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Field Trip Guidebook

TRIP 5

PRE-TERTIARY GEOLOGY OF SAN JUAN ISLANDS, WASHINGTON AND SOUTHEAST VANCOUVER ISLAND, BRITISH COLUMBIA

by

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FOREWORD

(J. E. Muller)

The Victoria Region straddles the boundary between two major structural domains of the Cordillera, named by King (1969) in the early development stage of plate tectonic theory. The Cordilleran Foldbelt includes the larger eastern part of the mountain chain, underlain by crystalline, volcanic and sedimentary rocks of predominantly Paleozoic and Mesozoic age. Its westernmost part is the Insular Belt that includes the "Vancouver Island Terrane," bounded on the south by San Juan fault, and a part of the San Juan Islands (Figure 1).

The Pacific Foldbelt lacks a pre-Mesozoic basement and is composed of late Mesozoic and Tertiary, mainly pelagic and neritic strata, commonly with chaotic style of deformation, together with basic crystalline rocks. It is only present in the conterminous western United States and western Alaska. It is missing in British Columbia and southeast Alaska except for a narrow strip from the west coast of Vancouver Island to Victoria, continuing in San Juan Islands. Muller (1977) divided the Pacific Foldbelt in an inner belt of mainly Mesozoic rocks and an outer belt of mainly Tertiary rocks. The Inner Pacific Belt of Mesozoic rocks included the Franciscan Terrane of California and the Chugach Terrane of Alaska, along with the areally much smaller Pacific Rim and Leech River complexes of Vancouver Island and correlative formations on San Juan Islands.

On southwest Vancouver Island the Pacific and Insular belts are separated by the high-angle San Juan Fault system. On southeast Vancouver Island and San Juan Islands the separation of the two terranes is more complex as the structural style changes from mainly high-angle faults, typical of Vancouver Island, to a combination of normal, reverse and flat thrustfaults prevailing on San Juan Islands.

The Outer Pacific Belt is composed mainly of the Olympic Terrane, but has counterparts in southwestern Alaska. Disregarding Tertiary volcanic rocks in interior Washington and Oregon, included by King in the Pacific Belt, it is composed solely of Tertiary pelagic and neritic strata, locally with a substratum of early Tertiary basalt and gabbro. To the north this terrane is separated from the Inner Pacific and Insular belts by the Leech River fault on south Vancouver Island.

The initiative of the 1983 G.A.C. Victoria fieldtrip committee to explore the linkage of these distinct geological terranes across the International Boundary has been met with interest by geologists with recent experience in one or more of the domains on both sides of the border. Unfortunately, logistics, dependent on several ferry crossings, do not permit to cover all terranes in one fieldtrip. This trip, preceding the Annual G.A.C. Meeting, deals only with the pre-Tertiary structure and stratigraphy of the San Juan Islands and south Vancouver Island, north of the Leech River Fault. Another trip, following the meeting, will examine the exclusively Tertiary rocks of the Olympic Terrane, south of that fault.

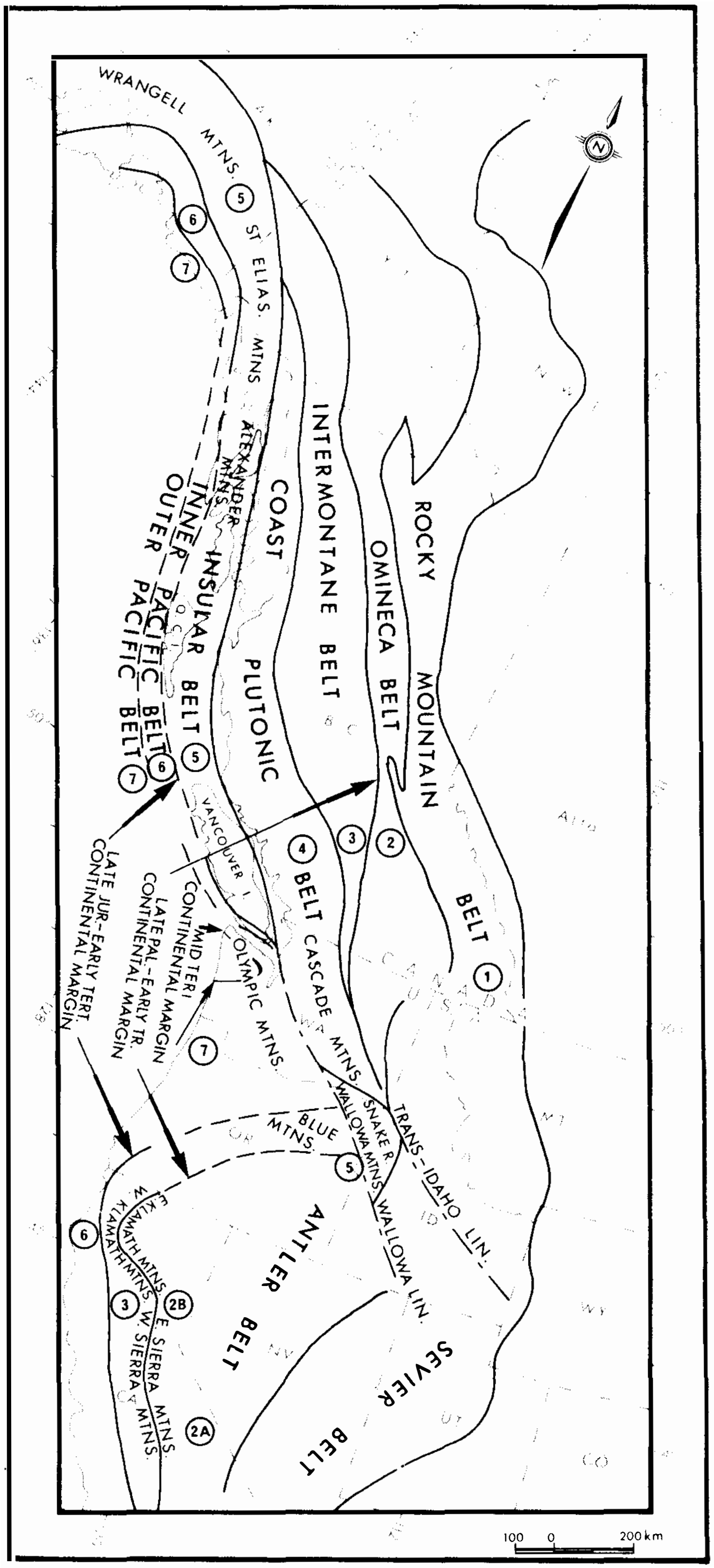


FIGURE 1

Outline map of Cordilleran Belts (Muller, 1977)

LEGEND FOR FIGURE 2

TERTIARY

- PERIPHERAL ROCKS: CARMANAH: clastic strata
- T CORE ROCKS: metaclastic, metavolcanic rocks
- CHUCKANUT: clastic strata, coal
- CATFACE INTRUSIONS AND OTHER: granitoid rocks
- METCHOSIN, CRESCENT: basalt
- SOOKE GABBRO

CRETACEOUS

- NANAIMO: clastic strata, coal
- COAST INTRUSIONS: granitoid rocks

JURASSIC AND CRETACEOUS

- SPIEDEN, LUMMI, NOOKSACK: clastic strata
- K LEECH RIVER, CONSTITUTION, DARRINGTON, SHUKSAN: metaclastic and metavolcanic rocks

JURASSIC

- J BONANZA, WELLS CREEK, HARRISON LAKE, FIDALGO (PART): intermediate volcanic, volcaniclastic rocks
- ISLAND INTRUSIONS: granitoid rocks

JURASSIC AND OLDER

- PM Volcanic rocks of NW Cascades
- um Ultramafic rocks
- WARK, COLQUITZ, TURTLEBACK, VEDDER gneiss, migmatite, metadiorite (Jurassic metamorphism)

TRIASSIC

- T KARMUTSEN: metabasalt
- CULTUS: pelite

PERMIAN AND TRIASSIC

- PT ORCAS, TRAFTON: chert, metabasalt

PALEOZOIC

- SICKER, CHILLIWACK: metavolcanic, carbonate, pelitic rocks
- SALTSPRING INTRUSIONS: metagranitoid rock
- Contact
- Fault
- Hypothetical fault
- Thrust Fault
- International Boundary

The guide is divided in two parts. The first one by Brandon, Cowan and Vance reviews in some detail the geology of San Juan Islands and its relationship to Vancouver Island and the Mainland. The general discussion is followed by roadlogs for days 1, 2 and 3, respectively by Muller, Vance, and Cowan and Brandon. The second part, by Muller, briefly outlines the geology of Vancouver Island and includes roadlogs for days 4 and 5. A concluding overview by Muller examines stratigraphic and structural relationships between Vancouver Island and San Juan Islands, seen from the larger island's geological vantage point.

Text and figures of the first part were prepared at the University of Washington while this foreword and the second part were written and drafted at the Geological Survey of Canada office in Vancouver. Drafting, minimal non-technical editing and preparation of camera-ready copy under the auspices of the Survey are hereby gratefully acknowledged.

THE GEOLOGY OF THE SAN JUAN ISLANDS, WASHINGTON

(M. T. Brandon, D. S. Cowan and J. A. Vance)

Introduction

The San Juan Islands of Washington State (Figure 3) are a region of complex geology which remains incompletely understood and controversial. Many of the pre-Upper Cretaceous rocks are sheared and weakly metamorphosed. Though small, the area shares stratigraphic and tectonic features with Vancouver Island and with the Mainland. Critical geologic relationships in the San Juans are keys to understanding the tectonic history of the western Cordillera. This is a review of San Juan Island stratigraphy and structure in the light of recent mapping and new fossil and radiometric dating.

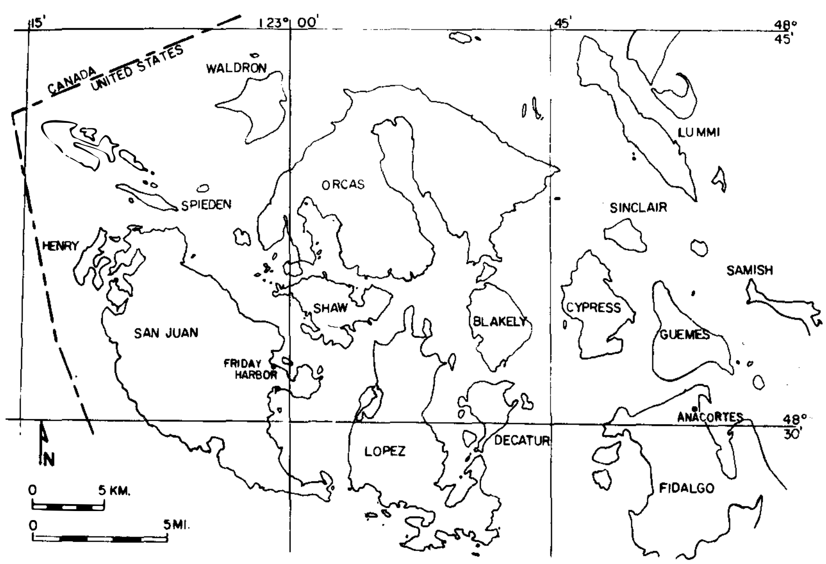


Figure 3 Location map of San Juan Islands.

The San Juan Islands were originally mapped by Roy D. McLellan (1927). He delineated the distribution of lithologic units, the order of their superposition, made important fossil discoveries and recognized the pattern of open northwest-trending folds. His work is impressive in view of the difficulty of the geology, particularly because most of it was done by rowboat. Later studies show that some of his age assignments are in error and that some of his units are composite.

The next advance was through the work of Danner (1957, 1966 and 1977). His reconnaissance, and especially the mapping and description of the limestone deposits and their fossils, led to a clearer understanding of San Juan stratigraphy.

Vance (1968) first recognized the widespread presence of aragonite in San Juan rocks and described their low-grade metamorphism. He remapped Orcas Island and northern San Juan Island (Vance 1975, 1977), reinterpreted some key stratigraphic relations, and identified a series of large, southeast-dipping thrust slices.

(Whetten et al., 1978 and 1980) introduced the concept that the San Juan Islands include several unrelated, tectonically juxtaposed terranes. They also published important radiolarian and U/Pb dating done by E. A. Pessagno, Jr., D. L. Jones and R. A. Zartman. This has resolved several problems of age and sequence, and permits assessment of the displacement of San Juan faults.

Other recent important contributions to San Juan Island geology include: the stratigraphy of the Spieden and Haro Formations (Johnson, 1978 and 1981); mapping of southern San Juan Island (Brandon, 1980); mapping of Lopez Island by Cowan (Cowan and Miller, 1980); and the study of Lummi Island (Carroll, 1980).

Structural and Stratigraphic Units

The following descriptions of rock units are not ordered chronologically. Instead they are arranged in structural assemblages, each with moderate stratigraphic coherence and with its own metamorphic characteristics (Figure 4; for another synoptic stratigraphic table see Figure 20). 1) The Haro, Spieden, Nanaimo and Chuckanut are unmetamorphosed, well stratified Mesozoic units in the northernmost part of the islands. 2) South of these a complexly imbricated, metamorphosed and deformed succession includes Paleozoic igneous, volcaniclastic and sedimentary rocks (Turtleback Complex and unnamed "San Juan Paleozoic." 3) These are structurally overlain by Permian volcanic rocks (Deadman Bay), a lower Mesozoic chert-rich unit (Orcas) and a largely clastic Jurassic-Cretaceous unit (Constitution). 4) The structurally highest unit, the Decatur Complex, consists of a Middle Jurassic igneous complex (Fidalgo), unconformably overlain by Upper Jurassic-Lower Cretaceous graywacke and mudstone (Lummi). 5) Separately mapped faultzone complexes are the late Permian metavolcanic Garrison and the late Mesozoic metasedimentary Lopez.

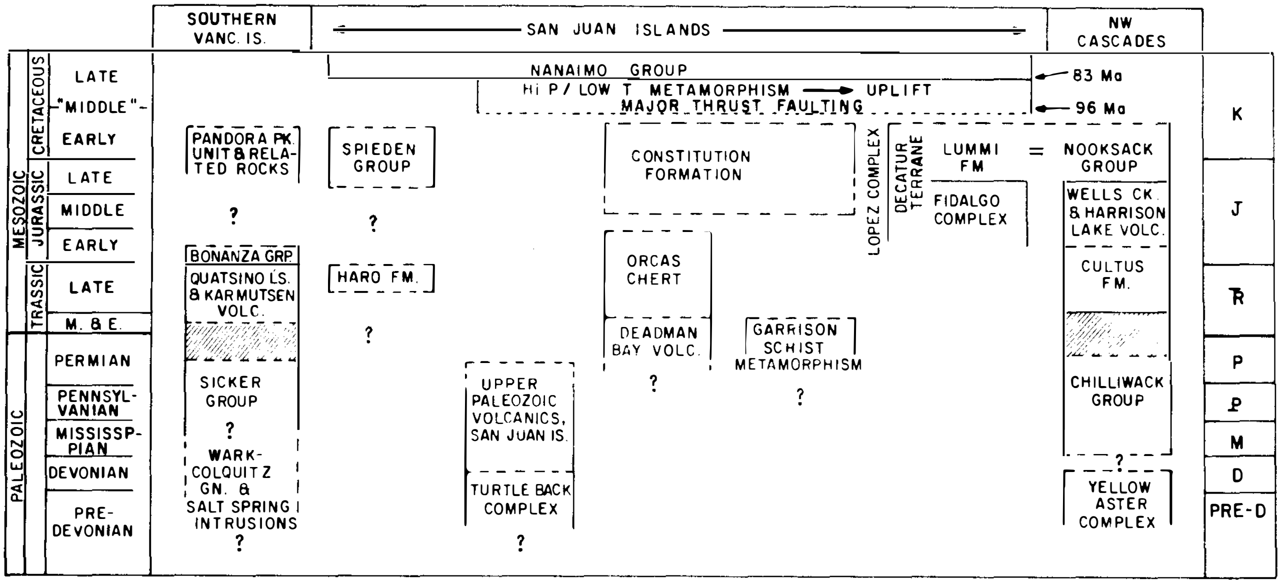


Figure 4

Generalized stratigraphic compilation for Mesozoic and older rocks of San Juan Islands, southern Vancouver Island, and northwestern Cascades of Washington and southern British Columbia. Stratigraphic data for areas outside the San Juan Islands are from Muller, 1977, 1980 a,b; Monger, 1970; Misch, 1966, 1977; Danner, 1966, 1977; and Rusmore, 1982. Dashed lines signify that the range of the unit is unknown. Question marks indicate poorly understood stratigraphic relationships. Hachured parts of the column represent probably stratigraphic unconformities. Units shown vertically within a column were probably originally stratigraphically related. Coeval units in separate columns are generally separated by faults and cannot be correlated confidently. Mid-Cretaceous thrust faulting and high-pressure metamorphism are shown at the top of the diagram. The Nanaimo Group represents a post-thrusting overlap assemblage.

Unmetamorphosed Mesozoic and Lower Tertiary Strata In The Northern San Juan Islands

Nanaimo Group and Chuckanut Formation

The Nanaimo Group is widely exposed on Vancouver Island and in the Gulf Islands. It overlies several pre-Upper Cretaceous rock units unconformably (Muller and Jeletzky, 1970). It crops out in the northernmost San Juan Islands and on the northern part of Orcas Island (Figure 5), where it consists of gently folded sandstone, conglomerate and mudstone of Late Cretaceous age (Johnson, 1978; Ward, 1978). These sediments, deposited in a submarine fan, contain clasts that were probably derived from the San Juan Islands to the south (Vance, 1975; Johnson, 1978). The contact of Nanaimo strata with older rocks is interpreted as a high-angle fault.

Vance (1975) first identified non-marine strata on Sucia Island as part of the Lower Tertiary Chuckanut Formation; this early Eocene age was confirmed by Johnson (1982). The Chuckanut is also exposed on the northern end of Lummi Island (Carroll, 1980) and in the foothills of the northwestern Cascades. This cross-bedded, arkosic sandstone unit may correlate with the Gabriola Formation in the Gulf Islands (Vance, 1975).

Spieden Group

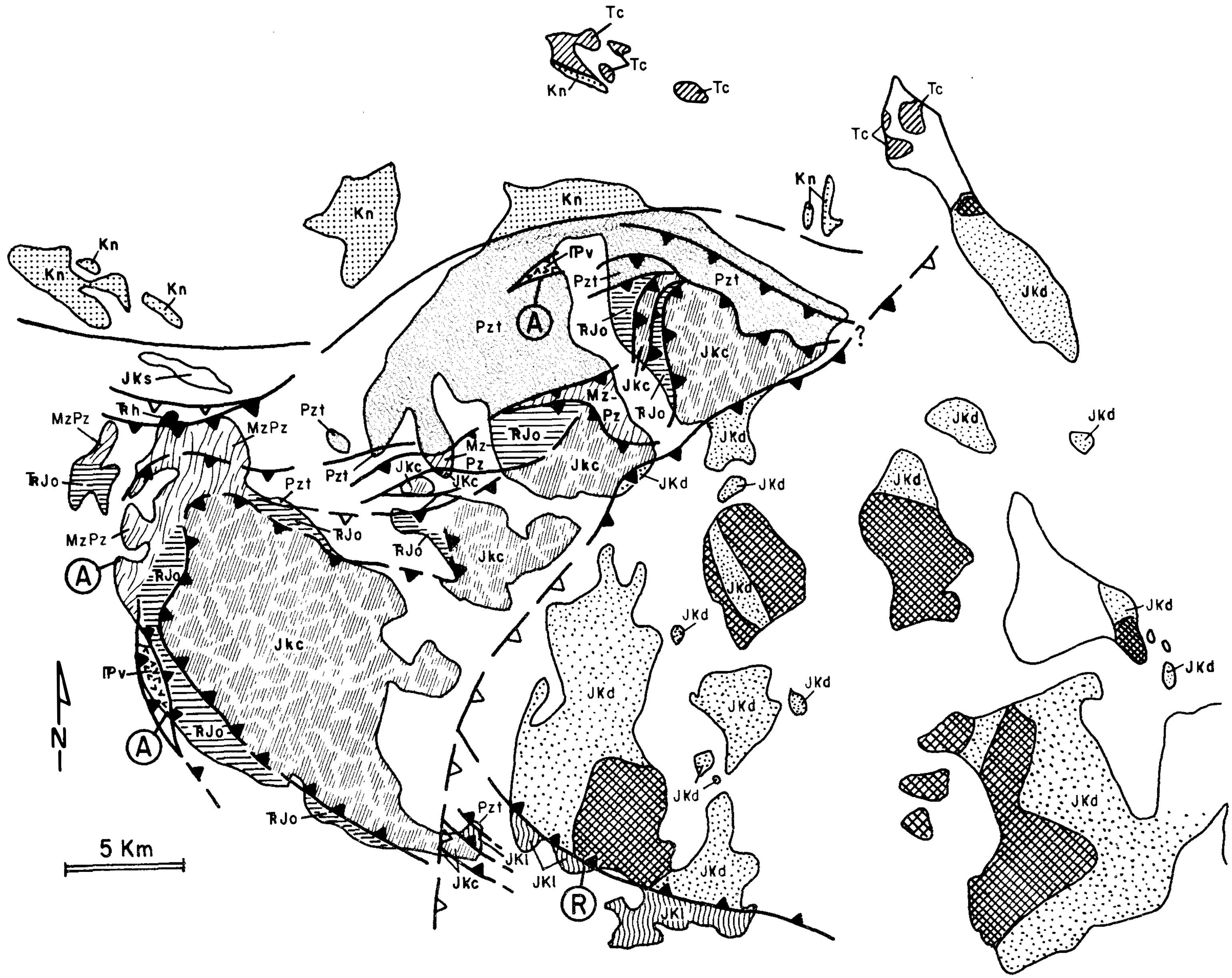
These strata, exposed only on Spieden and Sentinel Islands, consist of Upper Jurassic and Lower Cretaceous mudstone and volcaniclastic sandstone and conglomerate (Johnson, 1981). The Upper Jurassic Spieden Bluff Formation contains volcanic breccia and conglomerate deposited near an active volcanic source. The Lower Cretaceous Sentinel Island Formation includes shallow marine and alluvial sediments rich in volcanic detritus. Although the Spieden Group is time-correlative with nearby units in the San Juan Islands (Lummi and Constitution formations), Vance (1975) and Johnson (1981) pointed out differences in its sedimentology, petrology, and metamorphism. The contacts of the Spieden Group with the Nanaimo Group to the north and the Haro Formation to the south are interpreted as high-angle faults.

Haro Formation

These steeply dipping Upper Triassic strata crop out only on, and immediately south of, Davison Head on the north end of San Juan Island. They consist of well-bedded siltstone, sandstone, conglomerate, and breccia with abundant andesitic and dacitic detritus (Vance, 1975; Johnson, 1978). These sediments were deposited near an active volcanic arc in generally shallow-marine environments. The age is based on the fossil *Halobia* found in thin-bedded limestone south of Davison Head. The contact of the Haro with the recrystallized and more highly deformed Triassic Orcas cherts to the south if inferred as a south-dipping thrust (Vance, 1975; Johnson, 1978).

DEFORMED AND METAMORPHOSED MESOZOIC AND PALEOZOIC ROCKS OF THE SAN JUAN ISLANDS

Lower, middle and upper Paleozoic plutonic and sedimentary rocks form a wide outcrop belt across northern Orcas Island and occur to the south and west at scattered localities on several smaller islands and on San Juan Island. Radiometric ages indicate that the plutonic rocks range from older than 470 m.y. to at least as young as 300 m.y., while fossils demonstrate the presence of strata of Middle Devonian, Early Pennsylvanian and Early Permian age. Contacts between the plutonic and supracrustal rocks of this belt are generally low-angle thrust faults with apparent major displacement, but we group these rocks in one structural-stratigraphic unit which we interpret as the plutonic and volcanic members of a Paleozoic magmatic arc. At several outcrops the plutonic rocks have intruded their volcanic cover. This relation is seen near Sea Acres on eastern Orcas Island and has been reported by Muller (1976) and Danner (1977) at Deer Harbor on western Orcas Island. This structural unit is imbricated internally and has been overthrust by and tectonically sliced into structurally overlying units.



Tc
Kn
JKd
Pzt
A
IPv
TRJo
JKc
Mz
Pz
MzPz
JKs
TRh
JKl
R
?
N
5 Km

Figure 5 A

Generalized geologic map of the San Juan Islands based on mapping by Vance (1975, 1977, and unpub.); Cowan (unpub.); Brandon (1980 and unpub.); Whetten (1975); Whetten et al. (1978); Johnson (1978); Carroll (1980); Brown et al. (1979); Gusey (1978); and Glassley (unpub.). Major faults are approximately located. Quaternary sediments are not shown. "R" denotes village of Richardson. "A" denotes Asiatic fusulinid localities in the Deadman Bay Volcanics.

- **Tc** — *Chuckanut Formation. Lower Tertiary, non-marine.*
- **Kn** — *Nanaimo Group. Marine conglomerate, sandstone, shale. Upper Cretaceous.*
- **JKs** — *Spieden Group. Conglomerate and sandstone with intermediate volcanic clasts. U. Jurassic and L. Cretaceous.*
- **Ŧh** — *Haro Formation. Conglomerate and sandstone with intermediate volcanic clasts and U. Triassic carbonates.*
- **JKd** — *Decatur terrane. Sandstone, mudstone, conglomerate of Lummi formation (U. Jurassic to L. Cretaceous) overlying ultramafic rocks, mafic to intermediate plutonic and volcanic rocks of M. to U. Jurassic Fidalgo Complex.*
- **JKl** — *Lopez Complex. Imbricated slices of Jurassic to mid-Cretaceous sandstone, pebbly mudstone, pillow lava and cherts.*
- **JKc** — *Constitution Formation. Massive volcaniclastic sandstone, and inter-bedded sequences of mudstone, pillow lava, tuff, and ribbon chert. Jurassic to L. Cretaceous.*
- **ŦJo** — *Orcas Chert. Deformed chert and basaltic volcanic rocks. Triassic-Lower Jurassic.*
- **MzPz** — *Intimately and complexly mixed imbricate zone containing Orcas Chert, Turtleback and Paleozoic limestone. May also include fragments of Deadman Bay Volcanics.*
- **IPv** — *Deadman Bay Volcanics. Pillow lavas, tuffaceous rocks, minor chert, and lime-stone with Asiatic fusulinids. U. Permian to Triassic.*
- **Pzt** — *Turtleback Complex (Devonian and older plutonic rocks) and related Paleozoic volcanic and volcaniclastic rocks with interbedded limestone of Devonian, Pennsylvanian, and early Permian ages.*

Turtleback Complex

Intrusives of this structural unit have been assigned by McLellan (1927) and later workers to the Turtleback Complex, a heterogeneous plutonic assemblage consisting of an earlier gabbroic phase and a later silicic, quartz dioritic to trondhjemitic phase. Basaltic to silicic dikes are the latest intrusive elements in the Turtleback Complex.

The chronology of the Turtleback Complex is imperfectly known, in part owing to a widely developed static metamorphic overprint in greenschist and lower amphibolite facies, that has hampered rigorous interpretation of radiometric ages. The best dates are from meta-tonalites and meta-tronhjemites characterized by abundant coarsely granular quartz. The dates are ^{207}Pb/^{206}/Pb ages of 399, 409 and 437 m.y. with an upper-intercept Concordia age of 471 m.y. (Mattinson, 1972; Whetten et al., 1978). Early to middle Paleozoic are therefore represented in the unit. U/Pb dating of a small trondhjemite body at Deer Harbor on Orcas Island yielded a ^{207}Pb/^{206}Pb age of 300 m.y. on two zircon fractions and a ^{206}Pb/^{238}U age of 282 m.y. on sphene. (Wendell Hoppe, written comm. 1982). This indicates the presence of younger intrusive Paleozoic rocks in the Turtleback Complex.

Several K/Ar dates have been determined on Turtleback rocks. Whetten et al. (1978) report a K/Ar age of 554 ± 16 m.y. on hornblende from a gabbro pegmatite on East Sound on Orcas Island. Uralitic amphibole from a metagabbro near Pt. Lawrence on Orcas Island yielded an age of 332 ± 16 m.y. (R. B. Forbes, personal comm.). This is probably a minimum age. A whole rock K/Ar date of 258± m.y. determined for a gneissic diorite from western Orcas Island (Danner, 1977) is probably a metamorphic age.

Zircon fission-track ages of 260, 275, and 294 m.y. (C. W. Naeser, and R. Zimmerman, written comm., 1980) from three Turtleback trondhjemites are probably related to the thermal event which reset the K/Ar ages. These ages appear to date the widespread static metamorphic overprint of the Turtleback rocks. The metamorphism may be a regional event or may be related to the extensive Turtleback dike swarms. Zircon from a silicic dike in the Turtleback Complex from the village of West Sound was determined by Vance to have a fission track age of 270 ± 54 m.y. (The mean age was calculated from the ages of seven zircon grains, each with unit weight. The error limit represents the standard error at the 95% significance corrected for the small sample size.) Since the dike appears to show the static overprint it is tentatively interpreted as a feeder to the Devonian-Pennsylvanian volcanic rocks. (It may be noted that the reset Turtleback ages are close to the K/Ar ages obtained on the Garrison amphibolites, discussed below. This appears to be coincidental, however, as the Garrison rocks display a high-pressure metamorphic mineral assemblage quite different from the Turtleback metamorphic overprint.)

In summary, U/Pb dating shows Ordovician (471 m.y.) and Pennsylvanian (300 m.y.) silicic plutonic rocks in the Turtleback Complex in addition to an earlier gabbroic phase. A static metamorphic event resulted in reset of partially reset K/Ar and zircon fission track ages in the range 330-260 m.y. Swarms of mafic to silicic hypabyssal dikes are the latest Turtleback element and appear to be at least 270 m.y. old, the fission track age of a silicic Turtleback dike.

Rocks probably correlative with the Turtleback Complex are younger parts of the Yellow Aster Complex in the northeast Washington Cascades (Misch, 1966). As in the San Juan Islands, they include a gabbroic to dioritic mafic phase and silicic plutonic phase. The Yellow Aster rocks are tectonic slices and blocks in the Shuksan thrust system and in other Cascade faults. U/Pb dates on zircon from trondhjemite range from 450 to 400 m.y. (Mattinson, 1972). Several units on southern Vancouver Island may correlate with the Turtleback Complex. The Tyee intrusions of the Saltspring Island area have yielded a U/Pb isochron with an upper intercept of 410 m.y. (Muller, 1980a). The Wark and Colquitz gneisses of the Victoria area contain mafic and silicic plutonic elements analogous to the Turtleback. They have discordant Paleozoic U/Pb ages, and precise age assignment is not possible due to a strong Jurassic metamorphic overprint (Muller, 1980b).

Paleozoic Volcanic and Sedimentary Rocks

Unnamed supracrustal rocks, possibly correlative with the Sicker Group of Vancouver Island, are widespread on Orcas Island and as scattered outcrops on San Juan Island and on Jones and O'Neal and other small islands south and west of Orcas Island (Danner, 1966 and 1977; Vance, 1975 and 1977). The rocks are volcaniclastic sediments with minor lavas and limestone interbeds. Limestone lenses contain Middle Devonian, Middle Pennsylvanian and Early Permian fossils (Danner, 1966 and 1977; Savage, 1982). Although not confirmed by fossils, other Paleozoic intervals may be present.

The dominant rocks are andesitic to dacitic pyroclastic rocks and volcaniclastic sediments. They include massive tuff-breccia and tuff, and thin-bedded volcanic sandstone and siltstone which are commonly graded. The volcanic provenance of these sediments, the presence of subordinate lavas (locally pillowed), and the interbedded limestone indicate shallow marine deposition in a volcanic arc. Dikes that may feed the volcanic rocks are locally abundant and range from mafic to silicic in composition.

The beds are generally in thrust fault contact with rocks of the Turtleback Complex. They lack the greenschist — to lower amphibolite -- facies static metamorphic overprint that distinguishes the Turtleback, though both share the intra-Cretaceous prehnite-aragonite grade metamorphism. At Sea Acres and Deer Harbor on Orcas Island, the Turtleback intrudes the Paleozoic supracrustal rocks. Although the age of the intruding Turtleback is not known, most of it appears early Paleozoic: thus the intruded beds may be pre-Devonian. The Supracrustal rocks and the Turtleback Complex appear to be the volcanic and plutonic members of a Paleozoic magmatic arc. This conclusion is supported by their similar range of ages, by their calc-alkaline composition and by locally preserved contacts showing intrusion of the plutonic rocks into their volcanic cover.

Danner (1966, 1977) described Devonian sediments on O'Neal Island as unconformably overlying the Turtleback Complex. The contacts are sheared and they may be thrust, as documented on Orcas Island. Our interpretation that the Paleozoic supracrustal rocks and the Turtleback Complex are members of a long-lived and probably intermittently active magmatic arc does not preclude unconformities within the sequence.

The correlation of the Devonian-Pennsylvanian-Lower Permian sequence of the San Juan Islands is controversial and as yet unresolved. Supracrustal rocks of broadly the same age are the Sicker Group of Vancouver Island and the Chilliwack Group of the northwest Cascades of northern Washington and southernmost British Columbia. The Sicker includes beds of demonstrated pre-Devonian, Mississippian, Pennsylvanian and Early Permian age (Muller, 1980a; Danner, 1977) while the Chilliwack includes Middle or Upper Devonian, Early Pennsylvanian and Early to Middle Permian (Danner, 1977). Danner (1977 and personal comm.) argues that major faunal differences rule out equivalence of the three units. Muller (1980a) favors correlation of the San Juan Paleozoic with the Sicker Group. Both consist dominantly of intermediate pyroclastic and volcaniclastic sediments, in contrast to the Chilliwack which has a much higher proportion of argillite, sandstone and mafic lavas. The correlation of the San Juan with the Sicker rocks is strengthened by the presence of Paleozoic intrusive rocks, the Turtleback and Tyee, in both units. If the Devonian-Pennsylvanian-Lower Permian of the San Juan Islands does correlate with the Sicker, it may represent a fragment of Wrangellia (Jones et al., 1977) in the San Juan Islands.

Garrison Schist

The metamorphic rocks referred to as the Garrison schist were first recognized by Danner (1966) at Garrison Bay on northern San Juan Island. Vance (1975, 1977) showed that this unit extends south as a narrow outcrop belt as far as Mt. Dallas and that small outcrops of similar rocks occur on Orcas Island. Danner (1977) reported Garrison on southern San Juan Island, while Brandon (1980) traced the unit to the south end of the island and Brandon and Cowan (unpublished work) mapped the unit on northern San Juan and on western Shaw Island (Figure 5 shows the known distribution of Garrison schist in the San Juan Islands). The Garrison rocks are green to black mafic schist and associated micaceous quartzite. Rare limestone lenses also appear to be part of the unit. The Garrison rocks are typically fractured, veined, microbrecciated and slickensided. Their well developed schistosity and the bright color of the greenschists best distinguish them from adjacent, less metamorphosed rocks.

The mafic schist includes two metamorphic facies. The belt of schist between Garrison Bay and Mt. Dallas consists largely of albite-epidote amphibolite with minor greenschist. Microprobe analyses show that the amphibole is barroisite indicating high-pressure metamorphism. The associated quartzite contains white mica and rare garnet and biotite. The Garrison outcrops on southern San Juan Island, western Shaw and on western Orcas Island are fine-grained greenschists with the assemblage albite-epidote-actinolite-chlorite and less commonly albite-epidote-chlorite-calcite. These rocks formed at lower temperature and pressure than the amphibolites.

Layering in the Garrison quartzite suggests derivation from ribbon cherts. The mafic compositon of the amphibolite and greenschist and their association with metachert suggests that the parent rocks are submarine basalt. Hornblende from Garrison amphibolite from Mt. Dallas on San Juan Island and Cascade Lake on Orcas Island yielded K/Ar ages of 242 ± 7 m.y. and 286 ± 10 m.y. respectively, indicating Permian or Early Triassic metamorphism (R. B. Forbes, writ. comm.; R. L. Armstrong, writ. comm.). A potassium-poor (K_2O = 0.132%) actinolite from a Garrison greenschist from Parks Bay, Shaw Island, gave a K/Ar age of 167 ± 6 m.y. (R.L. Armstrong, writ. comm.) If this Jurassic date is valid, the Garrison amphibolite and greenschist represent two metamorphic events. Clasts like Garrison greenschist in Constitution Formation conglomerate on Garrison Bay (Vance, 1977) and in Constitution sandstone (Brandon, 1980), indicate pre-Late (?) Jurassic metamorphism.

The Garrison schist occurs as a discontinuous tectonic sheet at or near the contact between the bedded cherts of the Triassic-Jurassic Orcas Formation and the overlying clastic sediments of the Constitution Formation. At most outcrops this exotic sheet is 1-4 m thick and is nowhere thicker than a few tens of meters. Apart from its faulted contacts, tectonic emplacement of the Garrison schist is implied by two observations. First, the metamorphism of the Garrison schist is older than either the Orcas or Constitution formations. Second is the striking contrast between the higher-grade synkinematic metamorphism of the Garrison and the lower grade of the adjacent sedimentary rocks. The Garrison, thus, cannot be the result of local metamorphism along a fault. Indeed, the fault slices of Garrison Schist and Turtleback Complex rocks are the only evidence of this major thrust. Vance (1977) proposed that the Garrison was emplaced in two stages: 1) a thin, discontinuous section of Orcas Chert and thicker, overlying Constitution Formation were thrust onto the Turtleback Complex and the Garrison Schist, forming the Orcas thrust; 2) a second fault (the Rosario thrust) cut the Orcas thrust at a low angle, dragging sheets and slices of Turtleback and Garrison along at the base of a thick plate of Constitution.

The Garrison albite-epidote amphibolite appears to correlate with similar, coarser-grained amphibolite in the northwestern Cascades. Most of the Cascade albite-epidote amphibolite occurs as tectonic lenses in the Shuksan thrust system (Misch, 1966, 1977). The best studies of the Cascade amphibolite are at Vedder Mountain at the International Border (Bernardi, 1977) and on the Middle Fork of the Nooksack River (Rady, 1981). Like the Garrison, these rocks are characterized by the mineral association, albite-epidote-barroisitic amphibole and have yielded Permian to Triassic radiometric ages (Armstrong, 1980). The Garrison greenschist resembles Shuksan greenschist of the northwestern Cascades (Misch, 1966), but is older than the Shuksan which is dated as 107-137 m.y. (Armstrong, 1980; Brown et al., 1982)

Orcas Chert and Deadman Bay Volcanics

The Orcas Chert and Deadman Bay Volcanics (Vance, 1975, 1977; Brandon, 1980) constitute a disrupted stratigraphic sequence of pillowed volcanics, limestone, chert and mudstone ranging from Permian through Lower Jurassic. Deadman Bay Volcanics is a new informal name for an unnamed unit previously called the Permian Volcanics. The Deadman Bay volcanic unit occurs in discontinuous fault slices structurally beneath the Orcas Chert and represents the oldest part of the sequence. It consists of submarine volcanic rocks, interbedded with minor limestone and ribbon chert. The younger Orcas Chert is composed of a complex association of ribbon chert and mudstone with minor limestone and pillowed volcanic flows.

Stratigraphic relations in the Deadman Bay Volcanics are best displayed in a 4 km-long fault slice of the unit on the west side of San Juan Island (Fig. 5).

Volcanic rocks include pillowed flows and associated fragmental volcanic rocks, some of which are basaltic andesite (Atkin, 1972). Interbedded limestone ranges from local irregular bodies between the pillows in lava, to thick, conformable tubular bodies (see maps in Danner, 1966). Limestones are generally massive and gray aragonite and calcite, with minor organic material (Danner, 1966).

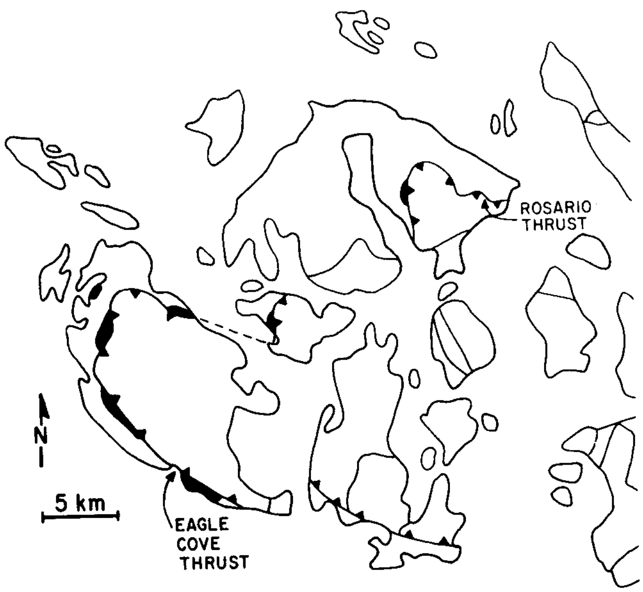


Figure 6

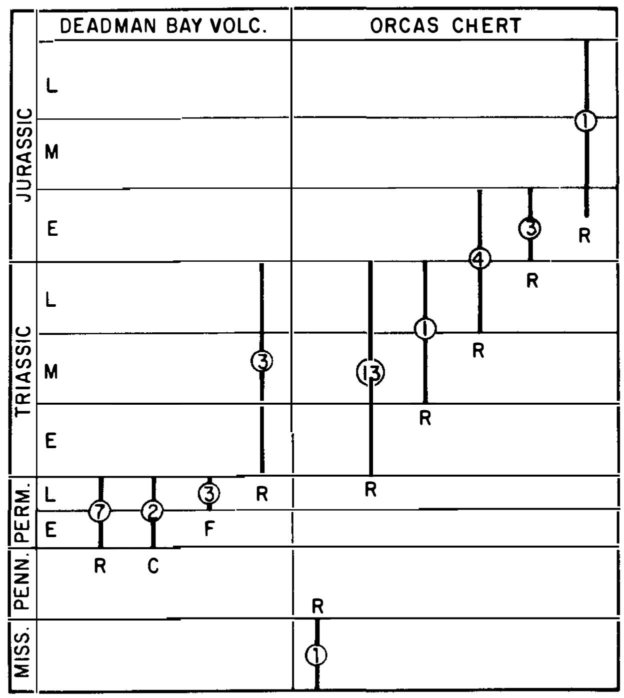


Figure 7

Figure 6

Map of outcrops of Garrison Schist. Solid pattern indicates areas containing one or more exposures. Most outcrops are associated with the Rosario-Eagle Cove thrust. See Figure 2 for overall geologic setting.

Figure 7

Compilation of fossil ages from the Orcas Chert and Deadman Bay Volcanics (Whetten et al., 1978; Danner, 1966; Brandon, 1980). Vertical bars represent possible age range for each fossil collection; number indicates number of fossil determinations with the indicated age range. Types of fossils determined are represented by letters near the bar: R = radiolaria from chert; C = conodont from chert; F = fusulinid from limestone.

Late Permian fusulinids, locally preserved in the limestone, represent some of the youngest Permian fossils in North America and are characteristic of the Asiatic fusulinid province (="Tethyan"), a faunal province exotic to North America (Danner, 1966; Monger and Ross, 1971). In the San Juan Islands, Asiatic fusulinid limestones appear to be restricted to the Deadman Bay Volcanics; they occur in three well documented localities (labelled as "A" in Fig. 5). Conodonts and radiolaria from ribbon cherts interbedded in the Deadman Bay Volcanics have yielded both Permian and Triassic ages (Fig. 7) (Whetten et al., 1978) indicating that the volcanics range into the Triassic.

The Orcas Chert consists of rhythmically bedded gray, green and black radiolarian ribbon chert, with minor pillowed volcanic rocks, tuff and limestone pods (olistoliths ?). Stratigraphic relations are difficult to resolve due to deformation and the absence of distinctive stratigraphic horizons. Twenty-two radiolarian fossil localities have yielded good fossil determinations ranging from Triassic through Jurassic (Fig. 4) (Whetten et al., 1978; Brandon, 1980). Despite the number of fossil collections, the stratigraphic range of the Orcas is broad because the fossils identified have wide ranges. The stratigraphic range of the Orcas could be as restricted as Upper Triassic-Lower Jurassic (Fig. 7). One anomalous Mississippian age, also shown in Figure 7 (sample 77-42b from Whetten et al., 1978), represents the only pre-Triassic age from the Orcas Chert, and the only pre-Permian radiolarian locality in the San Juan Islands. Two other samples from the same locality yielded Triassic radiolaria (samples 77-42a and 77-42c, Whetten et al., 1978) casting further suspicion on the Mississippian age.

Indirect evidence indicates that the Orcas was originally stratigraphically continuous with the Deadman Bay Volcanics, although the Orcas is thrust over the Deadman Bay Volcanics. Both units record varied submarine volcanism. Trace element geochemistry of pillowed flows from each unit indicates that the flows are similar (Fig. 8) and were probably erupted in the same volcanic setting. Triassic radiolarian chert is present in both units (Fig. 7) indicating chert disposition in the Deadman Bay Volcanics continued into the Triassic and might represent the precursor to more voluminous Triassic-Jurassic chert deposition in the Orcas Chert. The thrust displacement of these two units may be slight because the younger Orcas Chert rests structurally above the older Deadman Bay Volcanics.

Previous interpretations (Danner, 1966, 1977) have suggested that the Deadman Bay Volcanics are stratigraphically associated with the Pennsylvanian-Devonian calc-alkaline volcanic unit in a lower thrust sheet in the northern San Juan Islands (see above section on Paleozoic plutonic and volcaniclastic sedimentary rocks). This inferred stratigraphic relationship is not presently preserved, perhaps owing to the middle Cretaceous thrust faulting. However, these two units occur in structurally distinct positions and are separated by intervening structural units which include a thick package of lower Paleozoic plutonic rocks of the Turtleback Complex (Fig. 5). An alternative interpretation is that the Deadman Bay Volcanics and Pennsylvanian-Devonian Volcanics represent two unrelated Paleozoic terranes which have been juxtaposed. The distinctive Asiatic-fusulinid limestone in the Permian volcanics suggests correlations with similar rocks of the Cache Creek Group and Bridge River Group of central British Columbia (Monger, 1977) and the Trafton Group of the western Cascades foothills (Danner, 1966). The Pennsylvanian-Devonian volcanic rocks could be correlative to the Chilliwack Group of the North Cascades (Misch, 1977) or the Sicker Group of Vancouver Island (Muller, 1980a). Monger (1977) has discussed the regional tectonic setting of these different Paleozoic terranes.

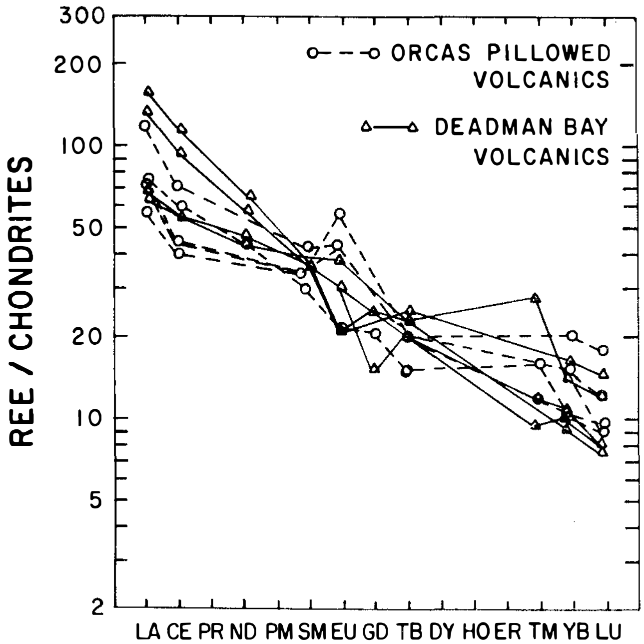


Figure 8

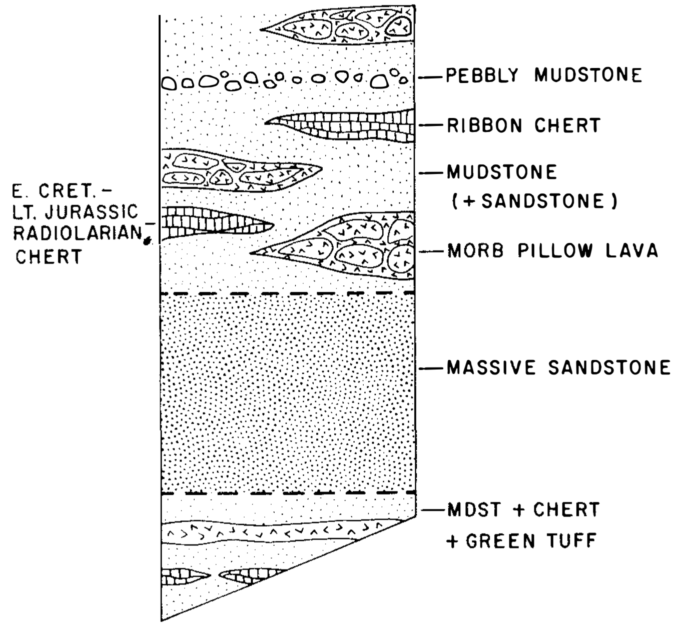


Figure 9

Figure 8

Normalized rare-earth element (REE) curves for volcanic rocks from the Orcas Chert unit and the Deadman Bay Volcanics. Because samples from both units show similar light —REE enrichment, they are interpreted to be related stratigraphically. Unpublished data from Whetten (U.S.G.S.), Vance, and Brandon and Cowan.

Figure 9

Generalized stratigraphic column of the Constitution formation as exposed on San Juan Island. The unit consists of a fault-bounded Jurassic-Lower Cretaceous clastic sequence, probably more than 4 km thick. The Constitution includes three informal members described in the text. They are a complex depositional association of massive sandstone and black mudstone with minor ribbon chert and pillowed basalt. The ages of radiolaria from interbedded chert indicate that the upper member of the Constitution is Late Jurassic-Early Cretaceous in age. The lower members are undated but are probably Jurassic or younger.

Constitution Formation

The Constitution Formation (Vance, 1975, 1977; Brandon, 1980) is a Jurassic-Lower Cretaceous clastic sequence, probably more than 4 km thick (Fig. 8). The thickest part of the formation is on southern San Juan Island in the southwest limb of a broad syncline which plunges gently southeast. Stratigraphic relations within the Constitution are best preserved here because thrust faults and imbrication are largely confined to the base and top of the unit.

As shown in Fig. 8, the Constitution Formation is a complex depositional association of massive sandstone and black mudstone with minor ribbon chert and pillowed basalt. Three members are recognized:

1) The lowest member which consists of black hemipelagic mudstone, and recrystallized ribbon chert, with subordinate pillowed flows, green tuff, tuffaceous sandstone and minor limestone olistoliths;

2) The middle member is composed of massive volcaniclastic sandstone with minor clast-supported conglomerate; and

3) The highest member, is black mudstone, with thin-bedded siliceous sandstone, and subordinate polymict pebbly mudstone, massive sandstone, radiolarian chert, and pillowed basalt.

Two radiolarian fossil collections from chert in the upper member of the Constitution are Late Jurassic - Early Cretaceous (Whetten et al., 1978; Brandon, 1980). The age of the lower members is not directly known; however, limestone olistoliths in the lowest unit contain Late Triassic conodonts (N. Savage, 1982, pers. comm.) indicating a Late Triassic maximum age.

Indirect evidence suggests a post-Early Jurassic age for the Constitution. Danner (1977, p.484; 1979, written comm.) identified a fusulinid from a limestone clast in a Constitution conglomerate as a Schwagerinid of "Tethyan aspect." He suggests that the clast was probably derived from Asiatic fusulinid-bearing limestones of the Orcas Chert and associated Deadman Bay Volcanics. If correct, this relation suggests that the Constitution is younger than the Early Jurassic-Permian Orcas-Deadman Bay sequence.

The contact between the Constitution and Orcas is the Rosario thrust on Orcas Island (Vance, 1977) and the Eagle Cove thrust on southern San Juan Island (Brandon, 1980) (Figs. 5 and 6). It is marked by slices of the exotic Permo-Triassic Garrison schist. The lowest member of the Constitution is chert and mudstone like that in the underlying Orcas Chert. Vance (1975) suggested that the lowest member of the Constitution represents a gradational transition from the older Orcas Chert, subsequently modified by thrusts. The Asiatic-fusulinid limestone clast in the Constitution Formation (Danner, 1977) indicates close proximity of the Constitution to the Orcas-Deadman Bay sequence. Fossil ages from the lowest Constitution member would clarify the original stratigraphic relation of the Constitution to the Orcas Chert.

Petrologic studies of sandstone and conglomerate clasts of the Constitution (Brandon, 1980; Vance, 1975, 1977) indicate that the source area was dominated by intermediate and silicic volcanic rocks with minor basalt. Volcanic clasts in the sandstone are angular first-cycle detritus, eroded from a volcanic arc. Minor amounts of metamorphic rock fragments and metamorphic minerals in the sandstone and conglomerate indicate that the source included subordinate schistose metabasalt of greenschist to albite-epidote amphibolite and blueschist facies. Assemblages and metamorphic textures in most of the metamorphic detritus resemble Permo-Triassic metabasaltic schists such as the Garrison Schist in the San Juan Islands and the rocks of Groat Mountain and Vedder Mountain in the North Cascades (Misch, 1977; Rady, 1981; Bernardi, 1977). Constitution sandstones also contain minor chert with locally preserved radiolaria, perhaps derived from the Orcas Chert.

Sandstone petrology and regional tectonic relations indicate that the Constitution was deposited in a convergent margin setting. The Constitution includes hemipelagic mudstone, pebbly mudstone and massive sandstone, with minor interbedded radiolarian ribbon chert and pillowed basalt. The lithofacies suggests deposition below wave base in a morphologically complex slope and slope-basin setting (see Brandon, 1980 for a more extensive discussion). The setting included areas isolated temporarily from clastic deposition, allowing accumulation of radiolarian chert.

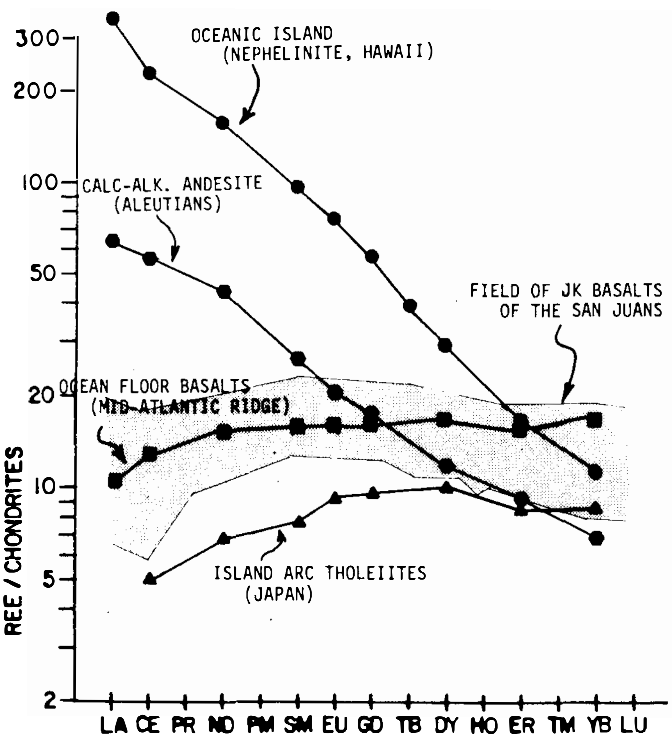


Figure 10 A

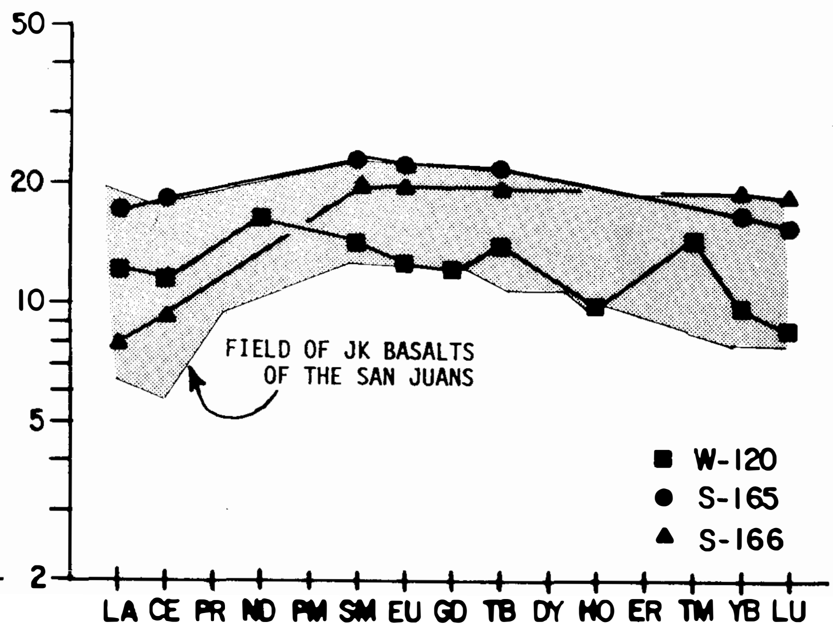


Figure 10 B

Figure 10 A

Normalized rare-earth element (REE) curves for basalt from the Constitution Formation on southern San Juan Island (W-120: Griffin Bay; S-165: south Mulno Cove; S-116: south Merrifield Cove). Shaded region represents the range of REE curves for Upper Jurassic-Lower Cretaceous basalt from the Lopez Complex and Decatur Terrane on Lopez, Fidalgo, and Lummi islands. (Data from Vance et al., 1980; and U. S. Geological Survey, unpub.)

Figure 10 B

Average REE curves for modern volcanic-tectonic settings (from Garcia, 1978). The shaded region shows the range of REE values for San Juan Jurassic-Lower Cretaceous basalts.

Interbedded pillow basalt in the Constitution attests to intermittent submarine volcanism within the dominantly clastic depositional environment. Basalt contains varying amounts of clinopyroxene and plagioclase microphenocrysts set in an altered glass matrix. Phenocryst assemblages and major and trace-element data (Fig. 9) indicate that the basalt is like modern MORB-type basalts (Mid-Ocean Ridge Basalts) (Vance et al., 1980; Brandon, 1980). The Constitution basalt may represent ocean floor volcanism, perhaps at a ridge or a "leaky"

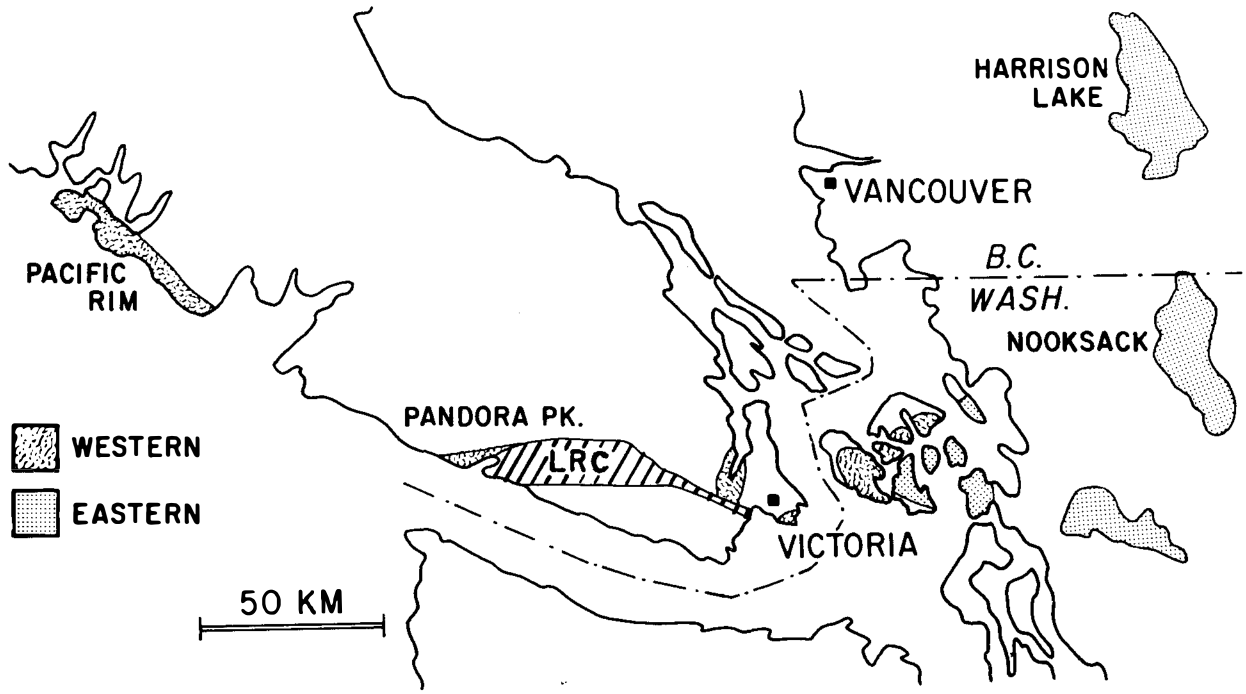


Figure 11

Map of distribution of two facies or lithologic associations of Upper Jurassic-Lower Cretaceous strata (Cowan and Brandon, 1981). The "western facies" is predominantly clastic sandstone, mudstone and pebbly mudstone, interbedded with basaltic flows, tuffs and radiolarian ribbon cherts. The "eastern facies" consists of well-bedded terrigenous clastic strata; volcanic flows and chert are restricted to the base of the section. The diagonally ruled unit labelled "LRC" is the mainly sedimentary Leech River Complex (Muller, 1980b; Fairchild and Cowan, 1982). The protolith is probably also Jurassic-Cretaceous but facies assignment is uncertain because of deformation and metamorphism.

transform fault. However, the relatively minor amount of basalt is unlike that of present ocean floors. Recent drilling by the Deep Sea Drilling Project in the Marianas forearc has documented MORB-type basalts erupted in a forearc above the trench (Hussong et al., 1982). This analogue may resemble the ancient tectonic setting of the Constitution.

The Constitution is not an accretionary subduction complex. It is structurally underlain by a variety of older rocks, some as old as early Paleozoic. Geologic relations discussed above suggest that the unit was deposited above older rocks which probably represented part of the upper-plate framework of a convergent margin system. The accretionary complex belonging to this system must have been farther west and has probably been removed and carried northward by Cenozoic transcurrent faulting (Cowan, 1982; Brandon and Cowan, in press).

The Constitution Formation is possibly correlative to other Jurassic-Lower Cretaceous rocks exposed around southern and western Vancouver Island (rocks of Gonzales Bay near Victoria - Muller, 1980b; Pandora Peak unit near Port Renfrew - Rusmore, 1982; Pacific Rim Complex, western Vancouver Island - Muller, 1973; Brandon, in press; Figs. 8 and 9). These units represent a distinctive "western facies" (Cowan and Brandon, 1981) of Jurassic-Lower Cretaceous rocks in the Pacific Northwest, characterized by marine clastic sequences of mudstone and massive sandstone with interbedded MORB-type basalt and radiolarian ribbon chert. These units have been affected by a high pressure lawsonite-prehnite metamorphic event. Despite these similarities, relations among the different "western facies" units is poorly understood. With further study this group of rocks will provide a better understanding of the original extent of the San Juan thrust system and its relationship to Wrangellia terrane of Vancouver Island.

Lopez Complex

The Lopez Complex (Cowan and Miller, 1980; Brandon, 1980) beneath the Lopez thrust, is along the southern coast of Lopez Island and on the southeast tip of San Juan Island (Figs. 4 and 12). It is a tectonic complex comprising fault-bound slices of a variety of predominantly Jurassic and Cretaceous rocks. The Lopez Complex represents a fault zone between the Decatur Terrane and the underlying Constitution Formation. It is distinguished as a separate map-unit by its diversity of rock types, and internal imbrication.

The most abundant rock type is medium- to coarse-grained sandstone with interbedded mudstone. Sandstones with abundant shale chips and others with conspicuous granules and pebbles of white and grey chert are present. Mafic pillow lavas, flows and breccias constitute about 20% of the complex. Radiolarian ribbon cherts are locally abundant. Olistostromal pebbly and bouldery mudstones, with graywacke, basalt, and chert clasts in a black mudstone matrix, are an important component of the central part of the complex. Most macro- and microfossil ages (Whetten et al., 1978) range from Jurassic to Early Cretaceous, but red tuffs at Richardson (labelled as "R" in Fig. 4) contain mid-Cretaceous (Albian-Cenomanian) foraminifera.

At map-scale, the Lopez Complex consists of northwest-striking, northeast-dipping elongate lenticular tectonic slices with distinctive rocks or suite of units. Sandstone in some slices resembles, and was probably derived from, the Lummi Formation. Other slices of interbedded sandstone, pebbly mudstone, chert, and tuff were derived from the Constitution Formation. A tectonic slice of probable Turtleback Complex occurs on the southeast end of San Juan Island (Fig. 12). Some slices, like the one with mid-Cretaceous pillow lava, breccia, and tuff at Richardson, were apparently derived from neither the Lummi nor Constitution; their source is not known. Thus, the Lopez Complex can be visualized as a thin zone, between two extensive lithotectonic units, partly made up of tectonic slices derived from these adjacent units and partly of slices unique to the zone. The unique rock types and the fragment of Turtleback Complex imply that the Lopez Complex and Lopez Thrust represent considerable tectonic transport and dislocation.

Another distinctive feature of the Lopez is a moderate to strong slaty cleavage, striking northwest and dipping northeast, superimposed on all rock types except the most massive basalt and graywacke. It may record flattening of the complex after the large-scale imbrication. This cleavage is also observed in structurally lower rocks on southern San Juan Island.

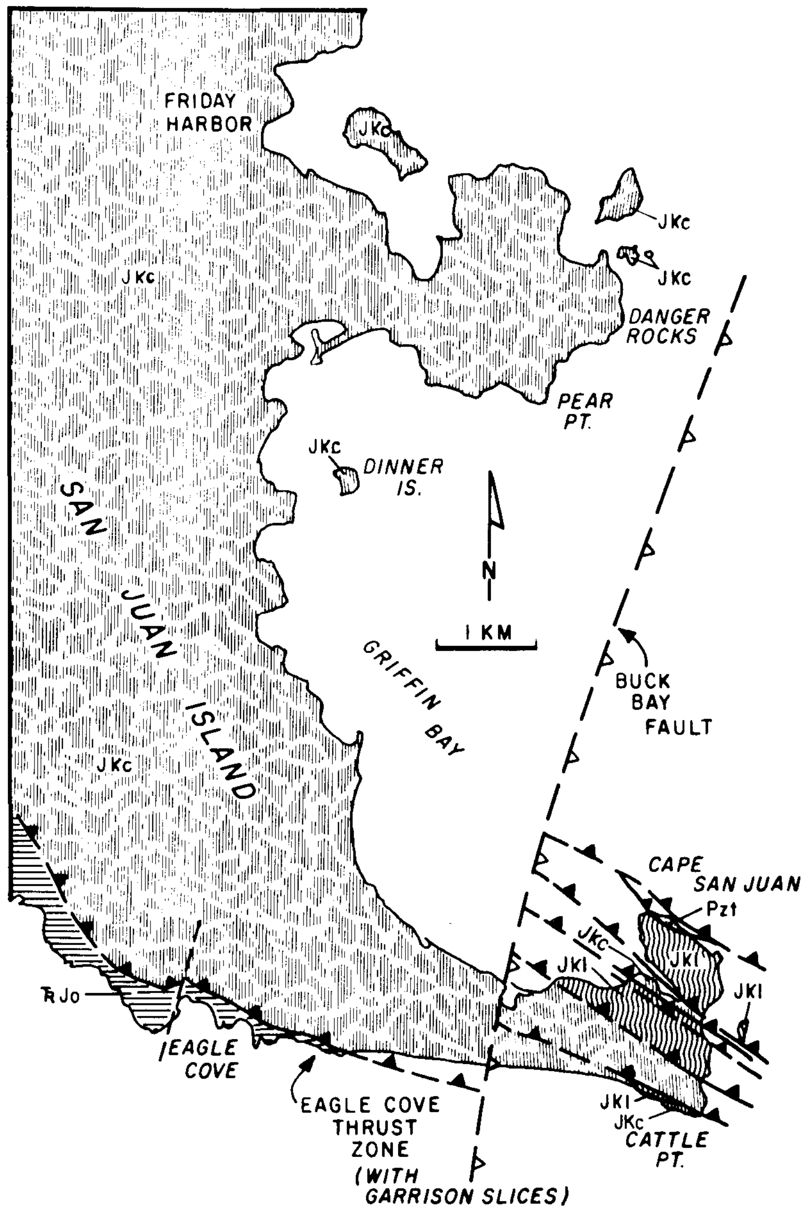


Figure 12

Geological map of south San Juan Island (Brandon, 1980). (For legend, see Figure 5.)

Some sandstone in the Lopez Complex contains lawsonite, as fibrous, brownish mats in plagioclase (Glassley et al., 1976). Most basalt contains metamorphic aragonite, pumpellyite, and chlorite which replaces microphenocrysts and groundmass and has filled veins and vesicles.

Decatur Terrane

The structurally highest unit in the San Juan Islands, above the Lopez Thrust, is the Decatur Terrane, named by Whetten et al. (1978). It is widely exposed in the eastern part of the archipelago (Fig. 4), where it comprises the Fidalgo Complex and overlying, predominantly clastic sedimentary rocks of the Lummi Formation (Fig. 11).

The Fidalgo Complex has been studied in detail on Fidalgo Island by Brown et al. (1979) and Gusey (1978). It consists of dunite, pyroxenite and layered gabbro, overlain by mafic to intermediate volcanic rocks; dikes of quartz diorite, diorite, and quartz albitite are abundant. Mafic pillow lavas, flows and tuffs, and metaplutonic breccias are common on Lopez and Decatur Islands. Brown et al. (1979) and Vance et al. (1980) interpret the Fidalgo Complex as ophiolite, but its original tectonic setting is controversial. It may have formed in a small spreading ocean basin, or may be related to an oceanic volcanic arc. Several radiometric ages (summarized in Whetten et al., 1978) indicate the Fidalgo Complex is Middle to Late Jurassic.

The plutonic and crystalline basement is overlain by sedimentary and volcanic rocks. This stratigraphically complex zone contains distinctive sandstone, conglomerate, and breccia with clasts from the underlying crystalline and volcanic rocks. On Fidalgo Island (Brown et al., 1979; Gusey, 1978), these are interbedded with mafic to intermediate volcanic rocks and tuffaceous and pelagic argillite; on Lopez Island, they are underlain by, and possibly interbedded with, pillow lava, volcanic breccia, and radiolarian ribbon chert. The basal units are succeeded by a thick sequence of well bedded lithic sandstone and mudstone, named the Lummi Formation (Vance, 1975). Individual sections exposed on various islands are broadly correlative, but cannot be placed within an overall succession because not enough is known about the internal stratigraphy of the formation. The sandstone contains chert and volcanic clasts. The formation is cut by numerous high-angle faults; mesoscopic folds are uncommon and locally associated with a weak slaty cleavage.

Radiolarians from chert at the base of the formation are Late Jurassic, and Late Jurassic-Early Cretaceous belemnites have been collected from sandstone and conglomerate (Whetten et al., 1978).

The Decatur Terrane preserves a distinctive assemblage of Middle Jurassic to Lower Cretaceous rocks that can be compared to coeval rocks elsewhere in the San Juan Islands and nearby on Vancouver Island and in the northwest Cascades. After the ophiolitic or arc-related Fidalgo Complex formed, it was disrupted, raised and locally eroded. It was subsequently inundated by terrigenous clastic sediments, from a nearby continental landmass (Fig. 13). A similar record of mid-Jurassic volcanic activity followed by deposition of marine clastic sediments is preserved in the northwest Cascades in the Wells Creek volcanics and Nooksack Group in Washington (Misch, 1966; 1977) and near Harrison Lake, B. C. (Monger, 1970) (Figs. 4, 11).

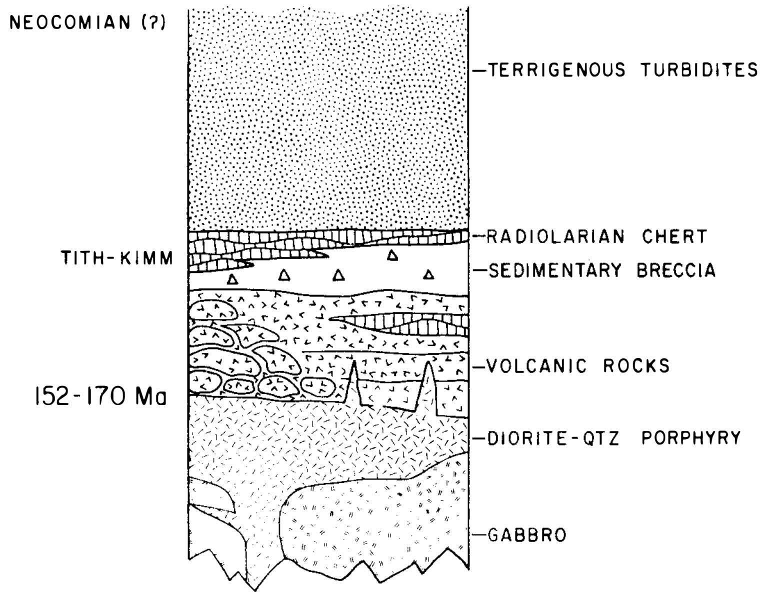


Figure 13

Generalized stratigraphic column of the Decatur Terrane summarized in part from Brown et al. (1979) and Gusey (1978). The Fidalgo Complex, in part of Middle Jurassic age, is overlain by a stratigraphically complicated zone comprising volcanic flows, second tuffs, argillite and chert, and breccia containing clasts of the underlying Fidalgo Complex. This zone is overlain depositionally by turbidite of the Lummi Formation.

The Lummi Formation represents a widely distributed "eastern facies" (Cowan and Brandon, 1981) of Upper Jurassic-Lower Cretaceous rocks (Fig. 8) comprising well stratified turbidites overlying an igneous basement with radiolarian cherts and volcanic flows confined to the base of the section. The Constitution Formation, separated from the Decatur Terrane by faults (Fig. 5), represents a coeval "western facies" characterized by volcaniclastic sandstone, complexly interbedded with oceanic basalt, basaltic tuff and ribbon chert. Alternative models for the origin and juxtaposition of these contrasting assemblages in the San Juan Islands are presented in the section entitled "Tectonic Models."

Timing of Deformation and High-Pressure Metamorphism

Mid-Cretaceous thrust faults and low grade, high-pressure metamorphism represent the earliest tectonic event to affect the pre-Late Cretaceous rocks in the San Juan Islands. It resulted in a stacked sequence of thrust sheets. Some of these sheets, such as the Decatur Terrane, are relatively coherent, but others are internally deformed.

Three imbricate fault zones are recognized in the San Juans. They are complex, ranging from 10's to 100's of meters thick and contain slices of exotic rock units, indicating that they accommodated large displacement. From lowest to highest, these zones are: 1) the Orcas fault zone (Vance, 1977) on Orcas Island, separating the Orcas Chert from structurally lower Paleozoic rocks of the Turtleback Complex and Paleozoic volcaniclastic rocks; 2) the Rosario-Eagle Cove

Thrust (Vance, 1977; Brandon, 1980), marked by numerous exotic slices of Garrison Schist and separating Constitution Formation from the underlying Orcas-Deadman Bay sequence; and 3) the Lopez Thrust and Lopez Complex (Cowan and Miller, 1980), containing exotic slices of Middle Cretaceous volcanic rocks and Turtleback Complex, and separating the Decatur Terrane from the underlying Constitution Formation.

The pre-Late Cretaceous rocks in the San Juan Islands were affected by a regional, low grade, high pressure metamorphic event (Vance, 1968; Glassley et al., 1976; Brandon, 1980). Metamorphism resulted in widespread aragonite, prehnite, and lawsonite. Coarse-grained aragonite occurs in limestones and also as cross-cutting veins in other rock types. Prehnite and lawsonite-bearing assemblages are strongly controlled by rock composition and therefore are best developed in volcaniclastic sandstones of the Jurassic-Cretaceous units. The presence of aragonite and lawsonite + quartz in these metamorphic assemblages indicates pressure above 3.5 kb, which correspond to lithostatic burial below more than 11 km (Liou, 1971; Crawford and Hoersch, 1972; Boettcher and Wyllie, 1968). Temperatures were under $\sim$ 200°C (Liou, 1971).

San Juan metamorphism is a static event; lawsonite, prehnite and aragonite assemblages are in veins or as small randomly oriented aggregates. Exotic slices in the imbricate fault zones were also affected by this metamorphism. Many slices show evidence of intense cataclasis and brecciation. The lawsonite-prehnite-aragonite metamorphism overprints this deformation and therefore post-dates thrust emplacement of these slices.

This and other evidence (discussed by Brandon, 1980) indicates that large-scale thrusts preceded high-pressure metamorphism. The youngest faulted and metamorphosed rocks are the middle Cretaceous Richardson volcanics, a large fault slice in the Lopez Complex on southern Lopez Island. Microfossils from these volcanics are dated as late Albian-early Cenomanian (Whetten et al., 1978; D. L. Jones, pers. comm., 1980) which is equivalent to 96 m.y. Brandon (1982) has described clasts of metamorphosed sandstone in an early Campanian conglomerate in the Upper Cretaceous Nanaimo Group to the north of the San Juan Islands (Fig. 4). Lawsonite and prehnite, like those in volcaniclastic sandstone in the San Juan Islands, are also found in the conglomerate clasts, indicating uplift and exposure of the San Juan rocks by early Campanian which is equivalent to 83 m.y. Several apatite fission track ages for San Juan rocks have substantiated this uplift age (Naeser and Zimmerman, written comm., 1980).

The constraints indicate that San Juan thrusting and metamorphism occured during a 13 m.y. interval. Brandon (1980, 1982) has argued that high-pressure metamorphism is a result of structural burial by thrusting. The thick Shuksan thrust sheet exposed in the northwestern Cascades (Misch, 1966, 1977) probably extended west over the San Juan Islands and accounts for much of the overlying structural cover. Uplift must have occurred as rapidly as burial. During this 13 m.y. event, San Juan rocks were displaced vertically more than 22 km with average vertical transport rates above 1.7 km/m.y. (1700 cm/k.y.).

This rapid uplift must have been accommodated by younger Late Cretaceous faults. Regional geologic relations indicate that the San Juan Islands are bounded by young, post-metamorphic faults. Three of these are in the archipelago

(Fig. 5): 1) the Nanaimo Group is truncated and faulted against pre-Late Cretaceous San Juan rocks along an unexposed fault in the north part of the islands; 2) two unmetamorphosed Mesozoic units (Spieden and Haro) on northern San Juan Island are faulted aginst metamorphosed San Juan rocks to the south; and 3) the Buck Bay fault, which crosses southeast Orcas and southern San Juan Island (Figs. 5 and 12), truncates some of the mid-Cretaceous faults in the islands (see map pattern in Fig. 4) and is probably also a young, post-metamorphic fault. These structures and others might have been involved in uplift of the San Juan rocks. Alternatively, these faults might be related to large-scale strike-slip fault displacements which have affected much of southern Vancouver Island to the west (Fairchild and Cowan, 1982). Although the younger, post-metamorphic structural history is poorly understood, the large uplift required to bring the San Juan Islands to surface indicates that this mid-Cretaceous thrust system is displaced, especially with respect to the rocks of southeastern Vancouver Island.

Tectonic Models

Early workers (McLellan, 1927; Danner, 1966) in the San Juan Islands were hampered by poor fossil control, and failed to recognize the presence of thrust faults. They placed San Juan rock units into an uncomplicated Paleozoic-Mesozoic stratigraphy which they envisioned as a generally normal succession. Vance (1975) was first to recognize mid-Cretaceous thrust faults on San Juan and Orcas Island. Fossil and radiometric ages (Whetten et al., 1978) indicated that stratigraphic relations are indeed complicated. They stressed the diverse nature of different lithotectonic terranes in the San Juans and suggested that they had been displaced, probably great distances, from their original locations, and subsequently tectonically assembled.

Coney et al. (1980) have suggested that many lithotectonic terranes in the western Cordillera of North America are in suspect settings, and may be displaced hundreds or thousands of kilometres prior to final emplacement. An increasing number of displaced terranes have been documented by paleomagnetic studies. In addition, faunal distinctions, such as the Asiatic fusulinids in the Deadman Bay Volcanics, have been used to distinguish some terranes as exotic and probably far-travelled (Monger and Ross, 1971). Ultimately, the identification and differentiation of terranes hinges on recognizing similarities and differences amongst coeval rock assemblages. It is difficult to determine a clear picture of how presently fault-bounded units might have originally been interrelated. More difficult is that even well documented, displaced terranes are commonly bounded by complex structures, which are not directly related to their tectonic boundaries.

To illustrate the difficulties, we present alternative hypotheses for the late Mesozoic tectonic evolution of the San Juan Islands. The authors disagree about which hypothesis best explains observed relations. The question is how rocks in the archipelago relate to each other, and to coeval rocks on Vancouver Island and in the northwestern Cascades on the Mainland. Another way of stating the problem is: how many of these units were already assembled before mid-Cretaceous thrusting, and where were they with respect to Vancouver Island and the Mainland?

Given the diversity of stratigraphic units, and their complex structural setting, it is encouraging that all three San Juan authors agree on some relationships:

1) Prior to mid-Cretaceous thrust faulting, most of the lithotectonic units in the San Juan Islands were intact stratigraphic sequences. The Lopez Complex might be an exception.

2) San Juan lithotectonic units were probably in an American continental margin setting by Late Jurassic, long before mid-Cretaceous thrust faulting. The proximity to America is indicated by the widespread occurrence of Upper Jurassic and younger terrigenous clastic rocks (Constitution, Spieden, Lummi and Nooksack units shown in Fig. 4) which contain minor continent-derived detritus. This relationship does not preclude large lateral displacement along the continental margin; however, major convergent suturing amongst lithotectonic units in the San Juan Islands does not seem to have occurred after the Late Jurassic.

3) The Upper Jurassic-Lower Cretaceous Lummi Formation in the San Juan Islands correlates with the Nooksack Group (Misch, 1966) of the northwestern Cascades (Fig. 4). This indicates an important Late Jurassic overlap developed across older units exposed in these areas: the middle Jurassic igneous basement of the Decatur Terrane and Jurassic intermediate volcanic rocks and older related rocks beneath the Nooksack Group in the northwestern Cascades. These older rocks were close by in Late Jurassic.

4) The Garrison Schist and Orcas-Deadman Bay sequence were in the source area and, therefore, close to the Constitution Formation by Late (?) Jurassic. This relationship is indicated by provenance studies of Constitution sandstones and conglomerates discussed above.

5) Upper Paleozoic calc-alkaline volcanic and volcaniclastic rocks of the northern San Juan Islands are a volcanic arc sequence related to intrusive rocks of the Turtleback Complex. This sequence represents a distinctive and important Paleozoic arc terrane in the San Juan Islands.

6) The Orcas chert and Deadman Bay Volcanics represent parts of an originally continuous Permian-thru-Lower Jurassic sequence different from older "supracrustal" Paleozoic rocks in the San Juan Islands. In-place stratigraphic occurrences of Asiatic fusulinid-bearing limestone in the San Juan Islands are restricted to the Permian part of the Orcas-Deadman Bay sequence.

Outside of this framework, relationships remain obscure. One serious uncertainty is how much transcurrent movement and fragmentation occurred during the Late Jurassic and Early Cretaceous, before mid-Cretaceous thrusting. The possibility of large displacements parallel to the continental margin of discrete lithotectonic units in the Pacific Northwest invites several hypotheses. A specific problem is the original relation between Upper Jurassic-Lower Cretaceous clastic units in the San Juan Islands: were the Constitution and Lummi Formations deposited in laterally related settings in the same continental margin or were the two units juxtaposed after displacement from separate original positions? These hypotheses, presented in more detail below, illustrate the range of possibilites.

The first hypothesis, favored by Brandon, recognizes that pre-Constitution units in the western San Juans are exotic with respect to the northwestern Cascades and Vancouver Island, but it proposes that these units were accreted prior to deposition of a blanket of Upper Jurassic-Cretaceous terrigenous clastic sediments. The Constitution, with minor interbedded chert and pillow basalt, represents a more "oceanic" or "western" facies of the sandstone-dominated Lummi Formation. Constitution Formation and related "western" facies were deposited along the southern edge of a lithologically diverse assemblage which included Wrangellia and other Paleozoic units in the western San Juans. The Jurassic-Cretaceous Pacific Rim Complex on the west coast of Vancouver Island is also part of this facies (Brandon, in press). According to this model, the mid-Cretaceous thrust faults in the San Juan Islands and North Cascades (Misch, 1966) record shortening of a previously assembled continental margin framework which resulted in the telescoping of overlying and contiguous facies (Lummi and Constitution). This hypothesis is part of a more regional tectonic model presented by Vance et al., 1980.

Another hypothesis, favored by Cowan, emphasizes that the Lopez Thrust and Lopez Complex represent a zone of significant tectonic transport. The lithologic contrast between the coeval Constitution Formation and Lummi Formation is too great to be explained by telescoping of originally contiguous facies on this thrust. The Constitution (together with its basement of Orcas Chert and Garrison Schist) and the Turtleback Complex and related Paleozoic volcanogenic rocks were derived from farther south along the North American continental margin and were transported northward parallel to the continental margin until they were emplaced against and beneath the Decatur Terrane during mid-Cretaceous thrusting. This model implies substantial transcurrent (or obliquely convergent) displacement prior to final thrusting.

Another unresolved problem concerns the relationship of Paleozoic volcanic rocks in the northern San Juan Islands to coeval, similar rocks elsewhere in the Pacific Northwest. Vance et al. (1980) have correlated the San Juan Paleozoic volcanics on lithologic grounds with the Sicker Group on Vancouver Island where it represents part of the Wrangellia Terrane (Jones et al., 1977). If correct, this correlation would extend Wrangellia into the San Juan Islands, demonstrating that part of Wrangellia was involved in mid-Cretaceous thrust faulting and high pressure lawsonite-prehnite-aragonite metamorphism. Vance et al. (1980) suggested that the mid-Cretaceous event represents northward obduction of an oceanic sequence (Deadman Bay-Orcas-Constitution) onto Wrangellia.

Well documented correlations of the San Juan Paleozoic volcanics are lacking. They may correlate with the Chilliwack Group of the northwestern Cascades rather than the Sicker. A third alternative is that the San Juan Paleozoic volcanics represent a Paleozoic terrane unique to the Pacific Northwest.

This summary of rival hypotheses illustrates some of the unresolved problems and how they affect our understanding of the Mesozoic tectonic evolution of this region. Paleomagnetic studies may help resolve some of these problems. Provenance studies of sandstone and conglomerate in the Jura-Cretaceous units may also improve our understanding of paleogeographic relations.

Conclusions

(D. S. Cowan)

The pre-Upper Cretaceous rock units in the San Juan Islands can be divided into two groups depending on whether they experienced important mid-Cretaceous deformation and metamorphism that may be related to the mid-Cretaceous thrusting in the Cascades (Misch, 1966). The unmetamorphosed Upper Triassic Haro Formation and Upper Jurassic-Lower Cretaceous Spieden Group occur in small, fault-bounded blocks in the northwest part of the islands; their basement is unknown. The metamorphosed and deformed assemblage is separated from the unmetamorphosed strata by probably high-angle, Late Cretaceous or early Tertiary faults and includes diverse rock units, juxtaposed by mid-Cretaceous thrusts. The structurally lowest units in the tectonic stack occur in the northern and western part of the San Juan Islands and the highest units are in the southeast. One of the outstanding tectonic problems in the area comprising southern Vancouver Island, the San Juan Islands and the western Cascades concerns the original relationships of rock units in the areas. Many units are partly or wholly time equivalent. Some interpretations emphasize lithologic similarities and conclude that rock units can be correlated across the region. Other interpretations stress lithologic contrasts and postulate that certain units in the San Juan's are allochthonous with respect to Vancouver Island and the Cascades. These alternatives have been explored in the section dealing with the geology of the San Juan Islands. In the following summary of units in the San Juan Islands time-correlative units of surrounding areas are mentioned to provide a basis for discussion and evaluation.

The structurally lowest unit consists of the Paleozoic plutonic Turtleback Complex and related Devonian, Pennsylvanian and Permian volcaniclastic strata. This assemblage resembles part of the Yellow Aster Complex and Chilliwack Group in the northwest Cascades and to the Sicker Group and associated Saltspring Intrusions on Vancouver Island. The Turtleback is overlain structurally by several thrust slices that include the Permo-Triassic Garrison Schist, Permian to Lower Jurassic Deadman Bay Volcanics and Orcas Chert, and Jurassic to Lower Cretaceous Constitution Formation. Metamorphic rocks of the Vedder Complex in the northwestern Cascades resemble the Garrison Schist. Rocks similar to the Constitution Formation, in terms of lithology, metamorphism and deformation occur in the Leech River Complex at Gonzales Bay, Finlayson Arm, Port Renfrew and the Pacific Rim Complex on Vancouver Island. The Constitution is structurally overlain by the Decatur Terrane, consisting of the Middle Jurassic to Lower Cretaceous Lummi Formation. Some plutonic and volcanic rocks in the Fidalgo Complex may correlate with the Island Intrusions and Bonanza Group of Vancouver Island and the volcanic part may correspond to the Middle Jurassic Harrison Lake Volcanics and Wells Creek Volcanics in the northwestern Cascades. Sandstone and mudstone of the Lummi Formation resemble the Nooksack Group in the northwestern Cascades and Upper Jurassic to Lower Cretaceous strata at Harrison Lake and they may correlate with the Kyuquot Group on northwestern Vancouver Island. It is emphasized that, even though certain units in the San Juan Islands correlate with coeval rocks on Vancouver Island, most of the rocks in the San Juan's have experienced a major mid-Cretaceous orogenic event involving complex thrusting and tectonic burial sufficient to induce the development of the high-pressure metamorphic minerals, lawsonite and aragonite. Satisfactory tectonic models will have to account for this well defined event and explain why many nearby units on Vancouver Island were unaffected by the mid-Cretaceous thrusting and metamorphism that characterize both the San Juan Islands and northwestern Cascades.

Subsequent to this mid-Cretaceous deformation, a molasse basin covered at least northern San Juan Islands and the northeast margin of Vancouver Island, resulting in deposition of marine and non-marine clastic strata of the Late Cretaceous Nanaimo Group and early Tertiary Chuckanut Formation

Acknowledgements

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DAY 1: EARLY TERTIARY MOLASSE ON MAINLAND; JURASSIC VOLCANIC-PLUTONIC-SEDIMENTARY COMPLEX OF FIDALGO ISLAND

(J. E. Muller)

Day 1 of the excursion deals chiefly with the Jurassic volcanic-plutonic complex and overlying clastic strata Fidalgo Island. In addition, the first stop is devoted to the molasse-type sequence laid down unconformably in early Tertiary time on older rocks, after they had been stacked as thrust sheets in mid-Cretaceous time.

From Vancouver, the route leads south to Oak Street Bridge via Highway 99 to the U.S. border at Blaine (50 km; 31.1 m). In Washington State, continue via Route 5 to Bellingham and at Exit 250 (92.6 km; 57.5 m) proceed on Route 11, Chuckanut Drive. Continue south, passing many outcrops of Chuckanut sandstone, enter Larrabee State Park.

STOP 1-1; Chuckanut Formation

103.4 km (64.3 m) Coastal exposures in Larrabee Park.

The Chuckanut Formation is well exposed along the coast of Samish Bay and along Chuckanut Drive. It contains non-marine arkosic sandstone, siltstone, shale and conglomerate that yielded fossil leaves, spores and pollen. With the Late Cretaceous, mainly marine, strata of the Nanaimo Group, the Chuckanut Formation is a molasse that filled the late-orogenic Georgia Basin, approximately coincident with Georgia Strait.

Coal seams were mined in several places and the largest mine was in northwest Bellingham, where coal of high volatile C bituminous rank was mined after 1918 for several decades. (Griggs (1970) measured and sampled 9484 feet (2891 m) of the type section along Samish Bay and Chuckanut Drive. The upper and lower parts of the section are characterized by thick sandstones with subordinate shale and some coal seams, laid down in swamps and lagoons between stream channels.

Griggs (1970) concluded on the basis of the palynomorphs that the Chuckanut is Late Cretaceous to Early Eocene, but younger than the Comox Formation (Santonian; basal unit of Nanaimo Group). Reiswig (1982) determined the age as middle Paleocene to late Eocene, or perhaps earliest Oligocene and noted that Griggs, in assigning an older age, had not recognized that many palynomorphs are reworked. Johnson (1982) obtained fission track ages that show that most of the Chuckanut is not older than early Eocene. The Chuckanut Formation, like the Nanaimo Group, lies unconformably on older rock units, in this region mainly on the Darrington Phyllite belonging to the mid-Cretaceous Shuksan thrust sheet.

The coastal outcrops show well bedded, in part cross-bedded, arkosic sandstone of the Chuckanut Formation with steep to vertical inclination, striking northwest and reappearing in a reef to the northwest. The strike changes by about 90 degrees on a steep dip-slope in Wildcat Cove, just north of the main park entrance at the boat launching site and in Muller's opinion is due to a north northwest trending fault parallel to the coast.

Continue along Chuckanut Drive, leading past excellent exposures of the Chuckanut type section. Past Oyster Creek, occupied by another north striking fault, roadcuts are in schistose greywacke and argillite, together with schistose intermediate metavolcanic rocks.

STOP 1-2: Jurassic (?) metavolcanic rocks

111.4 km (69.2 m) Deep cut and abandoned sharp curve in highway (above Windy Point). The rocks exposed in the deep cut are siliceous metavolcanic rocks with incipient schistosity and quartz-sericite schist with vertical inclination and westward plunging lineation. Schistose greywacke is exposed a few hundred meters to the north. The volcanic rocks were interpreted as segments of the Yellow Aster metamorphic complex (Schmidt, 1972), as lithologically resembling the "Fidalgo Ophiolite" (E. H. Brown, in Whetten et al., 1980), and as equivalents of Chilliwack Group Paleozoic volcanic rocks (Bechtel Report). These authors agree they are related to a larger mass of metavolcanic and gneissic rock on the top of Chuckanut Mountain. The Bechtel Report authors (1979, p.3, 1-42) consider these rocks, marked by a small magnetic anomaly over Chuckanut Mountain, to be exposed in a tectonic window, but Whetten et al., (1980), prefer the opposite relation where the metavolcanic rocks are a tectonic klippe above the metasedimentary rocks. The metavolcanic and metasedimentary rocks correlate to similar Jurassic rocks on Fidalgo Island. The rocks at road level may be imbricated by simple thrusts, but the metavolcanic rocks capping Chuckanut Mountain may be a klippe, superimposed on younger metasedimentary rocks.

Proceed on Highway 11; at 122.8 km (76.3 m) veer off right on Avon-Allen Road; at 130 km (80.8 m), turn right on Highway 20; at 146.0 km (90.7 m) turn left at Dean's Corner.

STOP 1-3 Metasedimentary rocks of Fidalgo Complex.

155.3 km (96.5 m). Just before bridge over Deception Pass. The pass was named by Captain George Vancouver, on his voyage of discovery, after failing to find here a significant inland waterway. The roadcuts near the bridge afford excellent exposures of the sequence of greywacke and argillite considered to be the highest unit of the Fidalgo Complex (Brown et al., 1979). According to these authors, the beds grade downward into pelagic siltstone, which in turn overlies breccia that caps the volcanic rocks of the complex (to be examined at Stop 1-4). The beds are also considered to be equivalent to the Lummi Formation. This greywacke-argillite sequence is dated as Late Jurassic-Early Cretaceous, on the basis of radiolarians in the underlying pelitic sediments. As the Chuckanut clastic sequence may be considered a late orogenic Molasse, so the more strongly folded and imbricated, locally schistose "Fidalgo greywacke" may be called pre-orogenic Flysch, overlying the Fidalgo volcanic-plutonic complex.

Continue to the park south of Deception Pass, passing volcanic rocks of the Fidalgo Complex, similar to those seen in Stop 1-2, and on to West Point (Lunch); 158.8 km (98.7 m). Backtrack via Deception Pass but now turn left at 163.2 km (101.4 m) to Rosario; pass turnoff to Rosario Road at 168.9 km (105.0 m) and pass turnoff to Marine Drive at 173.4 km (107.8 m).

STOP 1-4; Volcanic rocks, plagiogranite, breccia, chert, pelite.

171.9 km (106.8 m); Quarry, Marine Asphalt Company, (description according to E. H. Brown [in Cowan et al., 1977], and writer's observations). At the top of the quarry medium grained, light coloured, altered quartz diorite with albitized plagioclase ("plagiogranite") is exposed and also reddish brown weathering tuff. The contact between the volcanic and granitoid rock may be intrusive. K/Ar dates on similar metaquartzdiorite, from elsewhere on Fidalgo Island, are 155 ± 5 Ma and 170 ± 10 Mas. In the middle of the quarry is an almost vertical unconformity between metaquartzdiorite and black and brown argillite. It is marked by conglomerate with angular clasts of metavolcanic and minor metagranitoid rock of up to 5 cm diameter. Farther north the quarry wall exposes pelitic, in part cherty, strata. The radiolarian argillite is enriched in Mn, Co, Ni, and Cu. Radiolarians, obtained from chert in the quarry, indicate Late Jurassic, Kimmeridgian to Early Cretaceous, Neocomian age (Gusey, 1978). The greywacke and argillite, seen in Stop 1-3 overlies these pelitic strata elsewhere.

Brown, in his fieldguide (Cowan et al., 1977), suggests for the substratum of the pelagic sediments ophiolitic, ocean-ridge origin, although he would also consider an inactive island arc. The present writer prefers the latter, in view of the paucity of pillow basalt and the relative abundance of volcanic and plutonic rocks of intermediate composition. The sequence of an Early to Middle Jurassic volcanic-plutonic complex, unconformably overlain by Late Jurassic to Early Cretaceous clastic sequence closely resembles the Bonanza-Kyuquot Group sequence of northwest Vancouver Island and the Wells Creek-Nooksack Group sequence of the Cascade Mountains. Backtrack south and turn onto Marine Drive, 173.4 km (107.8 m). Turn off to Del Mar and Alexander Beach.

STOP 1-5; Gneissic gabbro, metaquartzdiorite, agmatite.

175.3 km (108.9 m); Parking at Alexander Beach (private property).

Shoreline exposures were mapped in detail by Brown (in Cowan et al., 1977). According to him, "cumulus gabbro is the host to dikes of foliated hornblende gabbro, plagiogranite, diabase and basalt. Graded bedding in the gabbro indicates tops to the northeast, toward the volcanic and sedimentary part of the section, away from the serpentinite exposed to the west on Burrows Island. The occurrence of hornblende instead of pyroxene in the gabbroic dikes and the hydrothermal alteration of cumulus gabbro near the dikes indicate high water content of the intrusive magmas. Intrusive relations are complex. Features of interest are the strong flow foliation in hornblende gabbro, and composite dikes of hornblende gabbro and plagiogranite, forming locally a lit-par-lit injection migmatite. Chemical trends and the sharp cross-cutting field relations of the dikes to the cumulus gabbro suggest that the two rock suites are not comagmatic." Similar migmatitic complexes are widespread in the Westcoast Complex of Vancouver Island, where K/Ar dates also indicate Jurassic age for the migmatite, but where the basaltic protolith, according to one U/Pb date, is late Paleozoic (Muller, 1977). Jurassic migmatite, quartzdioritic to granitic batholiths or plutons of the Island Intrusions and the Bonanza Group volcanic rocks are also a similar cogenetic volcanic-plutonic complex that may correlate with the Fidalgo.

Continue north on Marine Drive and, if time permits, turn left on Sunset Drive, 180.0 km (111.9 m). Turn left to yacht club, 180.7 km (112.3 m) and drive to west end of beach.

STOP 1-6; (optional) Fidalgo gabbro and serpentinite.

175.3 km (108.9 m). Quarry and beach west of marina. Medium to coarse grained gabbro and serpentinite are well exposed in quarry and beach. They also underlie adjacent Washington Park with Fidalgo Head, nearby Burrows and Allan Islands and more distant Cypress Island. According to Brown (in Cowan et al., 1977) and Gusey (1978), the rock is entirely composed of serpentinite, derived from harzburgite, with cross-cutting veins of pyroxenite. No unfaulted contact has been found between the ultramafic rocks and the gabbro-diorite migmatite complex as exposed in Stop 1-5. As noted, Brown (in Cowan et al., 1977, also in other publications) has interpreted the complex of ultrabasic, gabbroic, volcanic and overlying sedimentary rocks as an ophiolite complex or alternatively, a volcanic arc sequence.

Return to Marine Drive and proceed to ferry dock; board ferry to San Juan Island.

DAY 2: MESOZOIC ROCKS AND THRUSTZONES OF SAN JUAN ISLAND

(M. T. Brandon and D. S. Cowan)

The main goal of this part of the field trip is an introduction to some of the major stratigraphic units and structures in the San Juan Islands. Some of these will be visited again on Orcas Island. Stops on San Juan Island are located on a map (Fig. 14). Important roads on the island are also labelled; these main thoroughfares provide easy access to all of the trip localities.

STOP 2-1; Constitution Formation; massive sandstone.

Friday Harbor Laboratories, San Juan Island. Beach exposures near the docks in front of the laboratories (located NE of the town of Friday Harbor). Massive volcaniclastic sandstone exposed in the beach outcrops represent typical Constitution sandstone (the middle member shown in Fig. 8). Small white veins in the sandstone contain prehnite + aragonite/calcite ± lawsonite.

The sandstone is cut by numerous faults and fractures of unknown displacement. Locally, these faults disrupt the white veins, suggesting a late-stage faulting event in this area.

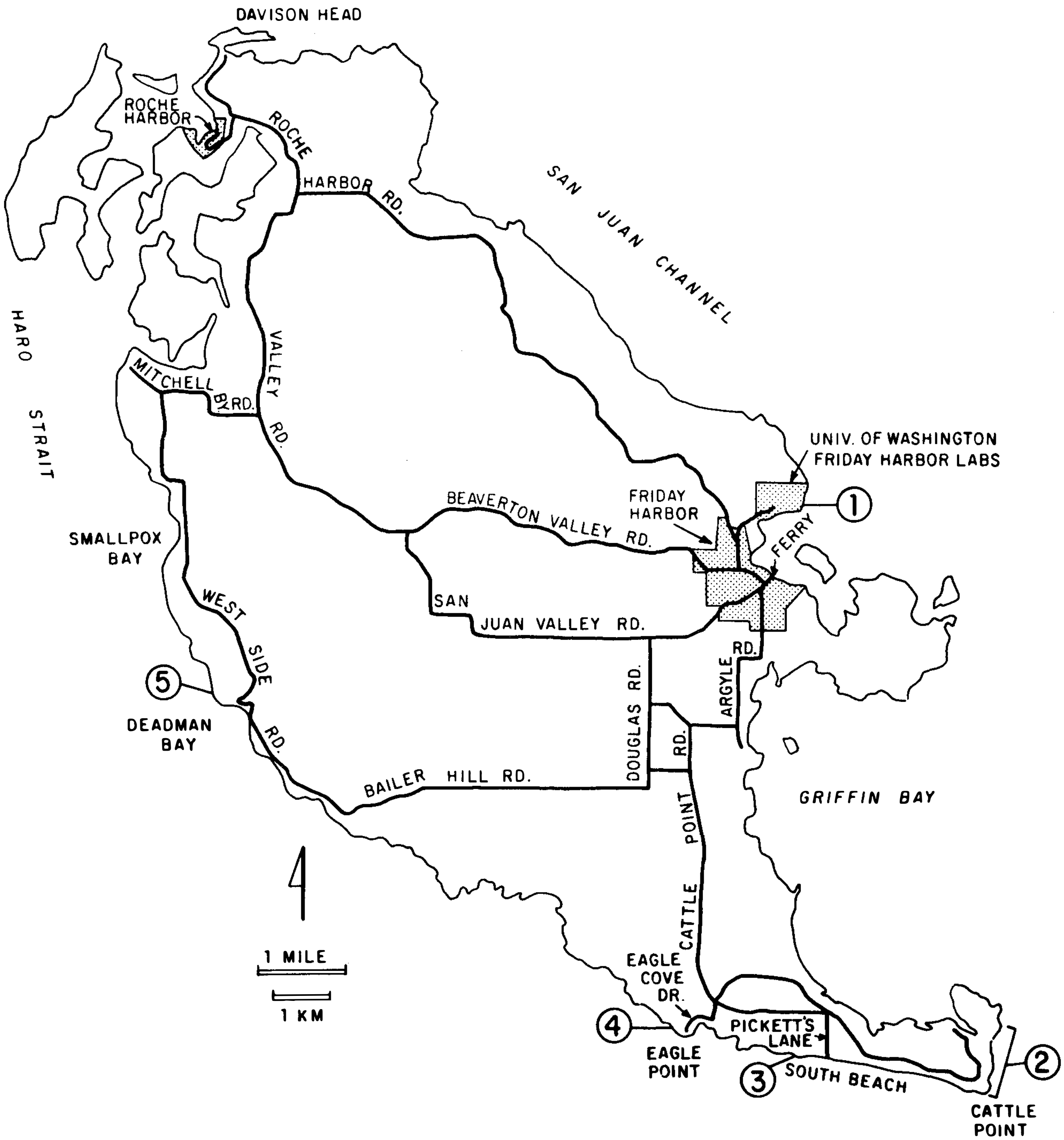


Figure 14

Map of San Juan Island showing principal roads and field-trip stops.

STOP 2-2; Imbricate fault zone between Lopez Complex and Constitution Formation.

Cattle Point, southeastern tip of San Juan Island. Park in small lot near abandoned concrete bunker. The sea-cliffs and beach south of the bunker and for about 100 m north are public property; beaches further north are partly private.

The structurally lowest part of the Lopez Complex is exposed across the SE tip of San Juan Island. The complex in this area consists of a highly imbricated NE-dipping fault zone containing sandstones unique to the Lopez Complex, structurally interleaved with slices of the underlying Constitution Formation (Fig. 10). The fault zone includes an exotic slice of the Turtleback Complex (lower Paleozoic quartz diorite) exposed on the NE side of Cape San Juan. The zone continues to the SE along strike onto southern Lopez Island where rocks as young as middle Cretaceous (late Albian-early Cenomanian $\cong$ 96 Ma) are involved in faulting and regional lawsonite-prehnite metamorphism.

We will look at some fault slices of Constitution Formation and other rocks of the Lopez Complex which are exposed on the beach around Cattle Point. Sandstones restricted to the Lopez Complex, occurring north of the parking area and bunker, consist of coarse volcaniclastic sandstone with minor mudstone and polymict conglomerate. Some sandstones contain prominent black shale chips. Constitution rocks, exposed mainly south of the parking area, include a poorly bedded, depositional association of mudstone, pebbly mudstone, volcaniclastic sandstone, and swirled green tuff along with minor limestone pods, ribbon chert, and green volcanic rocks. In addition to having been imbricated, these rocks are also strongly flattened and display a penetrative solution cleavage. Field relationships and thin-section textures from southern San Juan Island indicate that cleavage and associated flattening post-date faulting and lawsonite-prehnite metamorphism (Brandon, 1980). This stop is east of the regional prehnite-in isograd; sandstones contain lawsonite + quartz + aragonite/calcite assemblages with prehnite absent. In addition to its more typical dark fibrous habit, lawsonite at this locality also occurs in a rare fine-grained prismatic crystalline habit.

STOP 2-3; Constitution, Orcas and Garrison Formations;
Eagle Cove thrust zone - west end of South Beach.

Rocks exposed to the west of South Beach represent the southeastern limit of the northeast-dipping Eagle Cove thrust zone. At this location, the thrust places massive sandstone of the Constitution Formation over a structurally complex assortment of mudstone, green volcanic rocks (locally pillowed), green tuff, and ribbon chert. Some of the rocks in this zone might belong to the Constitution. Some of the chert and volcanics might belong to the Orcas. Several large slices of Permo-Triassic Garrison Schist occur in this fault zone at South Beach, and provide the best evidence for large displacements along this zone. The Garrison in this area consists of a cataclastic and brecciated very fine-grained schist consisting of chlorite + actinolite + epidote + plagioclase.

Of particular interest in these excellent coastal exposures is clear evidence that volcaniclastic sandstone and siltstone are interbedded with radiolarian ribbon chert and green tuffaceous rocks. In addition, original sedimentary layering has been variably disrupted due to locally intense layer-parallel shear and small-scale fragmentation in response to ductility contrasts between relatively mobile, invasive black mudstone and relatively stiff layers of sandstone and chert.

STOP 2-4; Constitution, Orcas and Garrison Formations;
Eagle Cove thrust zone - Eagle Cove and Eagle Point

The same structural zone, the Eagle Cove thrust, continues from South Beach northwestward to Eagle Cove. There too it consists of a northeast-dipping fault zone containing slices of exotic Garrison Schist. Exposures of the Constitution sandstone are restricted to low outcrops away from the coast to the north and northwest of Eagle Point. The Eagle Cove thrust is mapped at the highest occurrence of chert and mudstone and the lowest occurrence of massive sandstone. Orcas Chert and volcanic flows occur as disrupted fault slices in this area and are best exposed on Eagle Point. Radiolaria from cherts at this locality have been dated as Triassic (D. L. Jones, pers. comm, 1980). Slices of Garrison Schist are best exposed in outcrops around the cove. An entrained sequence of limestone pods in black mudstone is exposed in an outcrop on the west side of Eagle Cove. Brandon (1980) has interpreted the pods as olistoliths (small slide blocks). Conodonts from these pods indicate a late Triassic age (Savage, pers. comm., 1982).

STOP 2-5; Deadman Bay Volcanics
Deadman Bay, west side of San Juan Island

Deadman Bay is located at the southern end of a large, 4 km-long lenticular fault slice of Deadman Bay volcanics. Gray and green radiolarian 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 for over 3 km to the north of Deadman Bay.

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 reddish-weathering pillowed volcanic rocks, breccia and tuff with subordinate interbedded limestone. The sequence is disrupted by faults but generally strikes east and dips vertically in this area. Geopetal structures indicate younging to the north. Limestones are generally massive and gray and contain small amounts of intercalated green tuff. Bedding, where it is present in the limestones, is commonly contorted and appears to have been involved in early 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.

The limestones are locally fossiliferous. Danner (1966) has identified Late Permian fusulinids from this locality. These fusulinids belong to the Asiatic or "Tethyan" fusulinid province which suggests that these rocks are exotic to North America (Monger and Ross, 1971; Danner, 1977). Crinoid debris and fragments of other fossils can be found in many limestone pods.

STOP 2-6; Haro Formation

Davison Head, north tip of San Juan Island.

Drive north approximately 1.5 km from Roche Harbor and park on the causeway connecting Davison Head with San Juan Island. The Haro Formation underlies Davison Head and also extends along the coast south of the causeway. Best exposures are on the west side of Davison Head.

The Haro Formation was named and first described by McLellan (1927) who found Late Triassic *Halobia* occurring in shaly limestone on the shore south of the causeway. Danner (1966), Vance (1975) and Johnson (1978), have also described the stratigraphy and lithology of the formation. The following description is summarized from their work and a previous field guide by Cowan and Whetten (1977).

The Haro Formation consists mainly of bedded andesitic and dacitic volcaniclastic sandstone, siltstone, conglomerate breccia and minor flattened crystal tuff. Clasts are up to 1 meter in diameter. Graded bedding and cross bedding are locally present. Sparely fossiliferous limy siltstone and micritic limestone, exposed south of the causeway, are also included in the formation. A thickness in excess of 700 meters, estimated by Johnson (1978) is uncertain due to faulting, folding and discontinuous exposure. Steeply south dipping beds with probable south facing tops suggest that the Haro is separated from the adjacent coeval Orcas Chert by a south dipping thrust fault (Vance, 1975; Johnson, 1978), (Fig. 4). Metamorphic assemblages in the Haro indicate that the unit has never exceeded zeolite facies (Johnson, 1978), in contrast to the high-pressure metamorphism of the rocks to the south. The thrust fault bounding the Haro to the south is therefore post-metamorphic.

Vance (1975) and Johnson (1978) suggest that the Haro is derived from a nearby intermediate volcanic source, perhaps a subaerial volcanic arc, and was deposited in relatively shallow water. Compared with other Late Triassic units in the region it is unlike the Orcas Chert of San Juan Islands or the Cultus Formation of the Cascade Range, composed of mudstone and minor sandstone and lacking volcanic rocks (Monger, 1970). The fossil-bearing sedimentary part resembles the Parson Bay Formation, highest unit of the Vancouver Group of Vancouver Island (J. E. Muller, pers. comm.) but the volcanic rocks are in sharp contrast with the Karmutsen tholeiitic basalt of that group. D.L. Blackwell (pers. comm., 1983) has recognized Upper Triassic dacitic volcanic rocks in the northwestern Cascade Mountains and suggests they are a volcanic facies of the Cultus Formation. Stratigraphic relationships of these rocks are still uncertain as they occur as a disrupted slice in the Shuksan thrust zone (Misch, 1966). The discovery may help to improve present understanding of distribution and correlation of Triassic rocks in this region.

DAY 3: PALEOZOIC AND MESOZOIC OF ORCAS ISLAND

(J. A. Vance)

The stops on this excursion to Orcas Island (Fig. 13) were selected to illustrate the major stratigraphic and structural units, and highlight their metamorphism and structural relations. Unfavorable weather, tides or poor road conditions could necessitate omission of some stops. As many of the stops are beach exposures reached by side trips from the main roads, a strict road log mileage format is not followed in this guide. Instead the mileage between stops and principal junctions is noted. Access to several of the beach exposures is through private property. Later groups who may use this guide are requested to obtain the owner's permission to enter property where 'No Trespassing' signs are posted and to exercise courtesy and common sense in preserving the charm and beauty of the island.

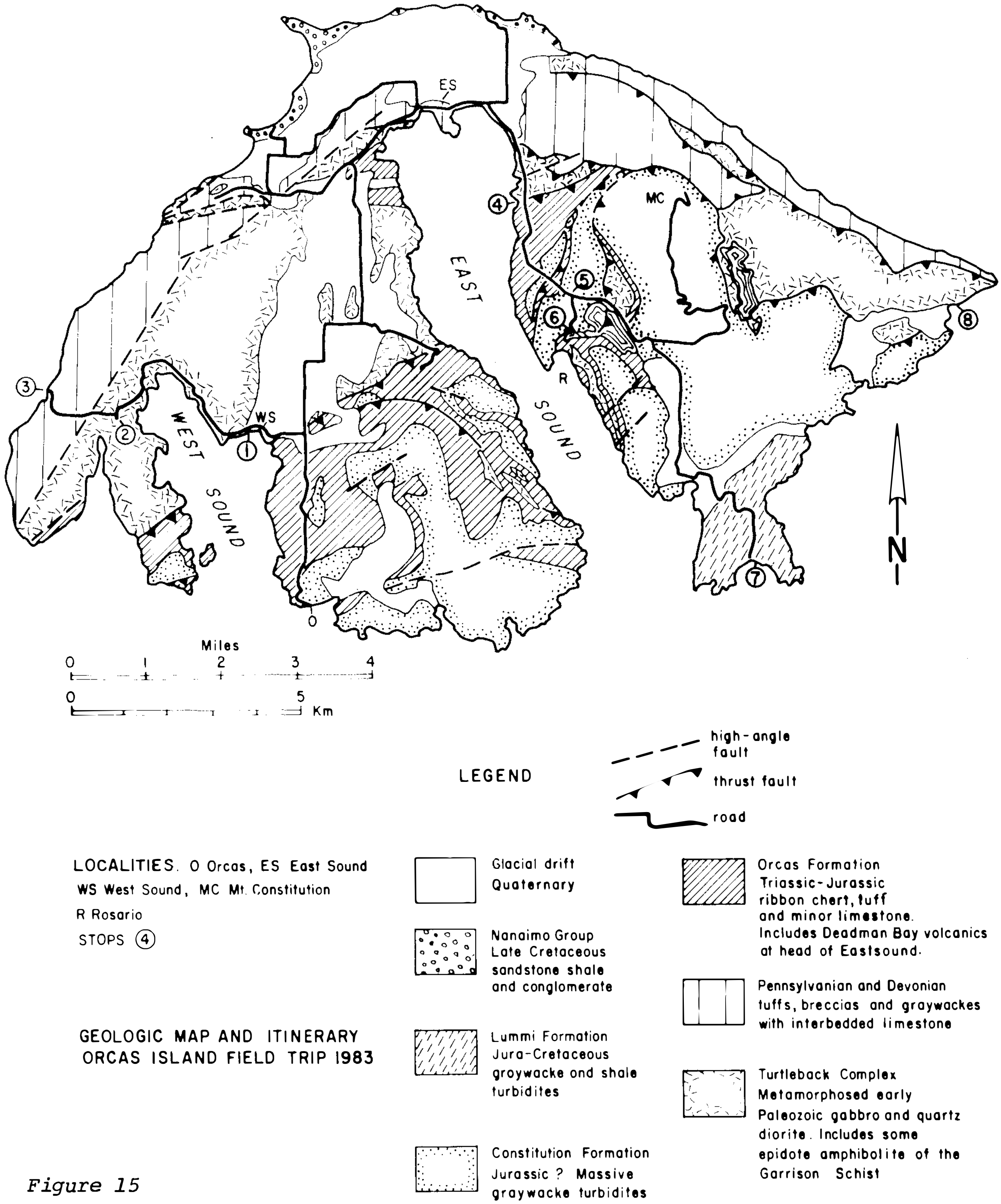


Figure 15

Generalized geologic map of Orcas Island showing principal roads and field-trip localities.

Village of Orcas (ferry landing). Outcrops of the Constitution Formation. These rocks are poorly bedded, massive, brownish volcanic siltstones and micro-graywackes. They are sheared, slickensided, and cut by small veinlets of prehnite.

Drive north 2.6 miles on the main road to the junction to West Sound. Scattered outcrops of Orcas ribbon chert are present between 0.5 miles and the junction. Junction to West Sound. Sheared siltstones of the Constitution Formation. From here a side trip leads to the village of West Sound and continues west past the head of Deer Harbor to Cormorant Bay (5.5 miles) on the west shore of the island.

STOP 3-1; Turtleback Complex; silicic dikes

The village of West Sound (0.9 miles)

Beach exposures at West Sound are an extreme example of dike injection in the Turtleback Complex. The host rock, a weakly gneissose leucocratic diorite, makes up less than 10% of the outcrop. It occurs as screens and blocks a few meters thick, cut by a complex of parallel, intersecting and branching dikes. Plagiophyric and aphanitic andesite and basalt are the most abundant dike rocks, but coarsely porphyritic rhyodacite is locally present. One of the silicic dikes gave a zircon fission track age of 270 $\pm$ 54 Ma. This is the age of the static greenschist facies metamorphic overprint of the plutonic rocks of the Turtleback Complex and is a minimum age for the dikes. These dikes may have served as feeders for the Devonian and Pennsylvanian volcanic sediments associated with the Turtleback. Alternatively, they may have caused the Turtleback metamorphic overprint.

Drive west along the head of West Sound in early Paleozoic plutonic rocks of the Turtleback Complex. At 1.8 - 1.9 miles are prominent roadcuts in Turtleback meta-gabbros. The gabbros are cut by small dikes and irregular bodies of intrusive quartz diorite, trondjhemite and pegmatite. Road cuts between 2.5 and 2.6 miles are part of an intrusive contact zone about half a mile wide between the earlier mafic phase of the Turtleback Complex and the younger silicic phase. The mafic rocks are gabbros and minor clinopyroxenite which have been intruded by dikes of leuco-quartz diorite and trondhjemite; agmatitic breccias consisting of angular clinopyroxenite blocks in a dioritic matrix are well developed. The plutonic rocks are cut by younger dacitic and basaltic dikes. All these rocks have experienced static metamorphism in the greenschist facies.

Continue west to 3.2 miles and park in the turnout at the small church on the left.

STOP 3-2; Turtleback Complex; meta-quartz diorite and trondhjemite.

Deer Harbor

The road cuts just before the church are typical of the silicic plutonic phase of the Turtleback Complex. These are medium grained homogeneous leucocratic meta-quartz diorites and trondhjemites. Clusters of large quartz grains are characteristic. U/Pb dating of zircon from two Orcas Island quartz diorites indicates primary crystallization of these rocks at about 460 m.y.

(Mattinson, 1972). The quartz diorites at this outcrop are cut by numerous basaltic dikes. Both rocks have experienced static greenschist facies metamorphism. The faulting and slickensiding of these rocks is related to Cretaceous deformation. Displacement on the faults was mostly minor as indicated by the lack of significant offset on the dikes.

Turn around, return 0.2 miles on the main road, then turn left on the dirt road to Cormorant Bay. Drive to the west shore of Orcas just north of Cormorant Bay. There is public access to the beach at a turn-around and parking area (1.2 miles from the main road). On the approach you have crossed a northeast-trending high-angle fault which juxtaposes the Turtleback Complex with Pennsylvanian volcanic rocks on the west.

STOP 3-3; Pennsylvanian volcanic rocks.

West shore of Orcas Island, north of Cormorant Bay.

The rocks exposed on the shore are massive, unsorted green to grayish tuffs and tuff-breccias of andesitic composition. Occasional fragments of limestone, in part fossiliferous, are scattered through these volcanic rocks, which are probably submarine debris flows. These Pennsylvanian outcrops display the minor faulting and slickensiding which typify the pre-Nanaimo rocks on Orcas. On a clear day a shallow northeast-trending syncline in Nanaimo strata is visible on Waldron Island three miles to the north. The northeast strike of the Pennsylvanian and Devonian rocks on western Orcas Island is probably related to Tertiary folding.

Outcrops at the point just south of Cormorant Bay (0.3 miles to the south) are in a bedded epiclastic phase of the Pennsylvanian volcanic rocks. (This is private property. Request permission at the big house if you wish to visit this locality.) The rocks at the point are varicolored water-laid andesitic tuffs in massive beds about a meter thick, intercalated with dark, thin-bedded, well-indurated tuffs and volcanic graywackes. These volcanic sediments have been intruded by sills and dikes of basalt and plagioclase porphyry. The beds are cut by high angle faults of small displacement.

Return to the West Sound-Orcas-East Sound intersection (5.5 miles). Drive 2.1 miles toward the village of East Sound past scattered exposures of Turtleback quartz diorite. The Turtleback Range is on the left skyline. Outcrops at Judd Cove at the head of East Sound are Permian basaltic volcanic rocks, ribbon cherts and limestones of the Deadman Bay unit. Continue to the community of East Sound, passing roadcuts mainly in Turtleback. Outcrops at East Sound are epiclastic andesitic tuffs and breccias of probable Pennsylvanian age. Quaternary deposits, including stratified outwash, glaciomarine drift and sandbars cover the narrow lowland area north of East Sound and unite the higher bedrock terrane making up the eastern and western flanks of Orcas Island.

Continue 1.1 miles east of East Sound to the junction with the Terrill Beach road. Turn right and proceed toward Moran State Park. At 0.6 miles are beach exposures of the thrust contact between andesitic tuffs and breccias of Pennsylvanian age to the north and overlying early Paleozoic plutonic rocks of the Turtleback Complex. The thrust dips about 20° south and is marked by a shear zone about 0.5 m wide. The Pennsylvanian epiclastic volcanic rocks contain a few scattered clasts of limestone and are cut by aphanitic silicic dikes. The sheared and brecciated Turtleback rocks are heterogeneous, consisting of gabbros and diabase intruded by quartz diorite and cut by later basalt dikes. This fault is one of several major low-angle thrusts separating large, interleaved tectonic sheets of Turtleback and Pennsylvanian strata on eastern Orcas Island.

Continue south 0.7 miles past scattered outcrops of Turtleback gabbro to the curve where the road crosses a small stream. Park, being careful not to block the access road to the house below. The next two stops are accessible from here by short walks.

STOP 3-4a; Turtleback Complex; metagabbro.

East shore of East Sound.

Walk 100 m north on the main road to the first road leading left to the shore. Ask permission at the cottage to visit the beach outcrops. Follow the road to the shore by the big old house opposite a small island. These rocks are Turtleback metagabbros. Cumulus layering is well displayed and dips southwest at about 40°. The gabbros are cut by small dikes of gabbro pegmatite and by dikes of pyroxenite, the latter probably injected as a cumulus mush. Whetten and others (1978) report a K/Ar date of 554 ± 16 Ma on hornblende from a gabbro pegmatite collected nearby. The gabbros have been statically metamorphosed under conditions transitional from greenschist to albite-epidote amphibolite facies.

Return to the car. The stream and bay below mark the position of the Orcas thrust fault, which has carried sedimentary rocks of apparent Mesozoic age, including Orcas cherts and graywackes of the overlying Constitution Formation, northward over the early Paleozoic Turtleback Complex and middle to upper Paleozoic strata. The Orcas thrust is a plate boundary or suture between a younger oceanic terrane to the southeast underthrust by elements of an older continental terrane lying to the northwest. From the parking area, walk south down the abandoned unsurfaced road to the beach.

STOP 3-4b; Orcas Chert

East shore of East Sound.

The slope above the beach displays bedded gray radiolarian cherts of the Orcas Chert (Triassic-Jurassic). Cherts with minor intercalated green tuff and scattered limestone lenses dip southeasterly here and are exposed almost continuously for more than 2 km along the shore of East Sound to the south. The apparent thickness of the ribbon chert sequence here is in excess of 400 m, but there is evidence for tectonic repetition by imbricate faulting. These bedded cherts consist of layers, typically 2-4 cm in thickness, separated by thin argillaceous partings. Pinch and swell of the chert layers is largely primary, but is accentuated by faulting subparallel to the bedding. Faint outlines of recrystallized radiolaria are visible in thin section.

Return to the car and follow the main road south. Outcrops of Orcas chert extend to the crest of the hill. Tight minor folds are well displayed in cherts in the prominent road cut on the right just before the hill crest. Continue

0.7 miles, mostly in graywackes of the Constitution Formation, to the junction to Rosario.

STOP 3-5; Constitution Formation

Junction Olga and Rosario roads.

The roadcuts at the junction are in typical massive graywacke siltstones of the Constitution Formation (Jurassic-Lower Cretaceous). Thin interbeds of ribbon chert define the attitude of the bedding. This outcrop illustrates the typical deformation style of the Constitution which is characterized by: 1) semi-penetrative shears sub-parallel to bedding; 2) micro-veinlets of prehnite and less typically, quartz or aragonite; and 3) irregularly oriented minor faults with prominent slickensides. Occasional larger prehnite veins 1-4 cm thick are present. Cleavage and bedding generally show a gentle southeast dip parallel to that of the imbricate thrust system in this area.

A side trip on the road to Rosario goes 0.5 miles, then left 0.1 miles to the tennis courts near the outlet of Cascade Lake.

STOP 3-6; Rosario thrust zone

Near Rosario Resort.

At this stop we will examine some of the "exotic" crystalline rocks tectonically emplaced along the Rosario thrust zone. The Rosario Thrust cuts the Orcas Thrust at a low angle repeating the structural sequence seen at stops 4 through 5: 1) Turtleback Complex plus Garrison Schist; 2) the Orcas Formation with the Orcas Thrust at its basal contact; and 3) the Constitution Formation conformably above the Orcas. Exposures around the outlet of Cascade Lake are Garrison Schist in tectonic contact with Orcas Chert and Constitution Formation. This is one of the few exposures of Garrison Schist on Orcas Island. The Garrison crops out more extensively on San Juan Island. At the present outcrop, a metamorphic age of 286 ± 10 Ma has been determined on hornblende by K/Ar dating (R. L. Armstrong, pers. comm.). The Garrison rocks here are fine-grained, sharply foliated albite-epidote amphibolites. These schists show extensive superimposed fracturing, micro-brecciation and slickensiding related to thrust faulting. Microfractures are filled with aragonite and prehnite. The Rosario thrust zone can be traced about 3 km south down the ridge above East Sound as a narrow strip of sheared Turtleback quartz diorite. To the north, the thrust is marked by a large tectonic lens of Turtleback gabbro which crosses Cascade Lake whence it can be followed north another three km.

Return to the main road and continue south into Moran State Park. The stream in the picnic area of the park (0.5 miles south of Rosario junction) marks the continuation of the Rosario Thrust which here has carried plutonic rocks of the Turtleback Complex over the Constitution Formation. The first series of road cuts along Cascade Lake is in Turtleback meta-gabbro and minor associated clinopyroxenite and dike rocks. Continue to the next stop.

The small valley just north of the prominent road cuts on the curve at the southeast corner of the lake marks the position of the fault contact between the Turtleback Complex and the Orcas Chert (the Orcas Thrust). The chert here is tectonically thinned to 10-15 m. The road cuts are in conglomeratic volcanic graywackes interpreted to be near the base of the Constitution Formation. Clasts to about 0.25 m in length are present. Andesitic and basaltic pebbles predominate in the conglomerates, but chert, aphanitic dike rocks, meta-plutonic rocks, and low grade schists (Garrison?) are also present. Abundant metamorphic prehnite and aragonite are developed in these rocks.

Drive south 2.4 miles to Olga Junction. Turn left and continue 0.6 miles to the junction to Obstruction Pass. Since Cascade Lake, exposures are mainly glacial drift. The bedrock is Constitution Formation. Continue 1.8 miles to Obstruction Pass and leave the car in the parking area by the resort. The peninsula north of Obstruction Pass is underlain by graywackes and shale of the Lummi Formation of Late Jurassic-Early Cretaceous age. The Lummi overlies the Constitution Formation with structural discordance interpreted as a southeast-dipping low-angle thrust (the Buck Bay fault). The contact is not exposed, but lies in the low area covered with glacial drift in the northern part of the peninsula.

STOP 3-7; Lummi Formation

Obstruction Pass

Walk 300 m east along the beach to the bedrock outcrops. These are typical graywacke, shale, and siltstone of the Lummi Formation. The graywacke beds range from about 0.3 m to 0.4 m in thickness. Many are graded. The bases of some graywacke beds are coarse chert-rich grits, commonly containing shale rip-up clasts. Slump folds are locally present. The shales are in part massive and in part interlaminated with siltstone. The Lummi of Orcas Island is much less deformed than the Constitution and is a structurally coherent unit. Cleavage is locally developed in the shales, however, and a sharp foliation may be present in the graywackes. These planar structures typically lie at a low angle to the bedding. On Orcas, the Lummi forms a broad southeast-plunging syncline. Dips are mostly gentle, but tight minor folds are locally present and high-angle faults of small displacement are common. The sporadic presence of aragonite and prehnite veinlets along with more common quartz indicates that the Lummi experienced the same metamorphism as the Constitution Formation.

Return to the main road (1.8 miles). Turn right and proceed 5.0 miles. Outcrops are Constitution Formation and Turtleback Complex. Follow a dirt road left 0.6 miles to a group of houses above the water.

STOP 3-8; Turtleback Complex; gabbro, diabase, microdiorite.

Point Lawrence

Hike approximately one mile to Point Lawrence, the easternmost point on the island. Beach exposures of the Turtleback Complex are gabbro, diabase and microdiorite. Minor types are gabbro pegmatites, pyroxenite and trondhjemite.

All rocks are highly altered. A K/Ar age of 332 $\pm$ 16 Ma. (R. B. Forbes, pers. comm.) was obtained on uralitic hornblende from a metagabbro here. This is probably the age of metamorphism and a minimum age for the gabbro.

At Point Lawrence, Turtleback gabbros overlie Pennsylvanian lapilli tuffs in low-angle fault contact. This is one of several major thrust faults which have intersliced large sheets of Turtleback and Devonian-Pennsylvanian strata on the island. About 200 m west of Point Lawrence, a large rocky outcrop of aragonite marble is exposed on the beach. The marble displays the typical coarse grained aragonite, commonly 1-10 cm in length, whcih characterizes the metamorphosed Paleozoic limestone in the San Juan Islands. This structurally anomalous marble outcrop, apparently surrounded by Turtleback Complex, is probably an infaulted slice or upfaulted block from the structurally underlying unit of Paleozoic volcaniclastic sedimentary rocks.

GEOLOGY OF VANCOUVER ISLAND

(J. E. Muller)

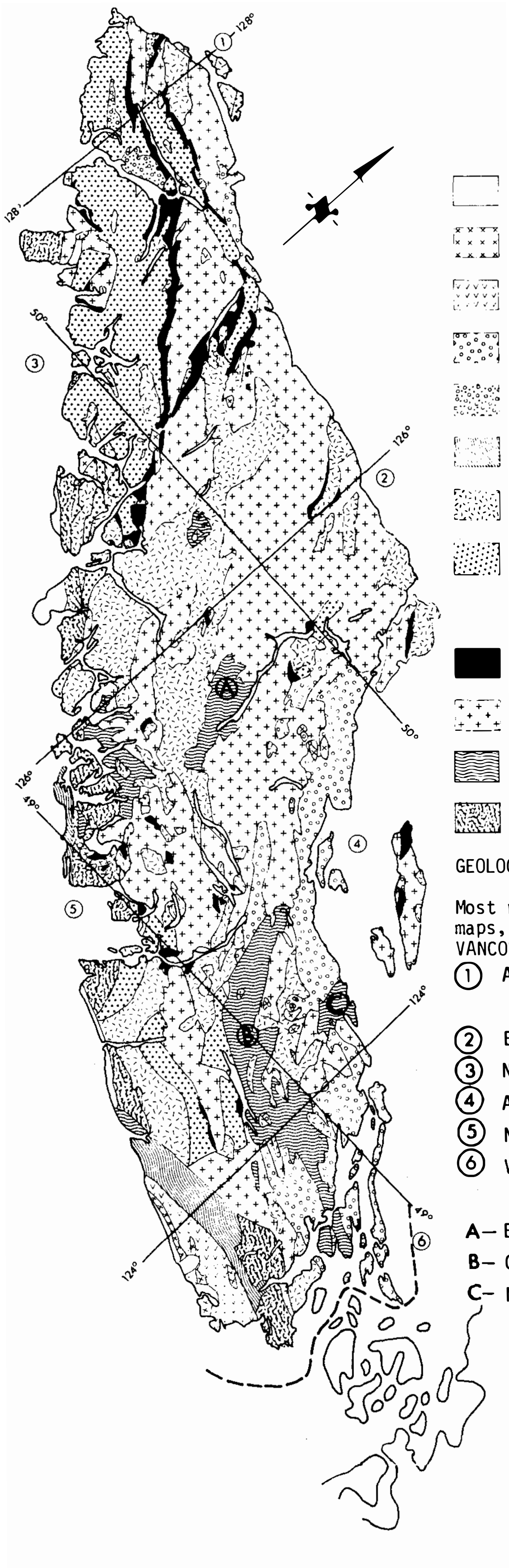
Introduction

Vancouver Island is underlain by three distinct eugeosynclinal terranes: the Paleozoic to Mesozoic Insular Belt, the Mesozoic Inner Pacific Belt and the Tertiary Outer Pacific Belt (Figure 1). Most of the island forms part of the Insular Belt and is here called Vancouver Island Terrane. It is underlain by middle Paleozoic, Triassic and Jurassic volcanic-plutonic suites, each with an overlying sedimentary sequence. The structural style is dominated by block-faulting and well ordered sedimentary and volcanic sequences permit satisfactory stratigraphic analysis along coastal cliffs and some river banks.

The Inner Pacific Belt is underlain by Mesozoic deformed, sheared and dismembered, or foliated sedimentary and volcanic rocks, mostly without detectable stratigraphic continuity. The Outer Pacific Belt on Vancouver Island is composed mainly of Tertiary basalt and gabbro.

The focus of this fieldtrip is on the suture zone between Insular and Pacific belts on southeast Vancouver Island and on San Juan Islands. In this zone, high-angle faults intersecting low-angle thrusts, form the structural pattern and no continuous pre-Cretaceous stratigraphic sequence is preserved. As in San Juan Islands, the stops to be visited should demonstrate structural relationships between the adjoining terranes and give examples of the component rock units of both. For the Vancouver Island Terrane only a minor, unrepresentative part of the stratigraphic column can be shown.

Geological exploration of the island has continued for more than a century and in the beginning was mainly concerned with the Cretaceous coal deposits. Most of the recorded geological work has been by government geologists, starting with J. Richardson (1872-1876). He was followed in 1887 by the patriarch of western Canadian geology, G. M. Dawson, who made a reconnaissance circumnavigation of the northern part of the island and gave the first account of Mesozoic volcanic and sedimentary stratigraphy. Special mention is also deserved for C. H. Clapp, who mapped the southeastern part (1909-1913), H. C. Gunning, who worked in the central part (1929-1932) and J. A. Jeletzky, who with his work on the west coast (1949-1953), made an important contribution to Mesozoic biostratigraphy. Many other geologists from the federal and provincial geological surveys and from several universities have contributed additional geological data. The writer started and completed reconnaissance mapping of the island on scale 1:250,000, shown in Figure 16 (1963-1981). He was aided by concurrent



LEGEND

CARMANAH GROUP	MIDDLE TERTIARY
CATFACE INTRUSIONS	EARLY TO MIDDLE TERTIARY
METCHOSIN VOLCANICS	EARLY TERTIARY
NANAIMO GROUP	LATE CRETACEOUS
QUEEN CHARLOTTE GROUP KYUQUOT GROUP LEECH RIVER FORMATION PACIFIC RIM COMPLEX	LATE JURASSIC TO EARLY CRETACEOUS
ISLAND INTRUSIONS	EARLY AND (?) MIDDLE JURASSIC
BONANZA GROUP	EARLY JURASSIC
VANCOUVER GROUP PARSON BAY FORMATION QUATSINO FORMATION KARMUTSEN FORMATION	LATE AND (?) MIDDLE TRIASSIC
SICKER GROUP	PALEOZOIC
METAMORPHIC COMPLEXES	JURASSIC AND OLDER

GEOLOGY NOT REVISED SINCE 1971

Most recent Geological Survey of Canada maps, scale 1:250,000 as follows:
VANCOUVER ISLAND AND GULF ISLANDS: O.F. 463

1. ALERT BAY - CAPE SCOTT (92L-102I) — Map 4-1974; Map 1552A in press
2. BUTE INLET (92K): O.F. 345
3. NOOTKA SOUND (92E): O.F. 344; Map 1537
4. ALBERNI (92E): Map 17-1968
5. NITINAT LAKE (92C): O.F. 821
6. VICTORIA (92B): O.F. 701 (1:100,000) Final map 1553A in press

A— BUTE LAKE UPLIFT
B— COWICHAN-HORNE LAKE UPLIFT
C— NANOOSE UPLIFT

MILES
0 20 40

Figure 16

work and collaboration of B. E. B. Cameron, D. Carlisle, D. J. T. Carson and K. E. Northcote and by many able and willing assistants. In those last twenty years, many graduate student thesis projects on the geology of Vancouver Island and the Gulf Islands have been completed at several western American universities and the University of British Columbia. These are available in the Geological Survey library in Vancouver and some have been condensed and published.

Recent synopses of Vancouver Island geology have been given in several papers (Muller, 1977; Muller et al., 1974, 1981) and earlier fieldtrip guidebooks (Muller, 1977; Price et al., 1981). Relevant geological maps are shown in Figure 16. For this introduction an outline of the geology, supplementing the stratigraphic table and diagram (Figures 17 and 18) and the maps and section (Figures 19a, 19b) are given. More detailed information is provided in the roadlogs for Day 4 and Day 5.

RELATIONSHIPS OF FORMATIONS OF VANCOUVER ISLAND

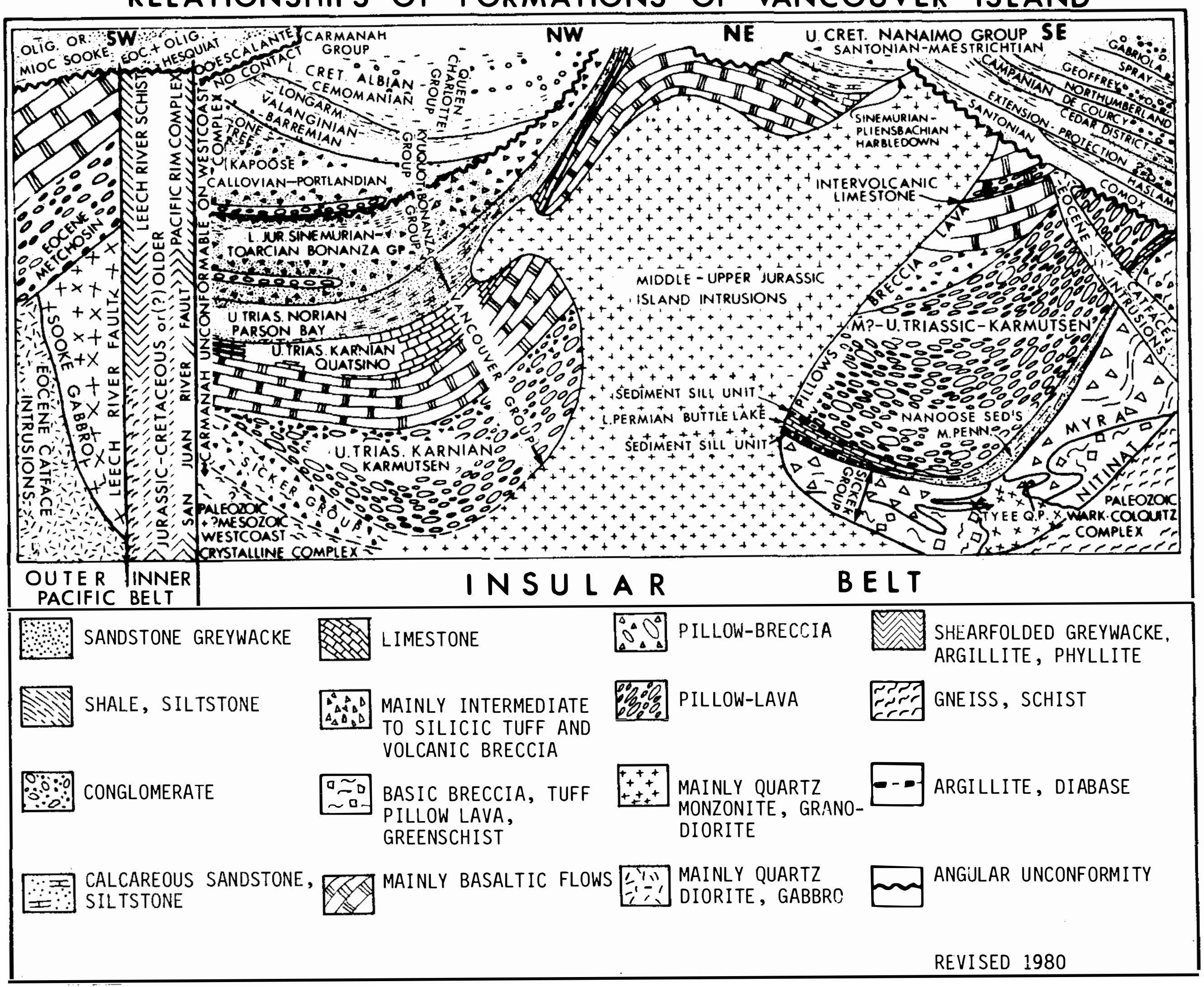


Figure 17

The succeeding Early Jurassic volcanic arc sequence (Bonanza Group) is coupled with coeval batholithic intrusions and migmatite complexes (Island intrusions, Westcoast Complex, Wark-Colquitz Complex), presumably derived from the older rocks. They are overlain unconformably on northwest Vancouver Island by a Late Jurassic to Early Cretaceous southwest dipping clastic wedge (Kyuquot Group and Queen Charlotte Group). Next, the Vancouver Island Terrane is overlain on the northeast by northeast dipping Late Cretaceous coal-bearing molasse (Nanaimo Group) and lastly, a fringe of Tertiary clastic strata overlies all older rocks on the southwest coast (Carmanah Group). The Vancouver Island Terrane extends with identical Paleozoic, Triassic and Late Cretaceous assemblages in the islands in the Strait of Georgia and is bounded by the Malaspina Fault between Texada Island and the Mainland.

In the southwest and south, the Vancouver Island Terrane adjoins the Pacific Rim Complex along the Westcoast Fault and the Leech River Complex along the San Juan Fault. Pacific Rim and Leech River complexes form the Inner Pacific Belt. They are both highly deformed and chaotic assemblages of greywacke, pelite, chert and metavolcanic rocks with minor limestone. The Pacific Rim Complex is low-grade metamorphic, commonly with melange texture and with rare Late Jurassic to Early Cretaceous fossils. The Leech River Complex is in part well foliated schist, ranging from low-grade phyllite to staurolite, andalusite and garnet bearing quartz biotite schist. They are probably more highly metamorphosed correlatives of the Pacific Rim rocks.

The Leech River Complex also contains schistose to gneissic greywacke sandstone, lithologically similar to rocks of the Lummi Formation of San Juan Islands. The San Juan Fault, where exposed, is a high-angle, probably oblique, thrust. It is interpreted as the locus of underthrusting of oceanic sediments of the Leech River Complex at a convergent margin. Underthrusting apparently occurred between earliest Cretaceous, the age of youngest known fossils in the Pacific Rim Complex and late Eocene, the age of the oldest Tertiary strata unconformably above Leech River schists. A new structural interpretation, not previously published, postulates that a slab of Wark-Colquitz rocks was broken off the edge of the VancouverIsland Terrane and carried northeastward by the underthrusting Leech River rocks (Figure 19a, 19b). This thrust plate underlies Victoria and is bounded by Survey Mountain Fault, San Juan Fault and a yet unnamed fault from Haro Strait across Finlayson Inlet. The rocks of the Malahat Highway (Stops 4-3 to 4-6) are in a half-window in the thrust plate, exposing the underlying Leech River Complex.

The southernmost part of Vancouver Island forms the north edge of the Olympic Terrane in the Outer Pacific Belt and is separated from the Inner Pacific Belt by the Leech River Fault. Suturing of the Olympic Terrane (Outer Pacific Belt) to the Leech River Complex (Inner Pacific Belt) occurred along Leech River Fault, probably by oblique, east-side-down, left-lateral motion (Stop 4-3). The time of movement was probably later than movement along San Juan Fault, but before movement on Callawah and Hurricane faults on the Olympic Peninsula in late Tertiary time. Northeast striking tensional faults through south Vancouver Island and the islands to the east (Figures 2, 19) may be the result of northeast compression of the Vancouver Island Terrane by the advancing Olympic Terrane.

The Vancouver Island rocks of this terrane are mainly pillowed and layered tholeiitic basalt and aquagene tuff and breccia (Metchosin Volcanics). At one place a gastropod coquina within tuff and breccia has yielded an early Eocene age. The volcanic rocks are underlain by diabase dike complexes and by gabbro. The main part of the terrane on Olympic Peninsula is composed of the Peripheral Rocks, comprising the Crescent Formation, coeval and similar to the Metchosin Volcanics and thick, younger clastic strata, roughly coeval with, and equivalent to the thinner Tertiary Carmanah Group. To the south, separated from the Peripheral Rocks by the Calawah and Hurricane faults, are tightly folded, faulted and penetratively sheared clastic continental slope and ocean deposits, including also some basalt. The core rocks are inferred to have been compressed and deformed during late Tertiary convergence.

DAY 4: MESOZOIC FORMATIONS OF THE VANCOUVER ISLAND TERRANE AND THE LEECH RIVER COMPLEX

Day 4 deals first with the Mesozoic part of the Vancouver Island Terrane as it occurs in "abbreviated" form near the Leech River Fault, its southern limit. Next we examine the Leech River Complex, along Malahat Highway in what is inferred to be a structural half-window in a thrustplate composed of the Wark-Colquitz Complex. For geology and locations of stops see Figures 19a and 19b.

The day starts with the ferry trip from Orcas Island to Sidney, B.C. From Ferry Terminal take 5th Street; left on Beacon to Patricia Highway, 1.2 km; north to Wain Road, 4.8 km; right on West Saanich Road, 6.4 km; left on Birch, 6.7 km and continue on Madrona. Beach access to Towner Bay.

STOP 4-1; Vertically upturned unconformity, Jurassic Island Intrusions (Saanich Granodiorite) and Late Cretaceous Nanaimo Group (Comox Formation)

10.2 km (6.4 m) Coastal exposures on Towner Bay.

The point south of the bay exhibits the unconformity between shattered, medium grained, light-colored quartzdiorite, called "Saanich Granodiorite," a part of the Jurassic Island Intrusions, with conglomerate, sandstone and siltstone of the basal Comox Formation in the Late Cretaceous Nanaimo Group. A K/Ar determination on hornblende from quartz diorite on Mount Newton, 6 km to the south, yielded an age of 169 ± 17 Ma, in accord with the Early to (?) Middle Jurassic age of the Island Intrusions. The Comox Formation is Santonian and the range of the Nanaimo Group is Santonian to Maestrichtian. The unconformity shows pockets in the quartz diorite, filled with sediment, a minor example of the commonly uneven unconformity surface that shows several meters of relief in other exposures. Clasts, up to 10 cm diameter, are diorite, quartzdiorite, white and green chert, volcanic rocks and black argillite. The sequence grades upward from conglomerate and sandstone to sandstone and siltstone.

The contact is vertical because it is rotated along a steeply inclined, normal or reversed, northeast trending northwest-down fault. The fault is one of a set of early-Tertiary faults, north of and about perpendicular to Leech River Fault, that limit the Nanaimo Basin on the southeast. The outcrop is a reminder that paleomagnetic measurements on granitic rocks may require substantial correction for post-intrusive tilting!

The Nanaimo Group is composed of four major transgressive sedimentary cycles, each composed of a lower deltaic to near-shore conglomerate-sandstone-shale (-coal) formation and an upper formation with marine sandstone, siltstone and thin-bedded turbiditic deposits. It is a post orogenic molasse deposit but is itself affected by later faulting. The Paleocene Chuckanut Formation, seen on Day 1, may be the upper non-marine part of this molasse sequence, only present in the easternmost San Juan Islands and on the Mainland.

Backtrack to West Saanich Road, 12.4 km; right and south on it, past Ocean Sciences Institute to McTavish, 18.2 km; to Highway 17, 21.7 km; south to Cordova Bay Road, 32.8 km; left on Fenn Ave., 35.1 km; to parking lot on Parker.

STOP 4-2; **Late** Triassic (?) metabasalt **and limestone.**

36.1 km (22.4 m) Coastal exposure on Cordova Bay; beach access from Parker Road.

The southeast part of the beach outcrops is composed of metabasaltic rocks, locally with well preserved amygdaloidal texture. The amygdules locally show the steep east dip of the flows. Elsewhere the rocks are recrystallised to fine-grained diorite. Farther north is an exposure with well preserved pillow structures. Still further are good exposures of recrystallised fine-grained limestone cut by fine-grained diabasic sills.

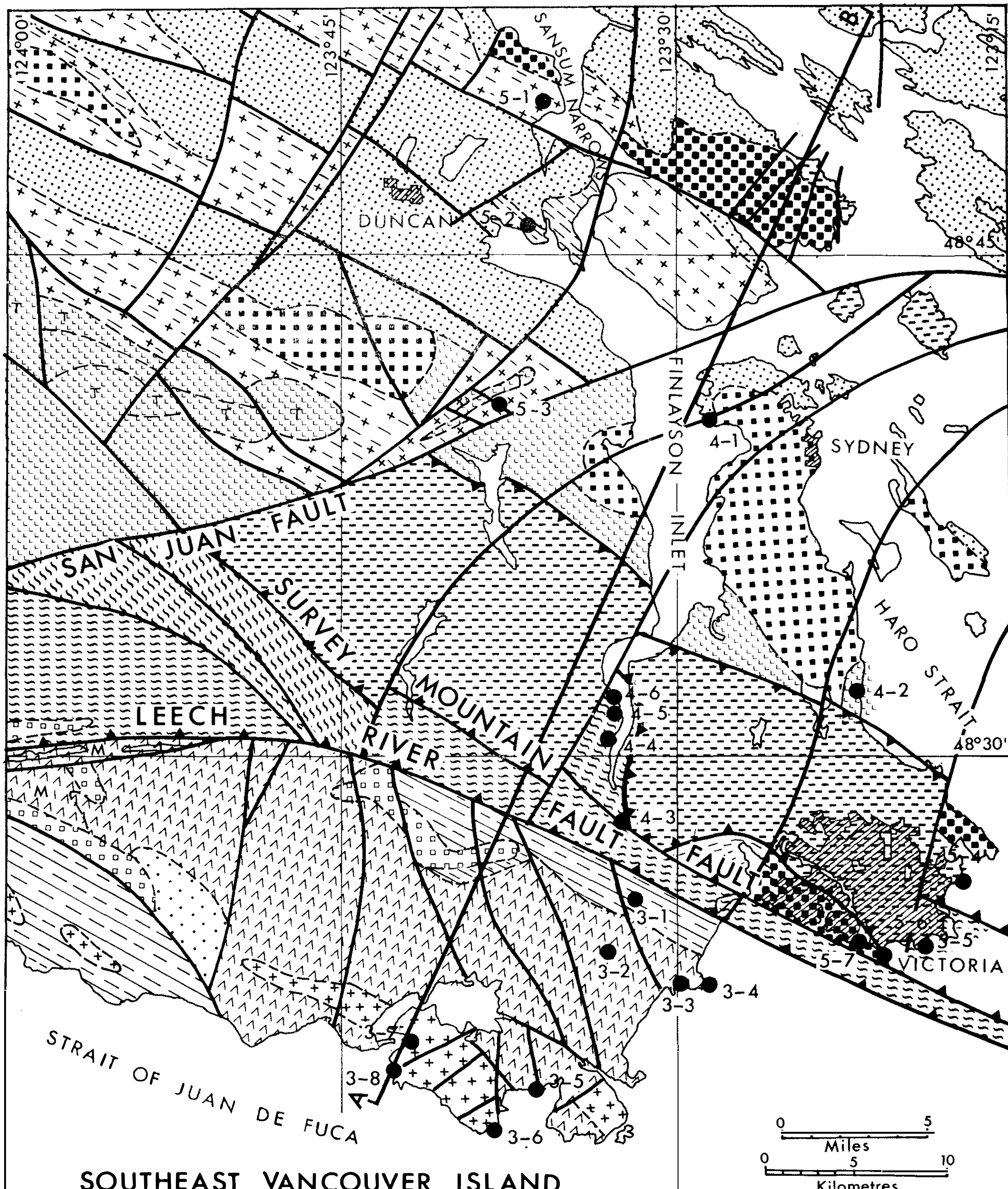
These exposures are tentatively correlated with the Vancouver Group. Farther north on Vancouver Island, that group is composed mainly of pillowed, brecciated and layered tholeiitic basalt, up to 6,000 m thick, (Karmutsen) overlain by Late Triassic carbonate and pelite (Quatsino and Parson Bay). The group is the most widespread sequence of the Insular Belt. See comments on probable origin from a rift zone at low paleolatitude in "General Geology". Although the Karmutsen basalt overlies the Sicker Group in several places, it may form the basal strata directly above gabbroic oceanic material elsewhere, like the Tertiary Metchosin Volcanics of the Olympic Terrane.

Continue south on Cordova to Royal Oak, 40.2 km; cross Highway 17 and continue on Wilkinson down to Highway 1, 47.9 km; continue to Shell Station near entrance of Goldstream Park. Between Stops 2 and 3 the route leads over the Wark-Colquitz Complex, to be examined on Day 5.

STOP 4-3; **Leech** River **Complex; Phyllites.**

58.4 km (36.3 m) The Leech River Complex is composed of Jurassic-Cretaceous metasedimentary and metavolcanic rocks underthrust northeastward below the Vancouver Island Terrane, forming the late Mesozoic continental margin. At this point, the complex occupies a zone a few km wide between Metchosin Volcanics of the Olympic Terrane to the south and Wark-Colquitz metamorphic rocks to the north. A northward reentrant of Leech River rocks, exposed along the shore of Finlayson Inlet and along Malahat Highway will be seen in following stops. It is interpreted as a half-window in the "Victoria thrustplate" of the Wark-Colquitz Complex. The contact with Metchosin Volcanics is a steep to vertical sinistral fault.

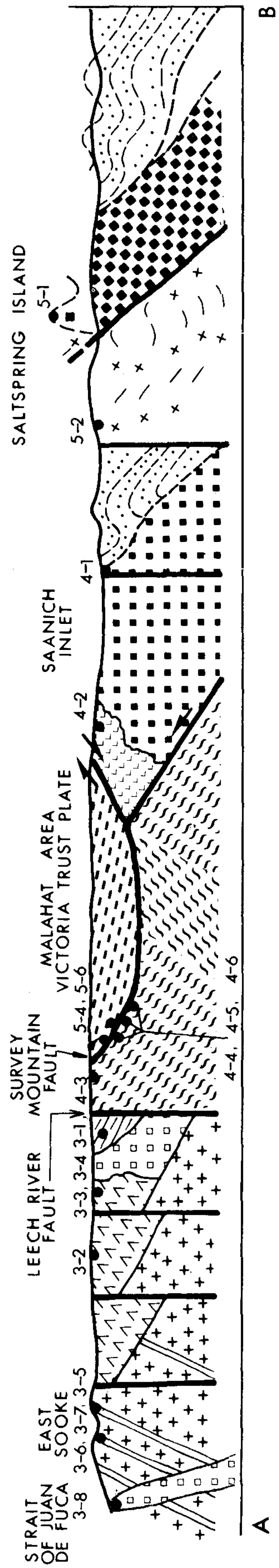
On the Victoria geological map (Muller, 1980b; in press) the Leech River Complex is divided into three lithologic units, inferred to be of oceanic or



SOUTHEAST VANCOUVER ISLAND

GENERAL GEOLOGY AND STOPS ON EXCURSIONS
1983-5, DAYS 4 & 5, 1983-12, DAY-3

Figure 19A



LEGEND

CARMANAH GROUP: sandstone, conglomerate

METCHOSIN VOLCANICS: basalt flows

METCHOSIN VOLCANICS: pillow basalt, breccia, diabase
M: metavolcanic rocks

CATFACE INTRUSIONS: quartz diorite

SOOKE GABBRO: gabbro, quartz diorite

MESOZOIC

NANAIMO GROUP: clastic sediments, coal

LEECH RIVER COMPLEX: schist, metagreywacke, chert, melange

ISLAND INTRUSIONS: granitoid rocks

BONANZA GROUP: intermediate volcanics, sediments

VANCOUVER GROUP: basaltic volcanics, sediments

MESOZOIC AND/OR PALEOZOIC

COLQUITZ GNEISS: granitoid gneiss

WARK DIORITE: metadiorite

PALEOZOIC

SICKER GROUP: metavolcanics, metasediments

SALTSPRING INTRUSIONS: metaquartzdiorite

— — — geological contact

thrust fault

normal fault

● 3-1 to 3-8: stops on fieldtrip #12

● 4-1 to 5-7: stops on fieldtrip #5

Figure 19B

continental-slope origin. Unit 1, composed of argillite, chert and volcanic rocks may be the oldest; Unit 2, with argillite, pelitic distal turbidites and their phyllitic equivalents is the middle part and Unit 3, with medium to coarse grained, massive to thick-bedded greywacke is considered youngest. The inferred upward coarsening sequence is based on the known upward transition from pelagic to neritic and littoral facies with increase in grain size of detrital rocks in the biostratigraphically documented Mesozoic column of Vancouver Island. This stop is inferred to be in the middle unit.

Along the north side of the highway, Leech River phyllite is well exposed. Slaty cleavage is parallel to the fault at azimuth 300. The cleavage shows kink bands and slickensides plunging steeply southeast, probably indicating oblique movement on the fault. A low ridge south of the highway, behind a recent housing development, exposes irregularly schistose quartz-chlorite rock inferred to be mylonitized (Jurassic?) volcanic rocks that elsewhere too are faulted together with sedimentary schists in the overthrust zone.

The complex, formerly considered Paleozoic on the basis of its metamorphic character, has not yielded fossils, but is interpreted as the eastern continuation of the Upper Jurassic to Lower Cretaceous Pacific Rim Complex of Vancouver Island. K-Argon dates on metamorphic biotite from schist and gneiss range from 36 to 42 Ma. Recent detailed work (Fairchild and Cowan, 1982; Rusmore, 1982) suggests that Leech River and Metchosin rocks, juxtaposed along the fault, are of different metamorphic facies and were faulted into position after metamorphism. On the west coast, Leech River schist north of the fault is overlain by late Eocene to Oligocene strata while south of the fault, Metchosin Volcanics are covered by late Oligocene to Miocene strata. Underthrusting of the Leech River Complex presumably occurred in the Cretaceous to early Eocene, perhaps simultaneous with thrusting in San Juan Islands. It was followed by sinistral movement along Leech River Fault that, judging from the differing ages of Oligocene strata on opposite sides of the fault, may have continued into Oligocene time.

Continue on Highway 1.

STOP 4-4; Leech River Formation; ribbon chert.

63.8 km (39.6 m) at hydro towers east of highway. The hydro towers are on a small hill, composed of east striking vertical ribbon chert. The beds of black to greenish grey, whitish weathering chert are 1-4 cm thick and separated by graphitic films. Dragfolds in the beds are interpreted as soft-sediment slumpfolds. Thin sections show them to be silicic rocks, composed of a fine dust of quartz, feldspar and actinolite. Despite best efforts, no datable radiolarians have been found in these beds. They resemble those of the Orcas Formation of San Juan Island, dated by radiolarians as Triassic to Early Jurassic, but also resemble cherts of the Pacific Rim Complex of West Vancouver Island with Late Jurassic, Tithonian radiolarians. The rocks are inferred to be part of the basal unit of the Leech River Complex. Minor outcrops of metabasalt are also present and on the west side of the highway the cut shows a layer of pillow basalt interbedded in chert and argillite.

Continue on Highway 1.

STOP 4-5; Leech River Complex; greywacke and argillite.

65.8 km (40.9 m) The cuts on both sides of the highway show a variety of bedded units. There are beds of greywacke, up to 60 cm thick, in places with rip-up shale fragments and separated by thin argillite laminae. There are also thin, fine-grained or graded units, a few cm thick and thick beds of argillite. A thin section of greywacke shows angular grains of mainly quartz and quartzite, less plagioclase, and minor chloritized mafics and volcanic fragments, in a matrix of fine quartz, epidote and chlorite. Unlike highly deformed pelitic rocks of this formation, the rocks exhibit symmetrical small folds with locally good axial cleavage. The beds are inferred to be in the upper unit of the complex.

Continue on Highway 1.

STOP 4-6; Tectonic melange of Leech River rocks.

66.4 km (41.3 m) At turnoff of 17 Mile Road. The cut on the highway shows (at close inspection) a finely textured tectonic melange. Melanges are not common in the Leech River Complex but coarser melange with large knockers of limestone, greywacke and volcanic rock are common in the Pacific Rim Complex of the west coast.

Proceed on Highway 1. 1.6 km farther north a fault zone is exposed on the highway's east side. It is one of several northeast striking faults through the region. This fault brings the Wark-Colquitz Complex in contact with the Leech River Complex and thus forms the west edge of the "Malahat-Finlayson window." From here the route leads past cuts in the Wark-Colquitz Complex, to be viewed on Day 5 in Victoria. The road to Duncan passes Jurassic volcanic and intrusive rocks coextensive with those of Saanich Peninsula and enters Cowichan Valley, underlain by Nanaimo Group strata, covered by glacial and fluvioglacial deposits.

105 km (65.2 m) City of Duncan for overnight stop.

DAY 5: THE PALEOZOIC SICKER GROUP AND THE WARK-COLQUITZ COMPLEX

Day 5 deals first with Sicker Group volcanic, sedimentary and related intrusive rocks near Duncan and, after returning to Victoria, with waterfront exposures of the Wark-Colquitz Complex thrust plate and underlying Leech River metavolcanic rocks. For geology and stops, see figures 19a, 19b.

From Duncan follow Maple Bay Road to Maple Bay and on via Arbutus Avenue to rotunda on Bayview Place.

STOP 5-1; Nitinat Formation and Tyee Quartz Porphyry.

11.4 km (7.1 m) The Sicker Group includes all Paleozoic rocks of Vancouver Island. This stop shows basic metavolcanic rocks of the Nitinat Formation and a vertical, 15 m wide, gneissose meta-quartz porphyry, called Tyee Quartz Porphyry by Clapp and Cooke (1917). The porphyry is probably a shallow offshoot of the Saltspring Intrusion, a pluton of meta-quartzdiorite that is exposed farther to the north and on Saltspring Island. The Nitinat, the oldest part of the Sicker Group, is composed of basic volcanic breccia, minor massive tuff and rarely, pillow lava. Most distinctive are dark green phenocrysts of commonly uralitized pyroxene. Much of this formation is metamorphosed to actinolite schist. The Myra Formation above the Nitinat is bedded rhyolitic and dacitic tuff and breccia, considered coeval and comagmatic with Saltspring Intrusions and Tyee Quartz Porphyry. Massive sulphide deposits (Cu-Zn-Pb-Au-Ag-Cd), interpreted to be of submarine volcanogenic (Kuroko type) origin are related to the Myra Formation. They were mined on Mount Sicker near Duncan and are still exploited at Western Mines near Buttle Lake. At Maple Bay some of these rocks occur in narrow, tightly folded synclines within the Nitinat Formation. The coarse-grained quartz porphyry at this stop is an intrusive sill within the uralite bearing metabasalt of the Nitinat Formation.

The stratigraphy and age of the lower, volcanic part of the Sicker Group hinges on this and similar outcrops. Until a few years ago that group was considered to be Pennsylvanian or older on the basis of the overlying Pennsylvanian fossiliferous sediments. However, quartz porphyry from this and other outcrops and metagranodiorite of the comagmatic Saltspring Intrusions yielded zircons that give slightly discordant ages. Pb^{207}/Pb^{206} ages range from 363 to 395 Ma (Devonian) and the metamorphism, based on a K/Ar dating of sericite is 180 Ma. Using that age as a lower intercept of a chord produces an upper intercept with concordia of 410 Ma (latest Silurian). Accordingly the Myra and Nitinat formations must be earliest Devonian or older. As noted in the comments on the Turtleback Complex of San Juan Islands, it appears to be roughly correlative to Saltspring and Tyee intrusive rocks.

Backtrack towards Duncan, but turn left on Tzouhalem Road, 20.4; turn left on Khempsen Road, 23.2.

STOP 5-2; Greywacke: "Nanoose unit" of Sicker Group

25.4 km (15.8 m) Khempsen Road, southwest base of Mount Tzuhalem.

Small quarries and roadcuts exhibit silicified greywacke with thin cyclical argillite laminate. The rocks resemble sequences with Middle Pennsylvanian fossils in lenses of calcarenite at Nanoose Peninsula on Vancouver Island and adjacent Ballenas Islands, and to strata on the northeast side of Orcas Island (not visited on this trip).

Backtrack to Tzouhalem Road and now turn south, 27.6 km; turn south on Highway 1, 31.4 km; right on Cobble Hill Road at 37.3 km; right under railway overpass, 42.3 km.

STOP 5-3; **Buttle** Lake Formation; limestone

43.0 km (26.7 m) Abandoned Ocean Cement limestone quarry. The Buttle Lake Formation is better known from Buttle Lake area where it contains an Early Permian macrofauna. There it disconformably overlies volcanic rocks of the Myra Formation and is itself disconformably overlain by the Karmutsen Formation.

The rocks in the quarry are thin- to thick-bedded limestone, with irregularly alternating beds of grey, commonly crinoidal calcarenite and black shaly to silty graphitic limestone. A few conodont fragments, obtained and determined by M. Orchard (pers. comm., 1981) are *Idiognathodus* sp., *Streptognathodus* sp., and *Neogondolella* sp., indicating Pennsylvanian to Early Permian age. The beds are disrupted by faults, but generally dip steeply northwest. Along the south margin of the quarry the limestone is underlain by beds of dark grey to black chert, thinly bedded tuff and greywacke and dark impure limestone. On the northeast end of the quarry, metabasalt is in contact with the limestone and is interpreted as the Karmutsen Formation. Pillow lava with quartz nests, a typical Karmutsen lithology, is exposed farther to the northeast on Cobble Hill. The quarry is located in a fault block between northeasterly striking faults branching off San Juan Fault.

Backtrack to Cobble Hill Road and turn south via Shawnigan Lake to junction with Highway 1, 60.1 km; follow Highway 1 south to Victoria; turn left on Hillside, 88.5; continue on Lansdowne, right on Rutland Avenue 94.3, right on Beach 94.6.

STOP 5-4; Cattle Point; Wark-Colquitz Complex

95.3 km (59.2 m) Cattle Point boat launching area. The wide glaciated shoreline outcrops at Cattle Point show a variety of fine- to medium-grained gneissic amphibolite, composed mainly of hornblende and sodic plagioclase with minor quartz. The gneiss is isoclinally folded with consistent near-vertical foliation striking NNW. A K/Ar date from this locality is 153 ± 14 Ma, indicating Jurassic metamorphism. Clapp (1913) distinguished and mapped Wark Diorite, composed mainly of massive hornblende metadiorite and Colquitz Gneiss, consisting chiefly of well foliated quartz-feldspar-biotite gneiss. Distinction of Wark Diorite and Colquitz Gneiss has also been attempted on the new Victoria geological map (Muller, 1980b). Clapp (1913) thought that the Colquitz intrudes the Wark, but in the present interpretation they represent basic and silicic parts of one complex, derived from Sicker volcanic and sedimentary rocks migmatized during Jurassic plutonism.

The writer proposes that the Wark-Colquitz Complex is a WNW trending thrustsheet, about 10 km wide that forms the SW edge of the Vancouver Island Terrane. It is inferred to have been carried northeastward and thrust against the Jurassic volcanic-plutonic complex of Saanich Peninsula, riding on the underthrusting Leech River Complex.

Continue along shoreline drive westward, following Beach, Terrace and King George, turn left on Crescent.

STOP 5-5; Leech River Complex; metavolcanic rocks

103.1 km (64.0 m) Harling Point, south of Chinese Cemetery.

The well glaciated coastal exposures show furrowed and striated surfaces with a consistent S20W direction of the last (Fraser) glaciation that flowed south over the Victoria area. The rocks are thinly laminated chloritic siliceous tuff and minor argillite containing dikes of sheared-out feldspar porphyry. The glaciated surfaces exhibit complex folding with great swirls and intricate crumpling. Axial foliation varies in azimuth from 310 to 350 and from 50 degrees northeast to steep southwest dips. Locally, the primary foliation is refolded into south-verging chevron folds of several meters amplitude. The rocks are interpreted as Jurassic volcanic rocks, roughly coeval with those of the Bonanza Group of the Vancouver Island Terrane and the Fidalgo Complex of San Juan Islands. Their structural position is below the inferred Wark-Colquitz

Complex thrustplate, and separated therefrom by a northeasterly, northwest-down, normal fault (Figure 19).

Continue along shoreline scenic drive.

STOP 5-6; Wark-Colquitz Complex

106.2 km (66.0 m) Clover Point. The outcrops on this point are again the Wark-Colquitz Complex that underlies most of Victoria. They are irregularly, light-dark banded rocks, more silicic than those at Cattle Point and interpreted as the migmatized Sicker Group. The foliation strikes north over most of the point, but turns into asymmetric east striking folds at the south end. The structures are tentatively explained by two thrust faults inferred to intersect near Clover Point (Figure 19a). The upper thrust carries Wark-Colquitz Complex above the Sicker Group and Jurassic intrusions surrounding Victoria's Inner Harbour. The structurally lower thrust, probably responsible for the east striking fold at the south tip of the point, is inferred to be the eastward extension of the Survey Mountain Fault. It carries the volcanic and intrusive rocks over Leech River schist and should be parallel and closely north of the Leech River Fault.

Continue on the shoreline scenic drive.

STOP 5-7; Dioritized basalt, intruded by metaquartzdiorite.

107.8 km (67.0 m) Finlayson Point. The shoreline outcrops expose an intrusive contact of granitoid rock and dioritized basaltic volcanic rock. The dark coloured rocks are biotite-hornblende quartz diorite and light coloured rocks are biotite granodiorite. Agmatitic textures are typical of contacts of Jurassic Island Intrusions with dioritized volcanic rocks that could be derived from Jurassic Bonanza, Triassic Karmutsen, or Paleozoic Sicker volcanic rocks. The intrusive granitoid rocks are not dated and may be Jurassic Island Intrusions or Paleozoic Saltspring Intrusions.

Continue along Marine Drive and Douglas Street to Downtown Victoria; 111.0 km (69.0 m); end of day and end of excursion.

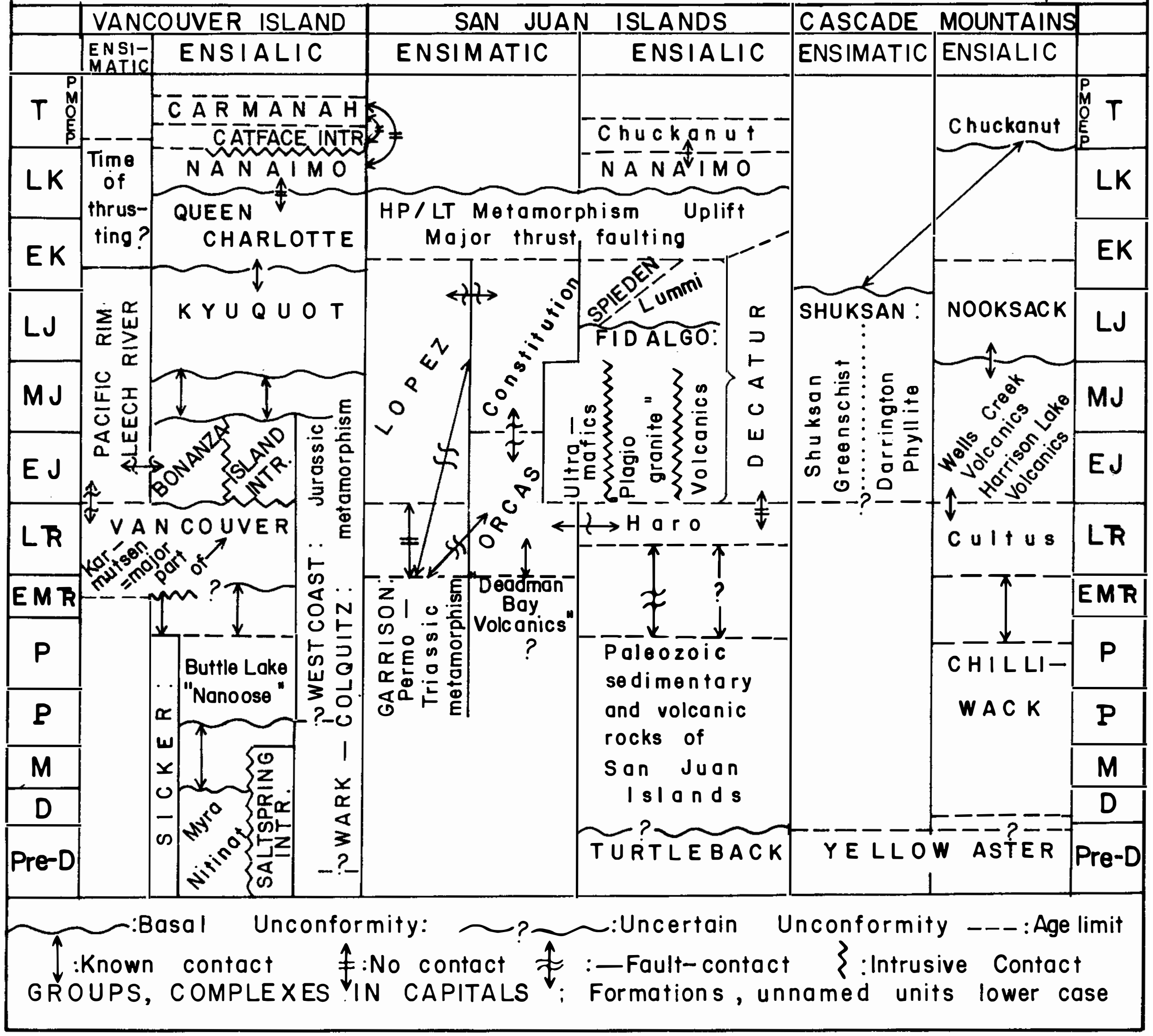
OVERVIEW

(J. E. Muller)

The aim of this fieldtrip is to examine the correlation (or non-correlation) of the geology of Vancouver Island and San Juan Islands, and more distantly, Cascade Mountains. We have made some progress in establishing stratigraphic and structural links, but unsolved problems and differences of interpretation remain. This is a synopsis of Muller's views of the geological connections between the regions, viewed from Vancouver Island.

Figure 2 shows the general geology and structure of the region on a scale of less than 1:1,000,000. Figure 20 shows a comparison of the stratigraphic columns in the three adjacent regions. For each region, the rocks are divided into two categories represented in two columns. "Ensimatic" rocks include rocks of oceanic origin, including ultramafic and mafic rocks, tholeiitic basalts, ribbon cherts, pelites and distal turbidities and — in the Permian and Triassic—

FIGURE 20 SYNOPSIS OF FORMATIONS (Olympic Terrane exluded)
S. W. BRITISH COLUMBIA AND N. W. WASHINGTON



clastic and carbonate strata. The Vancouver Group, composed of mainly oceanic basalt, is not in all respects ensialic. As noted, it may have formed in a Triassic rift zone in the Paleozoic volcanic arc where it was intruded as sills and extruded as Karmutsen basalt into and over Sicker Group rocks. Possibly the Karmutsen is locally oceanic basement, not underlain by Paleozoic rocks.

The Jurassic Island Intrusions - Bonanza Group magmatic arc intrudes and overlies the Vancouver Group. Next, a Late Jurassic - Early Cretaceous clastic wedge (Kyuquot and Queen Charlotte) unconformably overlies the combined magmatic complexes on the northwest, followed by a Late Cretaceous molasse (Nanaimo) on the southeast. Lastly all these rocks, including the Nanaimo Group, are intruded by early Tertiary plutons (Catface) and overlain unconformably on the southwest by Tertiary clastic strata (Carmanah).

The ensimatic, Late Jurassic to Early Cretaceous volcanic-sedimentary suite of Vancouver Island (Leech River and Pacific Rim) was thrust northeastward below the Vancouver Island Terrane along San Juan and Westcoast faults. Thrusting occurred between middle Cretaceous and late Eocene time, perhaps concurrent with thrusting in San Juan Islands.

The comparatively uncomplicated rock succession of Vancouver Island terminates at the Haro Fault. Northwest of that fault, the unmetamorphosed Triassic Haro, the Jurassic to Cretaceous Spieden, and the Late Cretaceous Nanaimo correlate with respectively Parson Bay Formation (top of Vancouver Group), Kyuquot Group and Nanaimo Group of the Vancouver Island Terrane. Spieden and Kyuquot groups have many fossil species in common (Muller, 1981; Johnson, 1981). These rocks probably overlie older rocks of the Vancouver Island Terrane.

Southeast of the Haro Fault, the Paleozoic part of the ensialic column of Figure 20 is a continental terrane (Vance et al., 1980) or a magmatic arc (San Juan authors of this guide), probably continuous with the Paleozoic of Vancouver Island and possibly also with that of the Mainland.

The many thousands of meters of tholeiitic basalt, overlain by Late Triassic carbonate and clastic sediments of the Vancouver Group apparently wedge out on south Vancouver Island to a few outcrops of basalt and limestone with insignificant thickness. On San Juan Islands, apart from *Halobia*-bearing Haro beds, the Vancouver Group is not represented and in Cascade Mountains the Cultus Formation is similar to Parson Bay but also lacks Karmutsen-type basalt.

The Fidalgo Complex is composed of basic to ultrabasic rocks, considered to be oceanic basement, intruded by and overlain by a Jurassic plutonic-volcanic complex. According to Brown et al. (1979) the two suites are not comagmatic. The ophiolitic part of the Fidalgo Complex is only dated indirectly by the Jurassic age of the intruding plagiogranite. It is here suggested that the ophiolite is comagmatic and correlative with the Late Triassic Karmutsen tholeiite of Vancouver Island. As noted, that sequence may also constitute oceanic basement although it overlies the Sicker Group elsewhere. The volcanic rocks of the Fidalgo are similar in age and lithology to the Wells Creek Volcanics of Cascade Mountains and the Bonanza volcanic rocks of Vancouver Island. The succeeding Lummi clastic sequence and the less metamorphosed Spieden Group correlate well in age and lithology with the Nooksack of Cascade

Mountains and the Kyuquot Group of Vancouver Island. Thus, similar Early to Middle Jurassic volcanic-plutonic terranes, overlain by Late Jurassic to Early Cretaceous clastic strata are present in all three regions (Figure 20). A connection between the crystalline terranes, albeit broken by faults and concealed by overlying strata, seems probable and is also suggested by the aeromagnetic anomaly map (Figure 21). It shows a conspicuous east trending positive anomaly that links the Jurassic Saanich Granodiorite of south Vancouver Island with the Fidalgo Complex and exhibits maxima over the ophiolitic parts of Cypress and Fidalgo islands.

The San Juan authors consider the formations, listed in the ensimatic column of Figure 20 to be allochthonous sheets stacked above the San Juan Paleozoic and below the Decatur Terrane:

Decatur

------ Lopez Complex in Lopex Thrust Zone ------

Constitution

------ Rosario-Eagle Cove Thrust ------

Orcas-Deadman

------ Orcas Fault Zone ------

Turtleback-Paleozoic

In this succession, the Decatur Terrane is the highest unit, structurally overlying Orcas and Constitution formations. It follows that the Decatur Terrane once should have been present above the Orcas and Constitution formations of San Juan Island and has been eroded off.

Another structural position of the Decatur may be considered alternatively. As noted, the Fidalgo ultrabasic rocks may be comagmatic with Karmutsen basalts of Vancouver Island and emplaced in a rift zone within the San Juan Paleozoic rocks. The Decatur could be autochthonous and perhaps, on Orcas and San Juan islands, underlie Orcas and Constitution thrust sheets. This interpretation would account for the massive, unsheared character of the ultrabasic Fidalgo rocks, a condition not to be expected for an ophiolite at the base of a major thrust sheet. The San Juan authors of this guidebook report prehnite and lawsonite assemblages to be best developed in the Jurassic and Cretaceous (Decatur) sandstones. The minerals indicate lithostatic burial below more than 11 km. Coal, collected by the writer from the Lummi Formation on Decatur Island, is anthracite with reflectance (% Ro) of 4.05 ± 0.4 (A. R. Sweet and W. S. Hopkins, pers. comm. 1975), indicating depth of burial between 3 and 4 km. These data suggest a deep, rather than a high structural position for the Decatur Terrane.

The Saanich-Fidalgo magmatic arc may be built on a converging continental margin interspersed with oceanic floor. In the adjacent ocean basin, Orcas and Constitution formations accumulated. Lummi, (and equivalent Kyuquot, Spieden and Nooksack) clastic strata were laid down on the volcanic-plutonic terrane in

Late Jurassic to Early Cretaceous time. During middle Cretaceous compression, the Orcas and Constitution offshore strata were thrust over the Turtleback-Paleozoic Complex and also over the Decatur Terrane. The thrust plates covering the autochthonous rocks were thin or absent in the north and Mesozoic rocks there (Nanaimo, Spieden and Haro formations) were not affected by burial metamorphism.

Subduction of the Lopez and Leech River complexes below the continental edge may have occurred later. On southeast Vancouver Island, the continental base of Wark-Colquitz gneiss was torn off by the underthrusting mass and carried northward against the Saanich-Fidalgo plutonic massif. The latter was raised and formed the southern margin of the Nanaimo Basin in Late Cretaceous time.

Renewed compression occurred in early Tertiary time, when the Olympic Terrane was pushed against the continental edge by oblique left-lateral movement along Leech River Fault. Large tensional, northeast striking faults developed perpendicular to that fault (Figure 2). Normal offsets along these faults exposed different structural levels in adjacent blocks. Thus the autochthonous Nanaimo, Spieden and Haro strata probably lie on Paleozoic or Mesozoic rocks of the Vancouver Island Terrane and are bounded to the southeast by the Haro Fault. Southeast of that fault, the San Juan Paleozoic is overlain by the Orcas and Constitution thrust sheets. According to the here proposed plan, some Jurassic volcanic rocks and overlying Lummi clastic strata, concealed by Orcas and Constitution thrusts, could lie between Orcas, Constitution and the Paleozoic. This structural sequence, underlying most of San Juan and Orcas islands, is bounded to the southeast by Buck Bay Fault. Southeast of this fault the Decatur Terrane is exposed, lying on early Mesozoic oceanic crust and exposed on Lopez and adjacent islands to the east.

Sources for Figure 21:

Geological Survey of Canada, 1959; Aeromagnetic Survey across the Cordillera; Aeromagnetic Map 749G, Scale 1:253,440

Geological Survey of Canada, 1979; Aeromagnetic Map, Victoria - Vancouver; Aeromagnetic Map 8191G, Scale 1:250,000

United States Geological Survey, 1977; Aeromagnetic Map of Northern and Eastern Parts of the Puget Sound Area, Washington; Open File Report No. 77-34, Scale 1:125,000

United States Geological Survey, 1978; Aeromagnetic Map of the Bellingham Area, Washington; Open File Report No. 78-358, Scale 1:62,500

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