The Late Cretaceous San Juan thrust system, Washington: Nappes related to the arrival of Wrangellia

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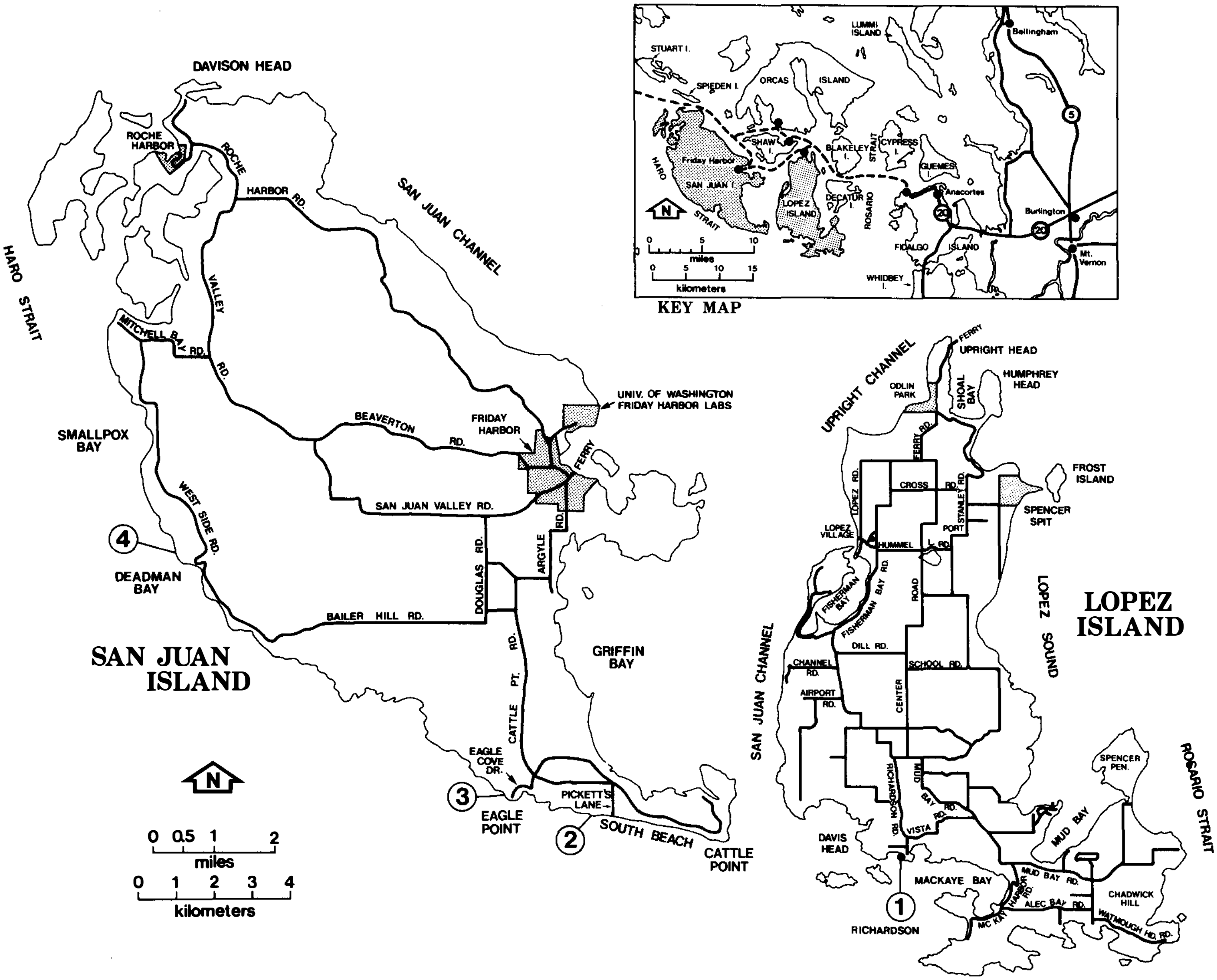


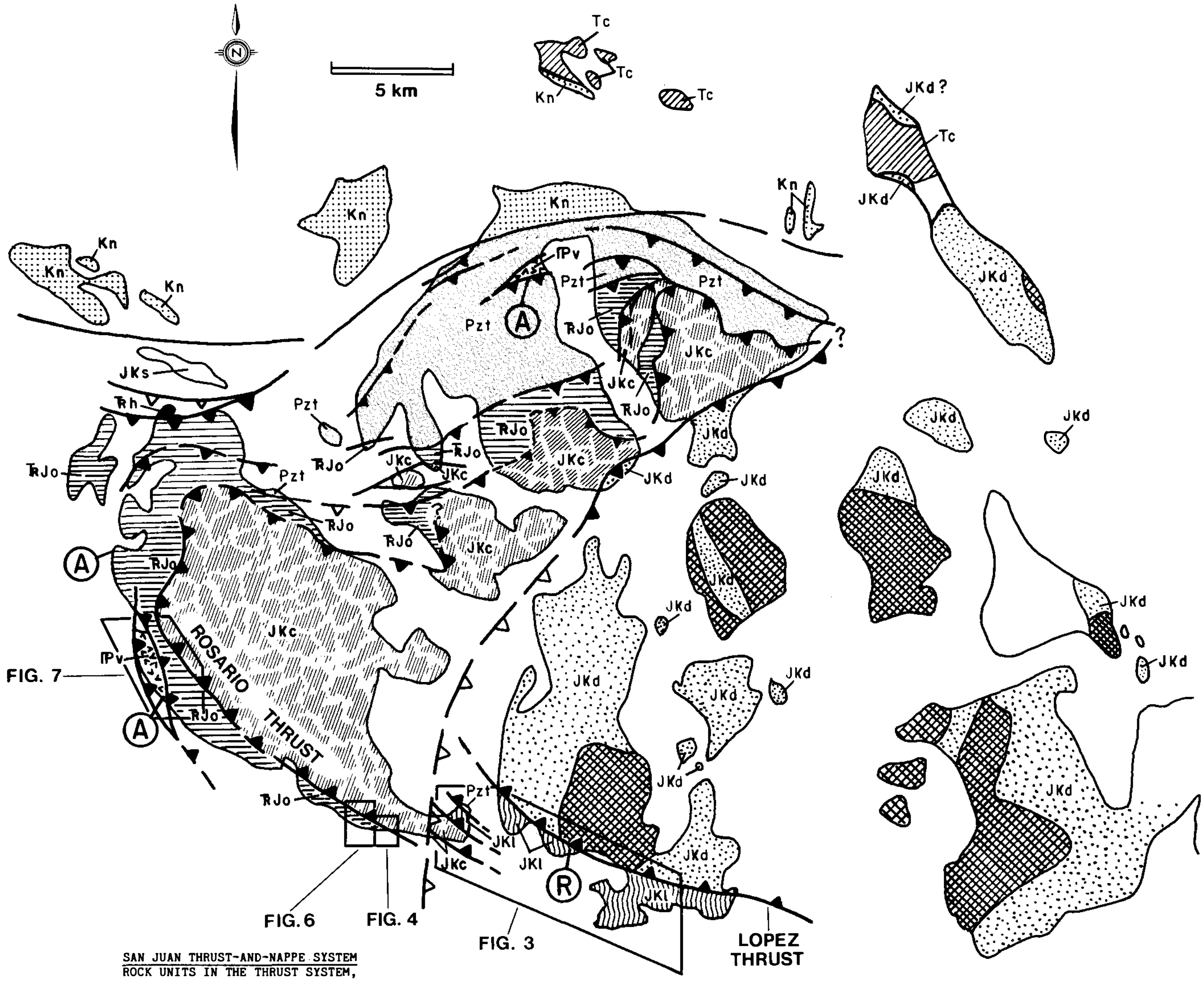
Figure 1. Map showing roads and ferries in vicinity of San Juan Islands. Numbers refer to stops in this guide.

LOCATION AND ACCESSIBILITY

The San Juan Islands are located at the north end of Puget Sound in northwestern Washington State. This field guide includes four localities: one on Lopez Island and three on San Juan Island. To reach the islands (Fig. 1), take I-5 to Exit 230, then drive west on Washington 20 to the Anacortes ferry terminal. Washington State ferries provide frequent daily service for cars and passengers to Lopez and San Juan Islands. Long waits should be expected on summer weekends.

SIGNIFICANCE

A variety of rock units ranging in age from early Paleozoic to Late Cretaceous are exposed in the San Juan archipelago. Mid-Cretaceous and older rocks occur in several thrust sheets or nappes, which are separated by a set of thrust faults and fault zones. These thrusts are broadly folded around axes gently plunging to the southeast (Fig. 2). The San Juan thrusts and nappes are part of a broader Late Cretaceous thrust system that extends 48 mi (80 km) eastward into the North Cascade Mountains. To the



SAN JUAN THRUST-AND-NAPPE SYSTEM
ROCK UNITS IN THE THRUST SYSTEM, SHOWN IN ASCENDING STRUCTURAL ORDER

- **JKd** — **Decatur Terrane.** A coherent terrane consisting of M. to U. Jurassic ophiolitic and arc-volcanic rocks of the Figalgo Complex (cross-hatch pattern), and U. Jurassic to Lw. Cretaceous sandstone, mudstone and conglomerate of the overlying Lummi Formation (stipple pattern).
- **JKl** — **Lopez Structural Complex.** Imbricated slices of Jurassic to mid-Cretaceous sandstone, pebbly mudstone, pillow lava and chert. Also contains rare slices of Turtleback quartz diorite.
- **JKc** — **Constitution Formation.** Massive volcaniclastic sandstone, with interbedded sequences of mudstone, chert, pillow lava and green tuff. Jurassic to Lw. Cretaceous.
- **RJo** — **Orcas Formation.** Ribbon chert and minor pillow basalt. Triassic and Lower Jurassic. Locally imbricated with slices of Turtleback Complex and Garrison Schist.
- **IPv** — **Deadman Bay Formation.** Pillow basalt with minor chert and Asiatic-fusulinid limestone. Lw. Permian to Triassic.
- **Pzt** — **Turtleback Complex and East Sound Group.** An undifferentiated stratigraphic sequence consisting of lower Paleozoic plutonic rocks of the Turtleback Complex, and upper Paleozoic arc-volcanic rocks and limestone of the East Sound Group.

EXTERNAL UNITS
ROCK UNITS FORWARD OF, AND BELOW, THE SAN JUAN THRUST SYSTEM

- **Tc** — **Chuckanut Formation.** Non-marine sandstone and conglomerate. Lower Tertiary.
- **Kn** — **Nanaimo Group.** Marine and non-marine sandstone, conglomerate and shale. Upper Cretaceous.
- **JKs** — **Spieden Group.** Sandstone and conglomerate with arc-volcanic clasts, U. Jurassic and Lw. Cretaceous.
- **Rh** — **Haro Formation.** Sandstone and conglomerate with arc-volcanic clasts. Also contains minor shelly interbeds. U. Triassic.

Figure 2. Generalized geologic map of San Juan Islands (modified from Brandon and others, 1983, and in prep.). Major faults are approximately located. Quaternary sediments are not shown. "R" denotes the village of Richardson. "A" denotes Tethyan fusulinid localities in the Deadman Bay Volcanics. Garrison Schist, which is restricted to a narrow zone beneath the Rosario thrust, is not included on this map.

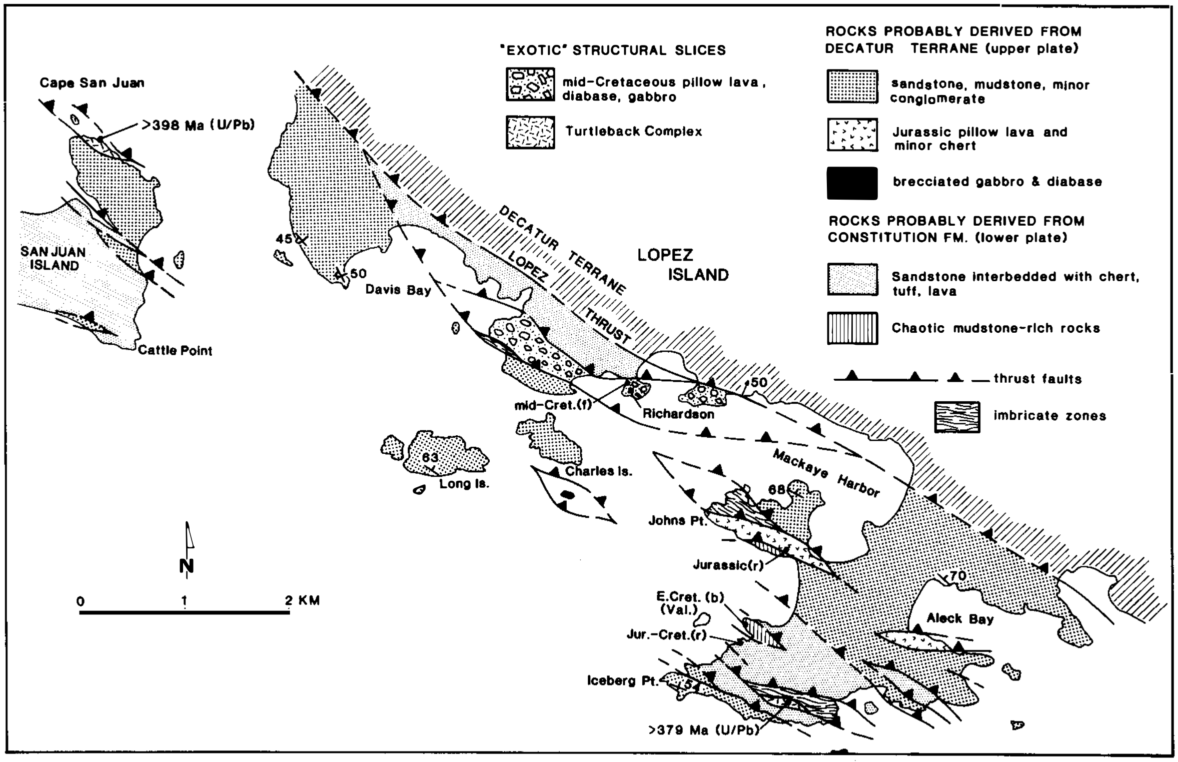


Figure 3. Geologic map of Lopez Structural Complex for Stop 1 at Richardson, Lopez Island (from Brandon and others, in prep., based on mapping by Cowan). Localities for U/Pb zircon dates are labeled U/Pb. Fossil localities are labeled as follows: r, radiolaria from chert; b, *Buchia* from sandstone; f, foraminifera from mudstone.

northwest of the San Juan nappes lies the Wrangellia terrane (Jones and others, 1977; Muller, 1977) exposed on Vancouver Island and adjacent smaller islands. We interpret the San Juan–Cascades thrust-and-nappe system as having been emplaced westward onto the Wrangellia terrane as Wrangellia was driven eastward and beneath the continental margin of North America during the Late Cretaceous (Brandon and Cowan, 1985). The field guide localities were chosen for several reasons: (1) they provide important constraints on the timing of deformation, (2) they illustrate styles of thrust-related deformation, and (3) they epitomize important stratigraphic units within the nappes. More detailed stratigraphic and structural information is in Vance (1975, 1977), Whetten and others (1978), Brown and others (1979), and Brandon and others (in prep.). The geology of the North Cascades is summarized in Misch (1966, 1977). Muller (in Brandon and others, 1983) provides a brief sketch of the geology of southern Vancouver Island nearest the San Juan Islands. Other more comprehensive field guides to the San Juan Islands and surrounding areas are Brandon and others (1983), Brown (1977), Vance (1977), Cowan and Whetten (1977), and Misch (1977).

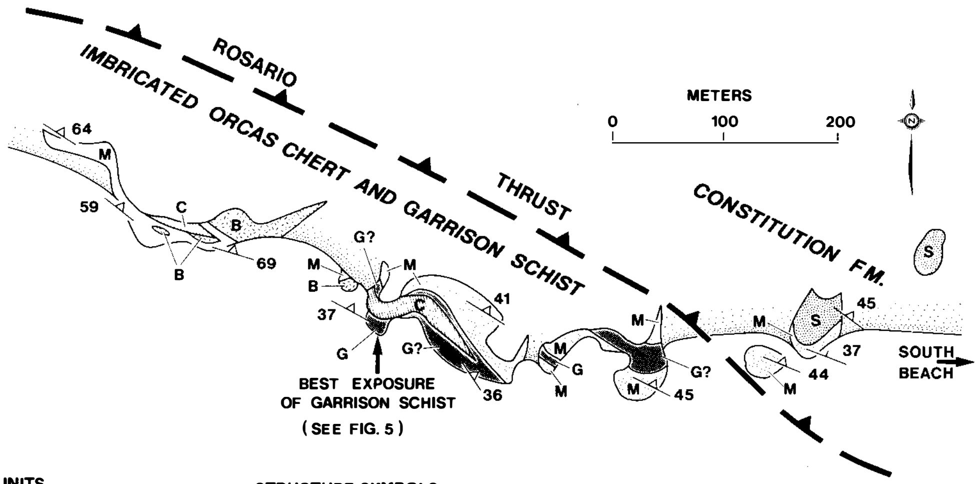
FIELD GUIDE LOCALITIES

Stop 1: Richardson, Lopez Island. An exotic slice of mid-Cretaceous basalts in the Lopez Structural Complex.

From the ferry terminal on Lopez Island, drive south to the hamlet of Richardson on the south shore of the island (Fig. 1). Park at the Richardson store where the road ends in a cul-de-sac. The outcrops to be examined are on the east side of the road and on the coast extending 250 ft (75 m) north of the store.

The brownish-red mudstones in the 10-ft (3-m)-high road cut opposite the store are very important because they are the youngest dated rocks in the San Juan thrust system. Foraminifera from these mudstones, first discovered by Danner (1966), have been dated as latest Albian (mid-Cretaceous, about 100 Ma) by W. Sliter (personal communication, 1986). These mudstones occur as an interbed in a small fault-bounded basaltic unit within the Lopez Structural Complex (Figs. 2, 3), a 1.8-mi (3-km)-thick imbricate fault zone that separates two relatively coherent Mesozoic units: the structurally lower Constitution Formation and the overlying Decatur terrane. The most prominent structure visible in this outcrop is a northeast-dipping slaty cleavage that postdates imbrication within the Lopez Complex.

More of this volcanic unit is exposed in the steep 15-ft (5-m)-high seacliff immediately north of the store. Note that the mudstone is part of a northeast-dipping stratigraphic sequence including (from bottom to top) pillow basalt, red and black mudstone, pillow breccia, and, finally, more pillow basalt at the north end of the exposure. The pillows indicate that the sequence is upright. Based on their trace-element composition (high TiO_2,



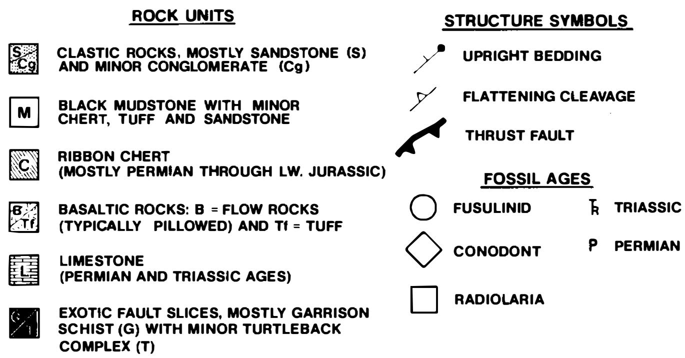


Figure 4. Outcrop map for Stop 2 in the South Beach area, San Juan Island (modified from Brandon, 1980).

light rare-earth element enriched; Brandon and others, in prep.), these pillowed basalts probably erupted in an "oceanic island" setting, and therefore might represent a mid-Cretaceous seamount. The mudstone contains small lenses of sand-sized volcanic quartz and feldspar, indicating that an intermediate arc volcanic terrane was nearby.

Amygdules and veins of metamorphic aragonite and pumpellyite are present in the Richardson basalts. Sandstone-rich units, present elsewhere in the Lopez Complex, contain lawsonite-aragonite metamorphic assemblages. These minerals formed during a very low-temperature, high-pressure regional metamorphism that affected most of the rocks in the San Juan thrust system. This metamorphic event occurred in the interval 100-83 Ma, and was related to rapid tectonic burial of nappes within the thrust system (Brandon and others, in prep.).

Stop 2: South Beach, San Juan Island. Exotic slices of Permo-Triassic metamorphic rock within the Rosario thrust zone.

From the ferry terminal at Friday Harbor, San Juan Island, drive through town, and then head south toward Cattle Point (Fig. 1). Take Pickett's Lane down to South Beach, and then follow the dirt road west about 0.2 mi (0.4 km) to the outcrops at the west end of the beach. The area to be examined on foot starts at these first outcrops, shown as the most easterly outcrops in Figure 4, and continues about 2,000 to 2,600 ft (600 to 800 m) to the west along the coast.

This area lies at the southwestern end of the Rosario thrust zone, which strikes offshore beyond this point. At this location, the thrust dips northeast, placing massive sandstone of the Constitution Formation over a structurally complex assortment of mudstone, green volcanic rocks (locally pillowed), green tuff and ribbon chert, which are assigned to the Orcas Chert. The best evidence for large thrust displacements is the exotic slices of Garrison Schist scattered through this fault zone. The Garrison experienced a greenschist- to amphibolite-grade, high-pressure metamorphism (barrositic amphiboles) during the Permo-Triassic, prior to its tectonic imbrication with sub-greenschist-grade Orcas Chert during the Late Cretaceous (Brandon and others, in prep.).

At the east side of the map (Fig. 4), the first outcrops belong to the Constitution Formation, and consist of a northeast-dipping depositional sequence including a thin horizon of mudstone, green tuff, and ribbon chert, overlain by a thick massive sandstone unit. Of particular interest is the clear interbedding of clastic rocks with radiolarian ribbon chert.

Farther west along the coast is a highly imbricated sequence of Orcas Chert with exotic slices of Garrison Schist. These rocks lie beneath the Rosario thrust, which is the highest recognized

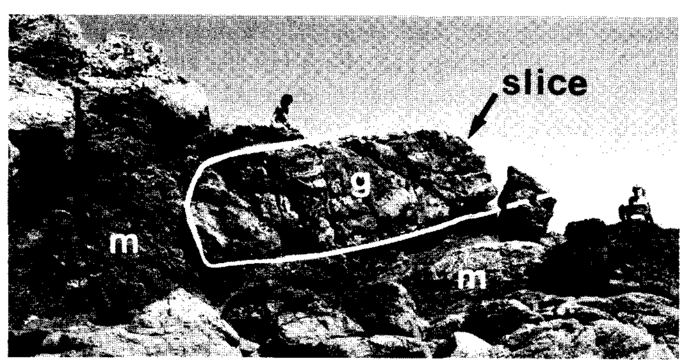


Figure 5. Photograph (looking east) of a slice of Garrison Schist (g) in Rosario thrust zone. The slice is surrounded by mudstone and chert of the Orcas Chert (m); see Figure 4 for location.

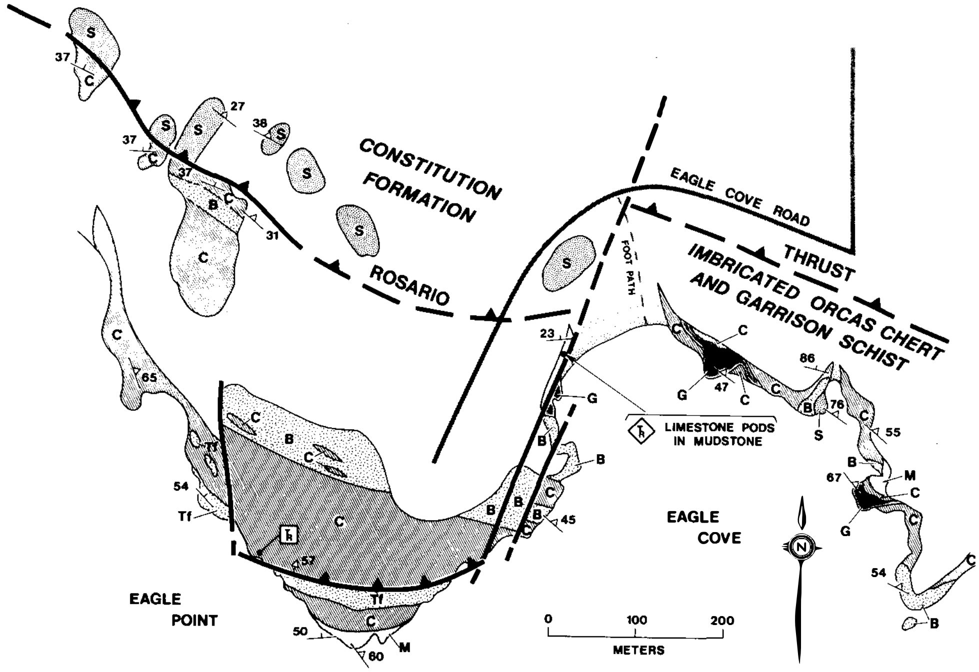


Figure 6. Outcrop map for Stop 3 in the Eagle Point and Eagle Cove area, San Juan Island (modified from Brandon, 1980); see Figure 4 for legend.

thrust within this imbricated fault zone. Here and elsewhere in the San Juan Islands, the slices of dark- to light-green Garrison Schist are localized within a 300- to 600-ft (100- to 200-m)-thick zone beneath the Rosario thrust. The Garrison in the South Beach area is a brecciated, fine-grained mafic schist consisting of chlorite+actinolite+epidote+plagioclase. Brecciation and cataclasis are attributed to tectonic emplacement of these fault slices. Structural relationships are best exposed at the location indicated on the map (Fig. 4) where a large, tabular slice 6 × 20 × 20 ft; (2 × 6 × 6 m) of Garrison is surrounded by disrupted black mudstone, ribbon chert, and minor unfoliated basalt of the Orcas (see Fig. 5). Note the small imbricate fault zone developed beneath the south side of this Garrison slice. These exotic slices were emplaced into the Rosario fault zone prior to the high-pressure regional metamorphism (lawsonite-prehnite-aragonite), as indicated by thin-section textures that show the cataclastic fabric of the schist cut by undeformed veins of aragonite.

Stop 3: Eagle Point and Eagle Cove, San Juan Island. Constitution, Orcas and Garrison Formations at the Rosario thrust.

Drive from Stop 2 toward Friday Harbor along Cattle Point road. Turn south (left) on Eagle Cove Drive, and park near Eagle Point at the end of the road. Walk southwest to seacliffs around the Triassic fossil locality labeled in Figure 6.

The Rosario thrust continues from South Beach northwestward to Eagle Cove (Figs. 2 and 6), where it also is a northeast-dipping fault zone containing exotic slices of Garrison Schist. Exposures of Constitution sandstone are restricted to the low outcrops north and northwest of Eagle Point. The Rosario thrust is mapped at the highest occurrence of chert and mudstone of the Orcas Formation (Fig. 6); the overlying Constitution Formation was relatively unaffected by faulting within the Rosario zone.

Radiolarian ribbon chert and volcanic flows of the Orcas Formation 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, personal communication, 1980). Note the mesoscale tight folds in the ribbon chert outcrops between the parking area and the point.

Slices of Garrison Schist are exposed in outcrops around Eagle Cove (Fig. 6). An entrained sequence of limestone pods in black mudstone is exposed on the west side of the cove. These pods, which have yielded Late Triassic conodonts (Savage, 1984), probably represent small olistoliths or slide blocks.

Stop 4: Deadman Bay, San Juan Island. Tethyan-fusulinid limestones in the Deadman Bay Volcanics.

Return to Cattle Point Road and drive north toward Friday Harbor. Turn west and connect with Bailer Hill Road, which turns into West Side Road where it meets the coast. Deadman Bay is a small cove located just south of where the road makes two sharp switchback turns (Fig. 7); park on the short road off West Side Road just before the first switchback. Walk southwest to the coast.

Deadman Bay is located at the southern end of a 2.4-mi (4-km) long fault slice of Deadman Bay Volcanics (Fig. 7). Gray and green ribbon chert exposed at the south side of the bay belonds to the Orcas Chert, which structurally overlies the Deadman Bay Volcanics along a northeast-dipping thrust fault. The trace of this fault follows the West Side Road to the north.

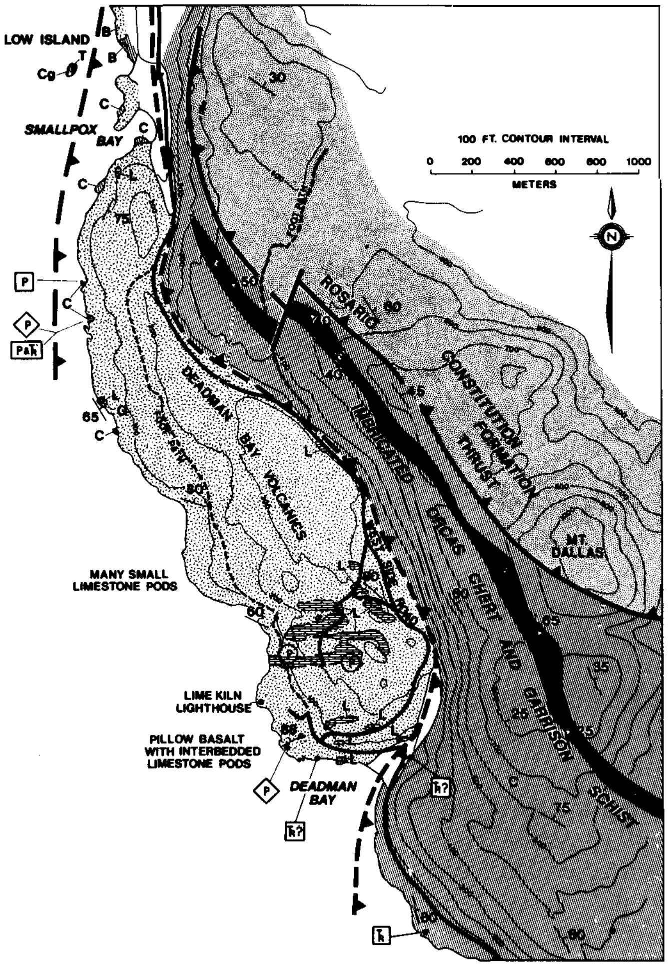


Figure 7. Geologic map for Stop 4 in Deadman Bay area, San Juan Island (modified from Danner, 1966; Vance, 1975; and unpublished mapping by Brandon and Cowan); see Figure 4 for legend.

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

Crinoid debris and fragments of other fossils can be found in many limestone pods. A thin limestone bed, clearly interbedded in the pillow basalt sequence at Deadman Bay, has yielded late(?) Leonardian (late Early Permian) conodonts (Fig. 7; M. J. Orchard, written communication, 1985). Danner (1966) has identified early Guadalupian (early Late Permian fusulinids) from limestone in the quarry to the north (Fig. 7). These fusulinids belong to the Tethyan or Asiatic fusulinid province, which suggests that the Deadman Bay Volcanics are exotic to North America. Trace-element geochemistry (high TiO_2 and light rare-earth element enrichment; Brandon and others, in prep.) indicates that the volcanics were probably erupted in an "oceanic island" setting.

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