowermost Campanian (84 Ma) strata of the Nanaimo Group, a synorogenic clastic sequence exposed to the north and northwest of the San Juan Islands. The Nanaimo Group also contains detritus from other parts of the San Juan-Cascade nappes, with the most obvious source being the Easton and Deadman Bay terranes. In the San Juan Islands, metamorphic conditions culminated at about 150°C and 600 Mpa (6 kb). These constraints require structural burial to depths of about 20 km and then uplift and return to the surface within a 16-m.y. interval, indicating a round trip with vertical velocities averaging about 2 km/m.y. Structural burial beneath an advancing thrust wedge to depths of 20 km implies much greater horizontal displacements, estimated to be at least 70 km or more.

Some parts of the nappe sequence were not affected by this high-pressure metamorphic event. Most notable is the Easton terrane (part of the Shuksan plate), although an isolated occurrence of metamorphic aragonite (Evans and Misch, 1976) may be related to the Late Cretaceous event. (Evans and Misch, 1976, attributed the aragonite to Early Cretaceous metamorphism of the Easton terrane.) The general absence of Late Cretaceous metamorphic assemblages in the Easton suggests that it may have formed a large part of the structural overburden required for high-pressure metamorphism of the lower part of the nappe sequence. Cobbles of Easton rocks in the Nanaimo Group demonstrate that the Easton was at the surface during Late Cretaceous thrusting. The easternmost part of the nappe sequence, the Ingalls ophiolite (shown in Fig. 1 as Decatur terrane in the Mount Stuart area), also lacks evidence of the prehnite-lawsonite-aragonite metamorphism. This part of the San Juan-Cascade nappes lies above the Skagit metamorphic core and thus would have been affected by higher thermal gradients in this more interior part of the orogen. The Skagit core does record an increase of at least 10 km in metamorphic depth during the Late Cretaceous (Evans and Berti, 1986), possibly caused by the emplacement of San Juan-Cascade nappes over the core.

At present, a controversial issue is the direction of transport and tectonic setting of the San Juan-Cascade nappes. One group (Brandon and Cowan, 1985; McGroder, 1988) argues that the nappes were formed by the impingement of Wrangellia with the American continental margin, during which the San Juan-Cascade nappes were driven to the southwest over a footwall plate composed of Wrangellia. Another group (Brown, 1987; Smith, 1988) argues that the nappes formed in a northwest-trending transpressive shear zone. A third group (Davis and others, 1978; Vance and others, 1980; Miller, 1985) favors northward obduction of Decatur ophiolitic terranes from sites within the "Columbian embayment", a postulated oceanic embayment thought to lie in the vicinity of southwest Washington and western Oregon. This assemblage was then affected to various degrees by a younger episode of southwest-directed thrusting.

Much of this controversy centers on differing opinions about the transport direction of the San Juan-Cascade nappes. The argument for top-to-the-southwest transport is based largely on regional-scale features of the orogen, such as the northwesterly trend of the Skagit metamorphic core and the synorogenic Nanaimo basin. These features are interpreted to have formed during collision, with the metamorphic core marking the site of greatest crustal thickening and the Nanaimo basin representing a flexurally induced foredeep. They record the regional-scale configuration of the orogen and thus provide information about the overall shortening direction across the orogen.

The main argument for transpressive shear rests on the interpretation of small-scale structures in the Mount Baker area, which Brown (1987) and Smith (1988) attributed to Late Cretaceous faulting. Strain indicators show a pronounced horizontal elongation, but the trend of this elongation varies from northwest in the region south of Mount Baker to southwest in the region north of Mount Baker. Shear-sense indicators also vary considerably—only 60 percent of them are consistent with transpressive dextral shear in a northwest direction.

Another argument that Brown (1987) uses to support the transpressive shear interpretation is the fact that many of the faults in the Mount Baker area are steep, which he interprets as evidence that they formed as strike-slip faults. This conclusion is poorly founded because the present attitudes of the faults cannot be confidently related to their initial orientations. It is well known that thrust imbrication causes old thrust faults to rotate into steeper orientations. Furthermore, the steep attitudes of these faults could also be caused by younger deformation. Upper Cretaceous and Lower Tertiary strata in the Cascades and San Juan Islands commonly have moderate or steep dips, and in a few places are even overturned. Even so, it is important to point out that the top-to-the-southwest interpretation, based on regional-scale features of the orogen, appears inconsistent with most of the kinematic data of Brown (1987) and Smith (1988). As such, the controversy remains. An important aspect of the work of Brown (1987) and Smith (1988) is that it has demonstrated the need to better resolve and integrate outcrop-scale and orogen-scale kinematic evidence.

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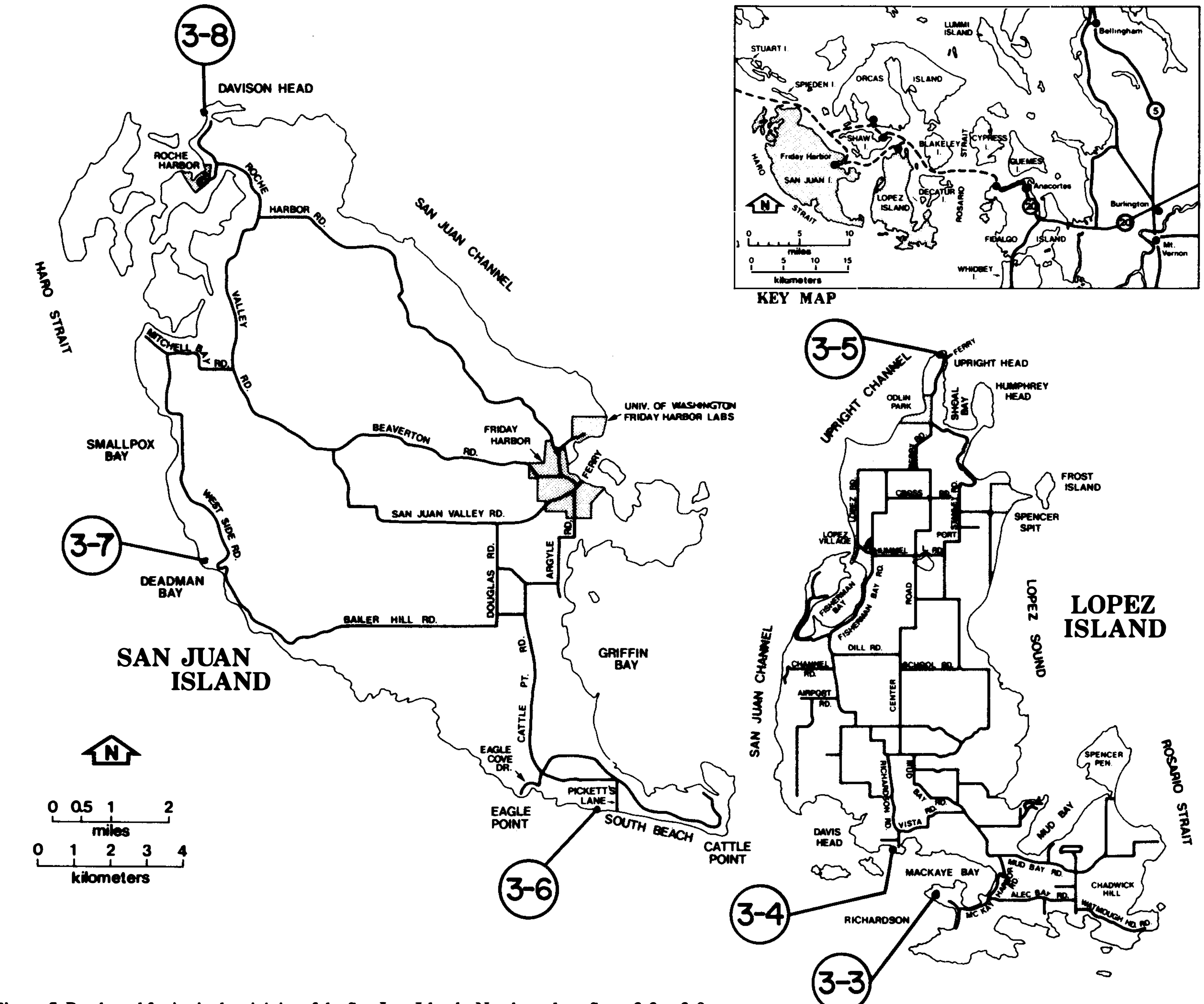

Figure 5. Roads and ferries in the vicinity of the San Juan Islands. Numbers show Stops 3-3 to 3-8.

Road Log

This log describes eight field stops (3-1 to 3-8 in Figs. 3 and 5) in the San Juan Islands. It is complemented by four field stops in the western North Cascades (2-7 to 2-11 in Haugerud, this volume). Collectively, these stops focus on the geology of the San Juan-Cascade nappes. Our goals are to: (1) examine timing constraints for thrusting and regional high-pressure metamorphism, (2) inspect outcrop-scale structures associated with some of the major thrusts, and (3) look at representative parts of the pre-Late Cretaceous tectonostratigraphic units found in the nappes. Other more comprehensive field guides to the San Juan Islands and surrounding areas are Brandon and others (1983), Brown (1977), Vance (1977), Cowan and Whetten (1977), Misch (1977), Brandon and Cowan (1987), and Gusey and Brown (1987). Several of the locality descriptions below are reproduced, with minor modifications, from the following original sources: Gusey and Brown (1987) for Stops 3-1 and 3-2 on Fidalgo Island; and Brandon and Cowan (1987) for Stops 3-4, 3-6, and 3-7.

Field Stops on Fidalgo Island

The first two stops are in the Fidalgo ophiolite (Decatur terrane), on the west side of Fidalgo Island (Figs. 3 and 6). From Interstate Highway 5, take exit 230 at Burlington and head west to Anacortes on Washington State Route (SR) 20 (inset map in Fig. 5). In Anacortes, follow the signs to the Washington State ferry terminal (Fig. 6), which will take you north on Commercial Avenue and then west (left) onto 12th Street (a spur of SR 20). Stay in the left lane at the junction to the ferry terminal and proceed straight ahead to Washington Park (Fig. 6). For the next two stops, cumulative mileage is shown in parentheses, starting at the park entrance.

Follow the loop road in the park. Stop near the leaning tree (0.4 mi).

STOP 3-1: Washington Park, Fidalgo Island—Serpentinized ultramafic rocks of the Fidalgo Igneous Complex.

The following text is reproduced with permission from Gusey and Brown (1987).

"Tidal exposures in this vicinity and to the west for several hundred meters display the ultramafic rock of the Fidalgo ophiolite. Look for chromite layers, relict pyroxenes, and original dunite-peridotite contacts in the serpentinite.

"The serpentinite exposed here is part of an ultramafic belt that is also exposed on nearby Burrows and Cypress Islands. Detailed analysis of the ultramafic rock on Cypress Island has shown the unserpentinized parts of the mass are largely harzburgite with a tectonite fabric, but possible relict igneous textures are visible (Raleigh, 1965).

"The serpentinite is thought to be the base of the Fidalgo ophiolite. Nowhere on Fidalgo Island, or elsewhere in the San Juan Islands, has a primary, unfaulted contact between the serpentinite and layered gabbro been observed. However, the close spatial relation of gabbroic and ultramafic rock and the indication from graded bedding in the gabbro suggest that the serpentinite lies down-section from the gabbro [Fig. 6]. Also, a small (30 x 50 m) lens of serpentinized peridotite occurs within the plagiogranite dike complex near the southern end of Fidalgo Island."

To reach Stop 3-2, proceed along the loop road to the park exit (2.4 mi) and head east on Sunset Avenue. Turn right (3.0 mi) onto Anaco Beach Road which becomes Marine Drive. Turn left (5.9 mi) onto Havekost Road and then turn right (6.8 mi) into the Marine Asphalt Company quarry. This quarry is still active. Stop at the office to ask for permission to enter.

STOP 3-2: Marine Asphalt Quarry, Fidalgo Island—Basal breccia and siliceous argillite resting on plutonic rocks of the Fidalgo Igneous Complex.

The following text is reproduced with permission from Gusey and Brown (1987).

"Here, plagiogranite exposed in the south quarry wall is overlain along an irregular contact by coarse sedimentary breccia containing clasts of plagiogranite, keratophyre, and spilite. Exposed on the west quarry wall, depositionally overlying the breccia, is steeply dipping pelagic argillite.

"Elsewhere on Fidalgo Island, sedimentary breccias apparently occupying the same stratigraphic position, that is, beneath pelagic argillite, contain clasts of serpentinite, cumulate gabbro, and pegmatitic diorite, as well as plagiogranite and volcanic rocks. Clast size ranges from 1 to 30 cm. These breccias may represent talus accumulations at the base of a submarine fault.

"Generally, the pelagic argillite unit is a radiolarian-bearing, metal-enriched, carbonate-free chloritic argillite with local minor tuf-

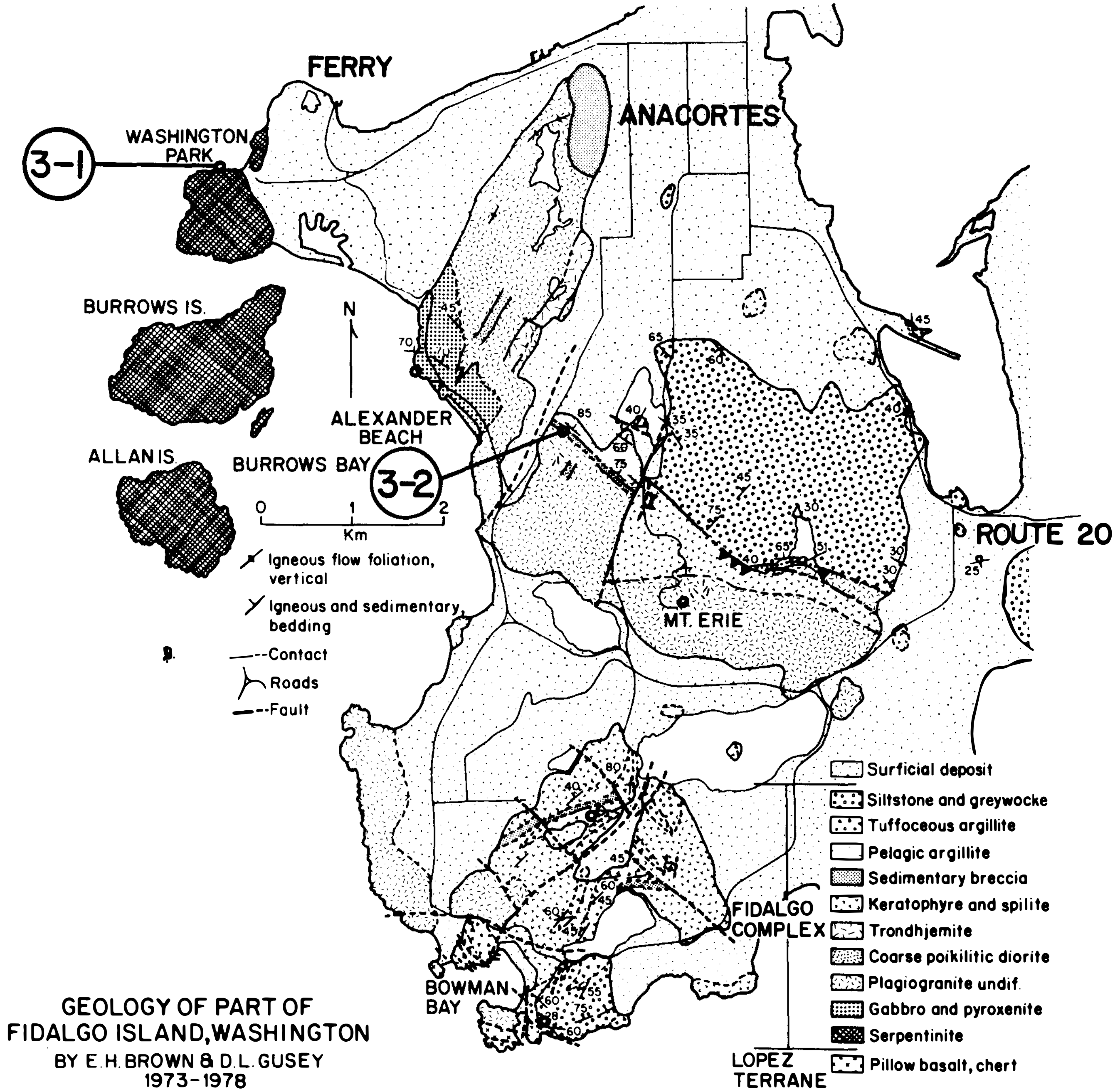

Figure 6. Geologic map of Fidalgo Island for Stops 3-1 and 3-2. Numbers refer to field stops locations. Reprinted with permission from Gusey and Brown (1987).

faceous debris. Radiolarians from an argillite bed approximately 55 m from the base of the unit have been dated as Late Kimmeridgian to Early Tithonian (Gusey, 1978). The concentration of metals (Ba, Cu, Ni, Co, and Mn) in the pelagic argillite is similar to that in present-day Pacific pelagic sediments (Brown, 1977).

"Of special interest within the pelagic argillite unit are thin (5 cm) interbeds of a chloritic sandstone. This sandstone consists of sand-sized chlorite grains in a micritic matrix. Diffractograms of the clay-size fraction indicate the presence of a well-crystallized, expandable chlorite. In thin section, mesh textures and cleavage traces are common in the chlorite. Also chlorite has been observed replacing pyroxene. Accessory minerals include chromite, quartz, plagioclase, clinopyroxene, garnet, amphibolite, and volcanic and sedimentary rock fragments. These beds are interpreted to have been deposited by turbidity currents from a nearby ultramafic source and subsequently chloritized (Gusey, 1978)."

To return to the Anacortes ferry terminal, retrace your way to the intersection of Anaco Beach Road and Sunset Avenue. Turn right on Sunset Avenue, then left at the entrance road to the Anacortes ferry terminal. Ferries from this terminal provide frequent service for cars and passengers to Lopez, San Juan, Orcas, and Shaw Islands. Long waits are to be expected on summer weekends.

Experience indicates that a road map is preferable to cumulative mileages for finding field stops in the San Juans because roads are too closely spaced for easy differentiation. Thus, the map in Figure 5 will be used for subsequent directions.

Field Stops on Lopez Island

For Stops 3-3, 3-4, and 3-5, take the Lopez Island ferry. The ferry disembarks at Upright Head on Lopez Island.

From the ferry terminal, head south on Ferry Road. At the T-intersection, turn left and then right onto Center Road and continue south to the next T-intersection, where you turn left and right again onto Mud Bay Road. Take the second right turn onto McKay Harbor Road. Follow this road to the intersection with Aleck Bay Road, and then continue southwest on McKay Harbor Road for another 0.5 mi to an unnamed dirt road that turns off to the right (north). Drive 0.3 mi on this road to a large grassy parking area adjacent to a wharf. The headland here, called Johns Point, is private property; you *must* ask permission to enter (currently at the small house about 75 m west of the parking area). Walk around the west end of the point where you will find nearly continuous exposures of bedrock.

STOP 3-3: Johns Point, Lopez Island—Fault slices and deformation in the Lopez Structural Complex.

The Lopez Structural Complex, which is the focus of Stops 3-3 and 3-4, is exposed along the south coast of Lopez Island and on the southeast tip of San Juan Island (Figs. 3 and 7). It represents a 2.5-km-thick imbricate fault zone that separates two fairly coherent Mesozoic units: the structurally lower Constitution Formation and the overlying Decatur terrane. At map scale (Fig. 7), the Lopez Complex consists of an imbricated series of elongate, lenticular fault slices, which dip moderately northeast beneath the Decatur terrane. Many of the fault slices are similar to, and were probably derived from the Constitution Formation and Decatur terrane; others contain exotic units that cannot be related to rock units in the footwall or the hangingwall. These exotic units are early Paleozoic tonalite (Turtleback Complex in Fig. 7, derived from the Chilliwack terrane) and the middle Cretaceous Richardson basalts.

The structural base of the Lopez Complex is not exposed. The top is the Lopez thrust, which marks the uppermost limit of significant structural interleaving of disparate rock units. This particular thrust is fairly easy to follow because it generally places igneous rocks of the Decatur terrane (Fidalgo Igneous Complex) over sedimentary units of the Lopez Complex. The most prominent structure visible in most outcrops in the Lopez is a northeast-dipping flattening cleavage. In the past, this cleavage was attributed to shearing within the fault zone, but subsequent work (Brandon and others, 1988) has shown that the cleavage formed by pressure-solution flow, that it is not restricted to the Lopez Complex, and that it postdates thrust faulting and regional high-pressure metamorphism. I attribute cleavage formation to late-stage ductile shortening as thrust slices moved through the warmest part of the thrust wedge (see fig. 29 of Brandon and others, 1988).

Most of the Lopez Complex is composed of two rock units derived from the Decatur terrane: (1) well-bedded turbidite sandstone and mudstone, with minor shale-chip and chert-pebble conglomerate; and (2) Jurassic pillow basalt and minor brecciated gabbro. Rock units from the Constitution Formation include: (1) chaotic mudstone-rich sequences composed mainly of olistostromal pebbly and bouldery mudstones, with clasts of sandstone, basalt, and chert dispersed in a black mudstone matrix; and (2) sandstone sequences with interbedded chert, green tuff, and basalt. The first of the Constitution-like units has yielded Early Cretaceous (Valanginian) ***Buchia***, and the second has yielded Jurassic or Cretaceous radiolarians from interbedded chert (Brandon and others, 1988).

All rock units in the Lopez Complex show some evidence of high-pressure metamorphism: sandstones contain lawsonite and aragonite; the slices of Turtleback tonalite contain rare lawsonite; basalts, including the Richardson basalts,

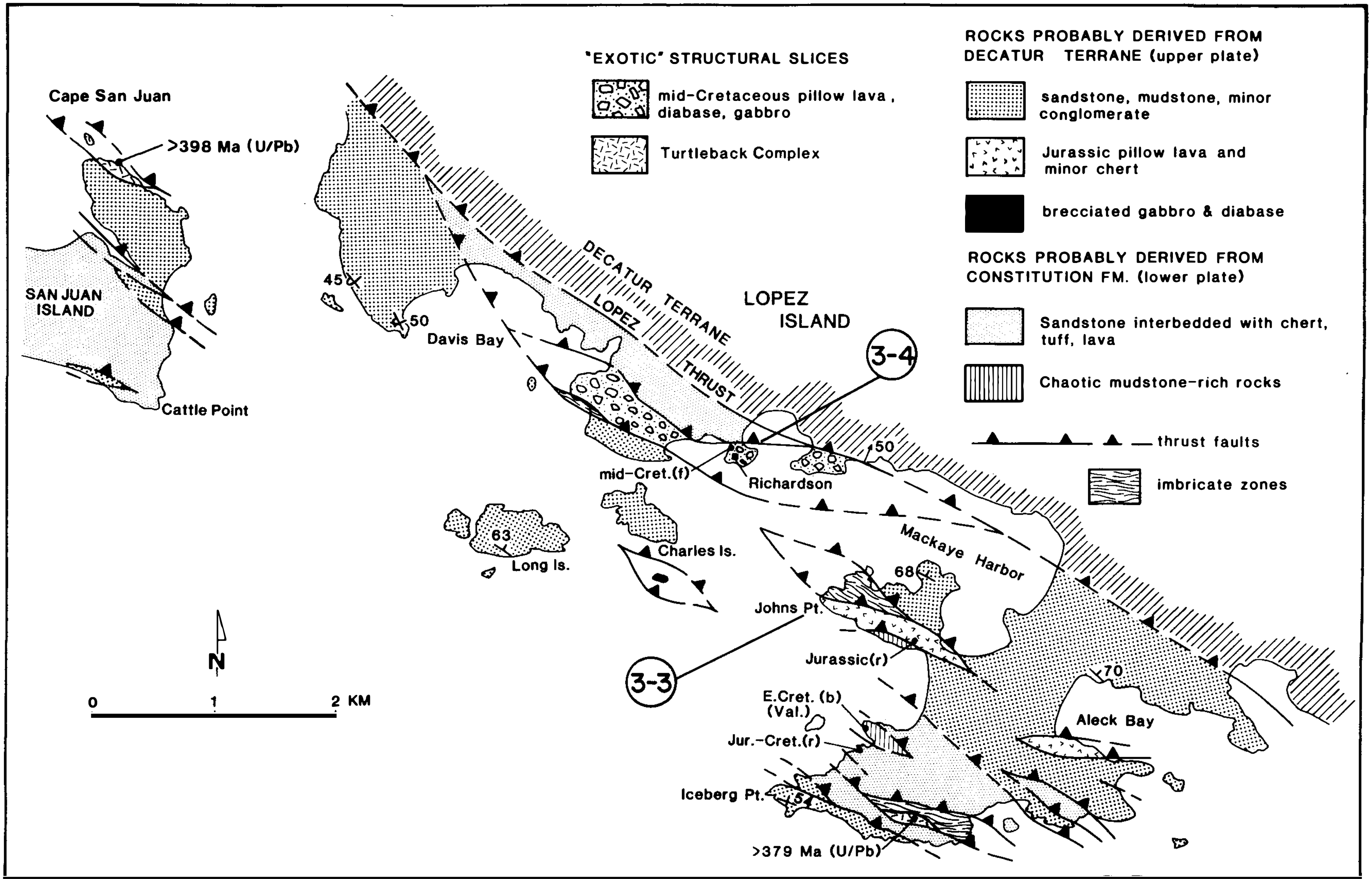

Figure 7. Geologic map for Stops 3-3 and 3-4 showing the internal structure of the Lopez Structural Complex, exposed on the southern perimeters of Lopez and San Juan Islands (Brandon and others, 1988). Numbers refer to the field stop locations. All contacts are faults. Strike and dip symbols show bedding attitude in stratified units. Fossil ages and isotopic dates are indicated by: "f" for foraminifera from mudstone at Richardson, "r" for radiolarians from chert, "b" for *Buchia pacifica* (Valanginian) from sandstone, and "U/Pb" for U/Pb zircon dates from Turtleback tonalite.

contain aragonite, pumpellyite, and chlorite; and gabbro associated with the Richardson basalts contains rare blue amphibole.

The diverse geology of Johns Point is representative of the Lopez Complex as a whole. As one moves from north to south around the peninsula, one can examine the following fault slices (Fig. 7): relatively coherent turbidites, a highly deformed fault zone, a thick slice of Jurassic pillow basalt (ocean-floor chemistry), and a polymictic pebbly mudstone with rounded clasts.

The pebbly mudstone unit highlights a persistent problem to unraveling the deformational histories of units like the Lopez Complex. There is abundant evidence, both at map scale and outcrop scale, for thrust-related imbrication and shearing; however, rock units within the complex also show evidence of syn-depositional mass-wasting. Thus, it becomes difficult to determine how much of the intermixing within the complex occurred by faulting and how much predates the development of the fault zone.

A good example of this problem is present at Johns Point. At the southern contact of the Jurassic basalt where it lies adjacent to pebbly mudstone, one can see thin mud-filled fissures in the basalt. The mud was presumably derived from the adjacent pebbly mudstone. These features certainly attest to the mobility of the mud, but past debates at this outcrop have produced two very different interpretations. The first concludes that the pebbly mudstone must have been soft and unlithified, and thus in a near-surface setting, when the basalt block was emplaced. In this case, the basalt is considered to be a submarine slide block, produced by a Late Jurassic or Early Cretaceous rock fall that travelled into a mud-rich basin. The second interpretation argues that the block/mudstone contact is a product of Late Cretaceous thrusting since much of the present structure of the Lopez Complex appears to be thrust related. The mobility of the mud is attributed to cataclastic flow of the mudstone matrix within a zone of large shear strain. This interpretation maintains that mud can remain highly mobile even at great depths.

To reach the next stop, follow McKay Harbor Road back to the T-intersection with Mud Bay Road. Turn left onto Mud Bay Road. Turn at the next left onto Vista Road, and then turn left at the T-intersection onto Richardson Road. Drive south to the hamlet of Richardson. Park at the Richardson store where the road ends in a cul-de-sac. The outcrops to be examined are on the east side of the road and on the coast extending 75 m north of the store.

STOP 3-4: Richardson, Lopez Island—An exotic slice of middle Cretaceous Richardson basalts in the Lopez Structural Complex.

The brownish-red mudstone bed in the 3-m-high roadcut opposite the store is very important because it has yielded the youngest fossils from the San Juan nappes. Foraminifera from these mudstones, first discovered by Danner (1966), have been identified as latest Albian (mid-Cretaceous, about 100 Ma). The mudstone bed forms a 1.5-m-thick interval in a sequence otherwise composed of basalt and minor gabbro. As already discussed, the Richardson basalts are unusual in that they do not appear to have been derived from the units bounding the Lopez Complex and thus may represent an exotic unit. In the Lopez Complex, these basalts are restricted to a single fault slice about 2.5 km long and 275 m thick (Fig. 7). At outcrop scale, the unit shows little evidence of fault deformation. Amygdules and veins of metamorphic aragonite and pumpellyite are present in the Richardson basalts, indicating that regional high-pressure metamorphism postdates the 100 Ma age of these basalts.

More of this volcanic unit is exposed in the steep, 5-m-high seacliff immediately north of the store. Note that the mudstone is part of a northeast-dipping stratigraphic sequence including, from bottom to top: pillow basalt, red and black mudstone, pillow breccia, and finally more pillow basalt at the north end of the outcrop. The pillows indicate that the sequence is upright.

On the basis of their trace-element composition (high TiO_2, light rare-earth element enriched; Brandon and others, 1988), these pillowed basalts probably erupted in an "oceanic-island" setting and thus may represent part of a middle Cretaceous seamount. The mudstone contains small lenses of sand-sized volcanic quartz and feldspar, indicating the proximity of an intermediate volcanic arc.

An isolated outcrop of gabbro is exposed at the northeast end of the coastal exposures at Richardson. The gabbro is chemically similar to the basalts (p. 67 *in* Brandon and others, 1988) and thus is included in the Richardson unit.

Retrace the route to the ferry terminal at Upright Head. While waiting for the ferry, we can examine the coastal outcrops in the vicinity of the loading ramp.

STOP 3-5: Upright Head, Lopez Island—Middle Cretaceous Obstruction Formation.

Upright Head exposes conglomerates that belong to the upper member of the Obstruction Formation (unit Ko in Figs. 3 and 4), a new unit recognized and studied by Garver (1988a). The Obstruction is composed of a lower sandstone member (> 400 m thick) and an upper conglomerate member (> 800 m thick). The base and top of the unit are not exposed, and age-diagnostic fossils have not been found.

The significance of this unit lies in Garver's discovery that the Obstruction Formation is younger than the Richardson basalts and that deposition of the unit probably postdates regional high-pressure metamorphism. The age of the unit is based on a suite of fission-track ages for detrital grains of zircon from a sandstone sample. The sandstone was not subjected to the zircon annealing temperature, so detrital ages provide a maximum limit for the depositional age of the sandstone. The youngest peak of the detrital age suite is 95 ± 6.8 Ma (error at 95% confidence level), indicating deposition at some time after the Albian (Garver, 1988a).

The Obstruction Formation lacks evidence of the regional high-pressure metamorphism. The observed assemblage is calcite-clay-white mica. Nearby Decatur terrane rocks contain prehnite plus rare aragonite. This metamorphic contrast does not require a difference in pressure-temperature conditions. Carbonate-clay-white mica assemblages are found elsewhere in the San Juan nappes and probably formed by excess CO_2 in the fluid phase (Brandon and others, 1988). Even so, Garver's interpretation of post-metamorphic deposition seems plausible, given the young age of the Obstruction. Further dating, especially apatite fission-track dating, would help to resolve the thermal history of the Obstruction.

If Garver's interpretation is correct, the Obstruction Formation would have been deposited on the San Juan nappes late in their thrust history, perhaps as a piggyback basin (a basin that forms on top of a moving thrust sheet). Conglomerates in the Obstruction contain clasts that may have been derived from the older nappes (chert, porphyritic dacite, metadiorite, bull quartz, and lawsonite-bearing meta-quartzite). Radiolarians from chert pebbles indicate a Lower Jurassic and possibly Middle Jurassic chert-rich source, with the Deadman Bay terrane a likely candidate (Garver, 1988a).

At Upright Head, the conglomerate clasts range up to 10 cm in diameter and are mainly chert with lesser mudstone, volcanic rock, and sandstone (Cowan and Whetten, 1977). In contrast to the Lopez Complex, the clasts are not noticeably flattened, and a cleavage is not present.

Field Stops on San Juan Island

Take the ferry to San Juan Island, which disembarks at Friday Harbor. Outcrops in the vicinity of Friday Harbor consist mainly of weathered massive sandstone of the Constitution Formation. The metamorphic assemblages in sandstones from this area include prehnite with minor lawsonite, whereas sandstones from the southern parts of Lopez and San Juan Islands include lawsonite without prehnite. This change is caused by a reaction which forms prehnite at the expense of lawsonite (Brandon and others, 1988).

To reach Stop 3-6, drive from the ferry terminal; follow the main street through the town of Friday Harbor. Leave town on San Juan Valley Road (Fig. 5). Follow the road as it turns left and becomes Douglas Road. This road makes another left and becomes Cattle Point Road. Follow Cattle Point Road into the park at the south end of the island. Turn right on Pickett's lane, which leads to a parking area at South Beach. Follow the dirt road to the right about 0.3 mi and park adjacent to the outcrops at the west end of the beach. The area of interest starts at these first outcrops (the most easterly outcrops in Fig. 8) and continues about 600 to 800 m to the west along the coast.

STOP 3-6: South Beach, San Juan Island—Exotic slices of Permian and Triassic metamorphic rock within the Rosario thrust zone.

The South Beach outcrops lie at the southwest end of the Rosario thrust zone, which extends offshore beyond this point. The thrust dips northeast here, placing massive sandstone of the Constitution Formation over a structurally complex assortment of mudstone, green volcanic rocks (locally pillowed), green tuff, and ribbon chert, which are collectively assigned to the Orcas Chert (Deadman Bay terrane; see Brandon and others, 1988). The best evidence for large thrust displacements across the fault is the presence of exotic slices of Garrison Schist (Vedder terrane) lying within the fault zone. The Garrison is a thoroughly recrystallized metamorphic rock that was metamorphosed under greenschist and amphibolite conditions during the Permian and Triassic, long before its tectonic emplacement along the Late Cretaceous Rosario thrust (Brandon and others, 1988).

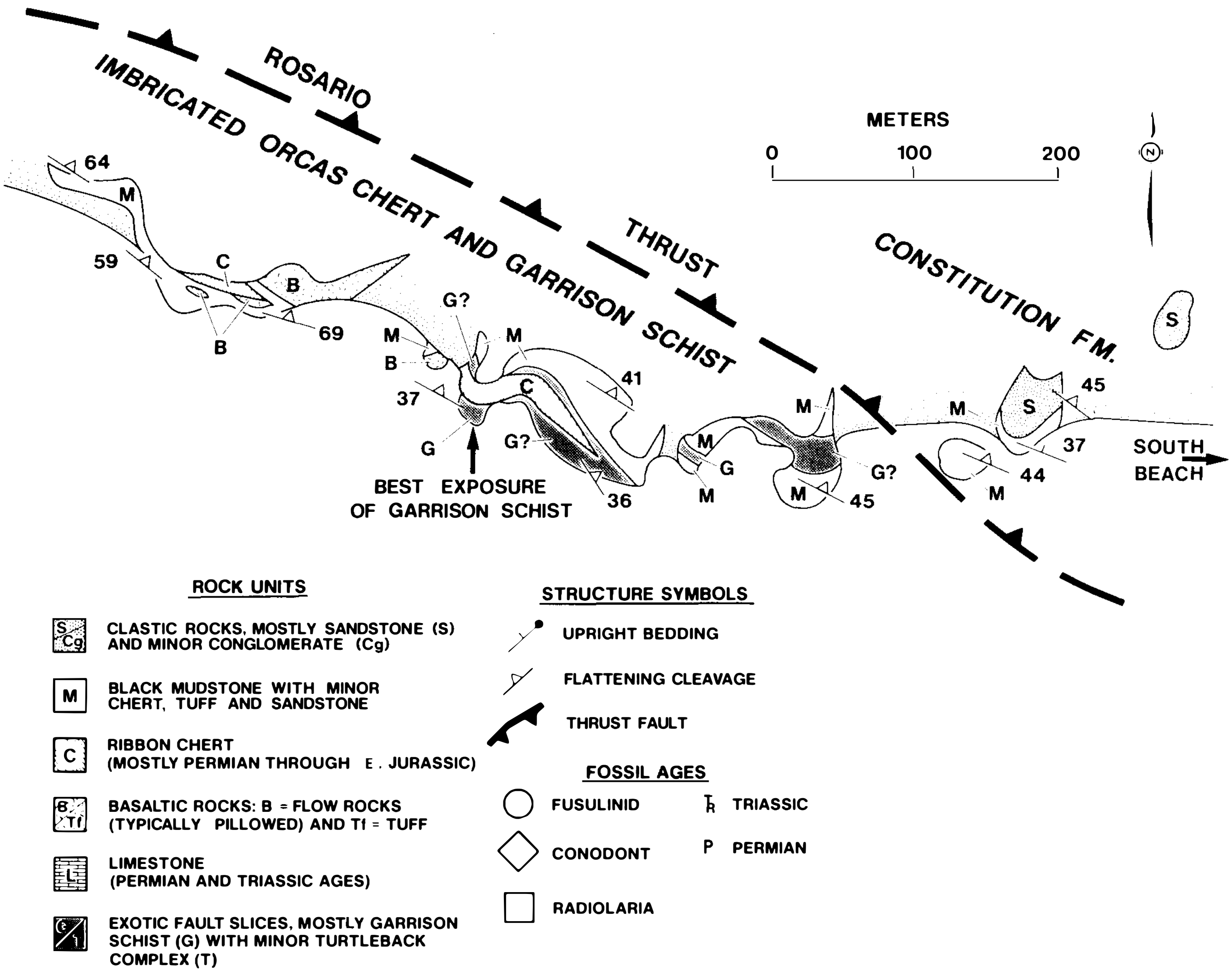

Figure 8. Outcrop map for Stop 3-6 showing the internal structure of the imbricate zone beneath the Rosario thrust at South Beach, southern San Juan Island (Brandon and others, 1988). Explanation is for both Figs. 8 and 9. Massive sandstone (S) and mudstone (M) of the Constitution Formation lie above the Rosario thrust. The area below the thrust consists of an imbricated fault zone containing ribbon chert (C) and pillow basalt (B) of the Orcas Chert, and small fault slices of Garrison Schist (G). The mudstone-rich unit (M) beneath the Rosario thrust is of uncertain affinity, and may belong to the Constitution or to the Orcas.

At the east side of the area shown in the map (Fig. 8), the first outcrops belong to the Constitution Formation (labeled "M" and "S" in Fig. 8) and consist of a northeast-dipping depositional sequence that includes a thin horizon of mudstone, green tuff, and ribbon chert, overlain by a thick massive sandstone unit. Of particular interest is the clear interbedding of clastic rocks with radiolarian-bearing ribbon chert.

Farther west along the coast is a highly imbricated sequence of Orcas Chert with exotic slices of Garrison Schist. These rocks lie beneath the Rosario thrust, which is the highest recognized thrust within this imbricated fault zone. Here, and elsewhere in the San Juan Islands, the slices of dark- to light-green Garrison Schist are localized in a 100- to 200-m-thick zone beneath the Rosario thrust. The Garrison in the South Beach area is a brecciated, fine-grained mafic schist consisting of chlorite + actinolite + epidote + plagioclase. Brecciation and cataclasis are attributed to tectonic emplacement of these fault slices. Structural relations are best exposed at the location indicated in Figure 8 where a large, tabular slice (2 x 6 x 6 m) of Garrison is surrounded by disrupted black mudstone, ribbon chert, and minor unfoliated basalt of the Orcas Chert. Note the small imbricate fault zone developed beneath the south side of this Garrison slice. These exotic slices were emplaced into the Rosario fault zone prior to high-pressure regional metamorphism (lawsonite-prehnite-aragonite) as indicated by thin-section textures which show the cataclastic fabric of the schist cut by undeformed veins of aragonite.

Return to Cattle Point Road and drive north toward Friday Harbor. Turn west and connect with Bailer Hill Road, which becomes West Side Road where it meets the coast. Deadman Bay is a small cove located just south of where the road makes two sharp switchbacks (Fig. 9). Park on the short road off West Side Road just before the first switchback. Walk southwest to the coast.

STOP 3-7: Deadman Bay, San Juan Island—Tethyan-fusulinid limestones in the Deadman Bay Volcanics.

Deadman Bay is located at the southern end of a 4-km-long fault slice of Deadman Bay Volcanics (Table 1, Fig. 9). Gray and green ribbon chert exposed at the south side of the bay belongs to the Orcas Chert, which structurally overlies the Deadman Bay Volcanics along a northeast-dipping thrust fault. The trace of this fault follows the West Side Road to the north.

The Deadman Bay Volcanics are well exposed along the coast on the rocky headlands between the bay and the lighthouse to the north. The unit is dominated by red and green pillow basalt, breccia, and tuff with subordinate interbedded limestone. It is distrupted in many places by faults, but it generally has a persistent easterly strike and, in this area, a near-vertical dip. Geopetal structures indicate younging to the north. Limestones in the unit are massive and gray, and they contain small amounts of intercalated green tuff. Bedding, where present in the limestones, is typically contorted and appears to have been deformed by soft-sediment slumping. Carbonate material occurs interstitially in the pillowed flows and might have been sucked into the pillowed framework by rapidly convecting currents generated by the cooling submarine flows or by churning as the lavas flowed across carbonate accumulations. Some of the limestones were converted to aragonite marble during Late Cretaceous high-pressure metamorphism.

Crinoid debris and fragments of other fossils can be found in many limestone pods. A thin limestone bed, clearly interbedded in the pillow basalt sequence at Deadman Bay, has yielded late Early Permian (late? Leonardian) conodonts (conodont locality at south end of map in Fig. 9). Limestone in a nearby quarry has yielded early Late Permian (early Guadalupian) fusulinids (fusulinid localities at south end of map in Fig. 9). These fusulinids are Tethyan, which suggests that the Deadman Bay Volcanics are exotic to North America. Trace-element chemistry (high TiO_2 and light rare-earth element enrichment; Brandon and others, 1988) indicates that the volcanics were probably erupted in an "oceanic-island" setting.

To reach the last stop on this trip, continue north on West Side Road, and turn right onto Mitchell Bay Road, which ends in a T-intersection with Roche Valley Road. Turn left and follow this road to a narrow causeway about 1 mi north of the town of Roche Harbor. This causeway connects Davison Head with San Juan Island. Park on the causeway. The best exposures are on the west side of Davison Head. The description below is modified from Brandon and others (1988).

STOP 3-8: Davison Head, San Juan Island—Upper Triassic Haro Formation.

A 700-m-thick section of steeply dipping, Upper Triassic Haro Formation crops out in the area surrounding Davison Head and also extends along the coast south of the causeway for a short distance (Vance, 1975; Johnson, 1978). The unit is not found elsewhere in the San Juan Islands. The Haro consists of well-bedded siltstone, sandstone, tuff, conglomerate, and breccia, all of which contain abundant andesitic and dacitic volcanic detritus. The local presence of crystal tuff indicates volcanism was contemporaneous with deposition (Johnson, 1978). South of Davison Head, thin coquina beds contain *Halobia* indicating a Carnian or Norian age. Minor interbeds of siliceous shale at two localities have yielded radiolarians with ages similar to that of *Halobia* (Igo and others, 1984: Carnian to Norian for one locality, and Norian to Pliensbachian for the other).

The Haro Formation and the Upper Jurassic and Lower Cretaceous Spieden Group, which underlies Spieden Island to the north of Davison

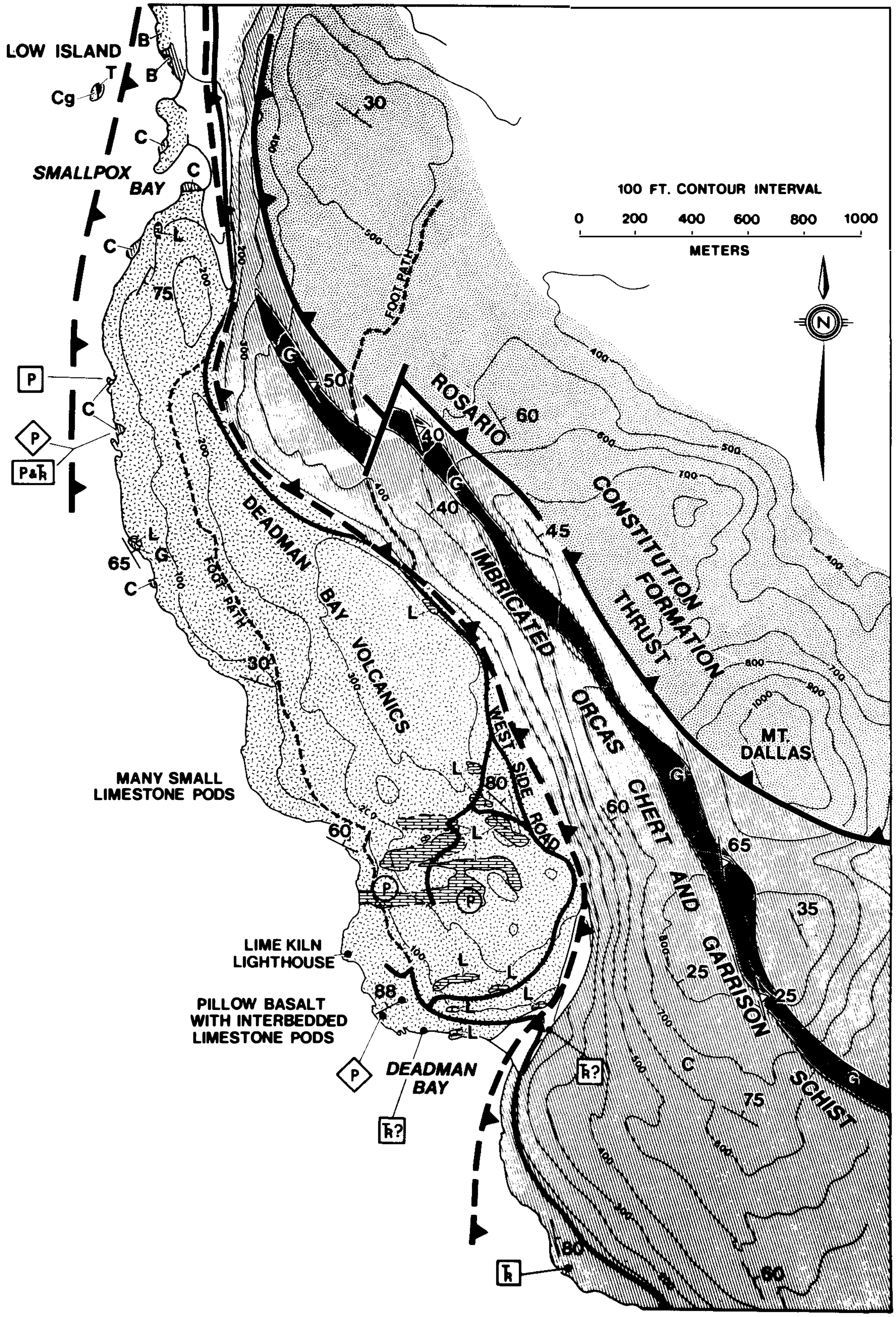

Figure 9. Geologic map for Stop 3-7 showing a large fault slice of Deadman Bay Volcanics on the west coast of San Juan Island. Map is from Brandon and others (1988); fossil localities are described there. See Figure 8 for explanation.

Head, are the only two pre-Late Cretaceous units in the San Juan Islands that have not been subjected to regional high-pressure metamorphism. Metamorphism of these two units is restricted to zeolite facies. For this reason, Brandon and others (1988) considered the Haro and Spieden to be external units within the San Juan-Cascade thrust system. Unlike many of the other thrust faults in the San Juan nappes, the Haro fault (Fig. 3), which separates the Haro Formation from nappes to the south, must postdate regional high-pressure metamorphism. Brandon and others (1988) argue that this fault is one of several post-metamorphic thrust faults bordering the northern and western perimeters of the San Juan nappes. It is suggested here that these faults represent the youngest thrusts of the San Juan-Cascade system. They are envisioned to have carried the already erosionally thinned nappes westward into the Nanaimo Basin and to have emplaced the nappes over rock units, such as the Haro and Spieden, which were never subjected to substantial structural burial. An implication of this interpretation is that the San Juan nappes have also overridden a substantial portion of the Nanaimo Basin and thus are underlain by Upper Cretaceous strata of the Nanaimo Group.

The Haro Formation appears to be unrelated to other nearby Upper Triassic units. It is clearly different from the chert-rich Deadman Bay terrane. Coeval units in the Wrangellia terrane of Vancouver Island consist of tholeiitic basalt overlain by limestone and shale (Karmutsen, Quatsino, and Parsons Bay Formations: Muller, 1977), with no evidence of intermediate or silicic volcanic rocks. One unit that may be correlative is the Upper Triassic and Jurassic Cultus Formation (Table 1, Fig. 2) of the Cascade Range, which belongs to the Chilliwack terrane. In its type area in southernmost British Columbia, the Cultus consists of volcaniclastic sandstone and siltstone (Monger, 1970) but lacks the coarse-grained pyroclastic sediments that characterize the Haro. However, the Cultus as mapped in the Mount Baker area (Brown and others, 1987) and the Harrison Lake area (Camp Cove Formation in Monger, 1970; Arthur, 1986) is dominated by volcanic flows and pyroclastic rocks with distinctive radiolarian siliceous argillites. Radiolarians and conodonts from siliceous argillites at Harrison Lake are Middle Triassic, indicating that these rocks are slightly older than the Haro. Nonetheless, the common occurrence of volcanogenic rocks and siliceous argillites suggests that the Haro may be related to the Cultus. This possibility warrants further study and comparison.