Stratigraphy, depositional setting, and tectonic significance of the clastic cover to the Fidalgo Ophiolite, San Juan Islands, Washington

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The San Juan Islands of northwest Washington State comprise a diverse assemblage of Paleozoic and Mesozoic terranes amalgamated during a regional Cretaceous orogenic event. Detailed tectono-stratigraphy of the sedimentary cover to the Fidalgo Complex indicates the presence of several stratigraphically distinct units, which are described and formalized in this paper. The Fidalgo Complex and its sedimentary cover are the structurally highest rocks in the San Juan thrust system.

The Fidalgo Complex is a highly disrupted Middle to Upper Jurassic ophiolite with arc-related intrusives, volcanics, and sediments. The Trump unit is an informally named sequence of siliceous sediments, volcanic graywacke, and minor volcanics that occurs at the stratigraphically highest portion of the Fidalgo Complex. Complex facies, lithologies, and provenance indicate that deposition of this Oxfordian(?) to upper Tithonian unit occurred in an arc-proximal setting.

The upper Tithonian and younger Lummi Group (elevated here) lies depositionally above the Fidalgo Complex; locally the contact is an angular unconformity. The James Island Formation (new) is designated as a lower unit of the Lummi Group in the Decatur Island area. The chert-rich volcaniclastic sediments of the James Island Formation, locally containing ophiolitic debris, represent submarine-fan deposition within a tectonically active basin where basement blocks were uplifted along fault scarps.

Middle Cretaceous thrusting and lawsonite–prehnite–aragonite metamorphism predated deposition of the Obstruction Formation (new), which is inferred to unconformably overlie the Lummi Group – Fidalgo Complex. Metamorphism postdated the late Albian, as rocks of this age are metamorphosed. The Obstruction Formation (?Cenomanian–Turonian) does not have metamorphic lawsonite–prehnite–aragonite, which are characteristic of underlying terranes in the San Juan Islands. Instead, the Obstruction Formation contains clasts derived from underlying metamorphosed terranes in the San Juan Islands; some clasts show these high-pressure, low-temperature metamorphic minerals. The Obstruction Formation probably represents syn-thrusting sedimentation that occurred after the San Juan terranes were metamorphosed and rapidly brought to the surface by continued thrusting over a hanging-wall obstruction. Thrusting was most likely driven by the accretion of Wrangellia against the North American margin.

Les îles San Juan du nord-ouest de l'état de Washington incluent un assemblage varié de terranes, d'âge allant du Paléozoïque et au Mésozoïque, amalgamés au Crétacé durant un événement orogénique régional. La tectonostratigraphie détaillée de la couverture sédimentaire du complexe de Fidalgo indique la présence de plusieurs unités stratigraphiques distinctes qui sont décrites et formalisées dans le présent article. Les roches du complexe de Fidalgo et sa couverture sédimentaire occupent structuralement le sommet dans le système de chevauchement de San Juan.

Le complexe de Fidalgo est formé d'une ophiolite très fragmentée, d'âge jurassique moyen à tardif, et de roches intrusives, de volcanites et de sédiments associés à un arc. L'unité de Trump est une séquence informelle de sédiments siliceux, de grauwacke volcanique et de quelques volcanites qui apparaissent à la partie stratigraphique la plus haute. Les faciès complexes, les lithologies et la provenance révèlent que la sédimentation de cette unité, d'âge compris entre l'Oxfordien(?) et le Tithonien tardif, a eu lieu dans un contexte de proximité d'un arc.

Le Groupe de Lummi du Tithonien supérieur et le plus jeune (éléve ici) repose par-dessus le complexe de Fidalgo; localement le contact est une discordance angulaire. La Formation de James Island (nouvelle) représente une unité inférieure du Groupe de Lummi dans la région de l'île Decatur. Les sédiments volcanoclastiques riches en chert de la Formation de James Island, renferment localement des débris ophiolitiques, et ils représentent la sédimentation d'un cône sous-marin dans un bassin tectoniquement actif où les roches du socle furent soulevées le long d'escarpements de faille.

Le chevauchement au Crétacé moyen et l'assemblage métamorphique lawsonite–préhnite–aragonite sont des événements plus enciens que la période de l'accumulation des sédiments de la Formation d'Obstruction (nouvelle), qui est interprétée comme reposant en discordance sur le Groupe de Lummi – complexe de Fidalgo. Le métamorphisme est plus récent qu'Albien tardif car les roches de cet âge sont métamorphisées. La Formation d'Obstruction (?Cénomanien–Turonien) ne montre pas l'assemblage métamorphique lawsonite–préhnite–aragonite qui est caractéristique des terranes sus-jacents dans les îles San Juan. À la place, la Formation d'Obstruction renferme des fragments dérivés des terranes métamorphisés sous-jacents; certains fragments exhibent ces minéraux métamorphiques de haute pression et de basse température. La Formation d'Obstruction représente probablement une sédimentation synchevauchement qui est apparue après que les terranes de San Juan furent métamorphisés et exhumés rapidement à la surface par le chevauchement continu sur une une lèvre supérieure faisant obstruction. Le chevauchement était surtout poussé par l'accrétion du terrane de Wrangellia se butant contre la marge de l'Amérique du Nord.

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Introduction

The San Juan Islands of northwest Washington comprise a variety of Mesozoic and Paleozoic terranes that are situated between Wrangellia to the west and terranes of the North Cascades to the east (Fig. 1). Terranes of the San Juan Islands and the North Cascades were probably assembled in the early Late Cretaceous as Wrangellia was driven against the North American margin (Brandon and Cowan 1985; Brandon *et al.* 1988). This deformational event imbricated lithologically disparate units in the San Juan Islands into a series of thrust-bound packages that were subjected to high-pressure, low-temperature metamorphism (Glassely *et al.* 1976; Brandon 1980,

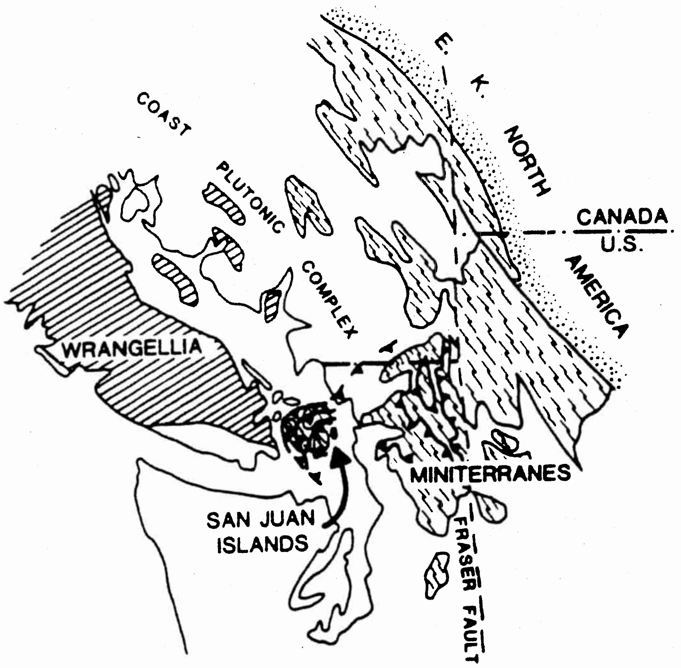

FIG. 1. Tectonic map of the Pacific Northwest showing major units involved in the middle Cretaceous thrust system. Ninety kilometres of dextral slip has been removed on the Fraser – Straight Creek fault. "Miniterranes" refers to numerous terranes that were affected by the regionally important middle Cretaceous orogenic event. "E. K. North America" represents the probable North American shoreline in the Early Cretaceous.

1982; Brandon *et al.* 1983). Thrusting and metamorphism were complete and uplift had occurred by late Santonian time, because adjacent Nanaimo Group sediments of that age contain clasts of metamorphosed San Juan lithologies.

Within the diverse terranes of the San Juan Islands are numerous upper Mesozoic clastic units whose provenance, structure, and tectonic history provide important information concerning the Jura-Cretaceous tectonic history of the San Juan Islands. This study provides the first detailed tectono-stratigraphic analysis of clastic rocks exposed in the eastern San Juan Islands (Fig. 2), within or overlapping the Decatur terrane (Whetten *et al.* 1978), and provides details of the tectonic events associated with terrane juxtaposition in the San Juan Islands.

The structurally highest thrust sheet in the San Juan Islands is the Decatur terrane, which comprises two main elements: (1) a Middle to Upper Jurassic ophiolite with Upper Jurassic arc-related volcanics and intrusives as well as coeval pelagic sediments, all of which are collectively known as the Fidalgo Complex (Brown 1977*a*, 1977*b*; Brown *et al.* 1979; Brandon *et al.* 1988); and (2) an Upper Jurassic (Tithonian) to (?)Lower Cretaceous terrigenous blanket that is herein referred to as the Lummi Group (revision of Vance (1975); see also Carroll (1980) and Garver (1985)).

The Decatur terrane was disrupted and metamorphosed prior to deposition of the lower Upper Cretaceous Obstruction Formation. Recognition of provenance and tectonic history of these chert-lithic clastic rocks of the Obstruction Formation marks a significant step forward in our understanding of middle Cretaceous tectonics within the San Juan Islands. The Obstruction Formation is interpreted as representing synthrusting deposits associated with a regionally important orogenic event that affected rocks throughout northwest Washington and southwest British Columbia. Knowledge of the clastic units in the San Juan Islands tells of terrane interactions within the San Juan Islands and between the San Juan terranes, North America, and Wrangellia.

The following descriptions of the stratigraphy in the eastern San Juan Islands includes, most importantly, the clastic cover of the Fidalgo Complex. The first section, however, presents new data that partly clarify the age and stratigraphy within the Fidalgo Complex.

Nomenclature

The work summarized in this report is the first detailed stratigraphic analysis of the upper Mesozoic clastic rocks of the eastern San Juan Islands. Vance (1975) proposed that the Lummi formation include most upper Mesozoic clastic rocks in the central and eastern San Juan Islands. This study identifies several distinctive stratigraphic units within Vance's Lummi formation. Therefore, I propose the following changes:

(1) Lummi formation is elevated to group status.

(2) The James Island Formation is proposed for rocks in the Decatur Island area that correspond to the lower part of the Lummi Group; elsewhere the Lummi Group is undifferentiated.

(3) A well-defined stratigraphic break marked by a sharp transition from siliceous sediments and graywacke to terrigenous sediments marks the base of the Lummi Group.

(4) Clastic rocks below this prominent stratigraphic break are removed from the Lummi Group and placed, more appropriately, in the Fidalgo Complex. These sediments belong to the informal Trump unit.

(5) Younger, chert-rich clastic rocks that lack metamorphic lawsonite – prehnite – aragonite are designated separately as the Obstruction Formation.

Fidalgo Complex—new data

The Fidalgo Complex comprises (1) a dismembered Middle to Upper Jurassic ophiolite complex, (2) Upper Jurassic intermediate to silicic intrusives, and (3) overlying and (or) facies-equivalent siliceous sediments and volcanic graywacke (this report; Gusey 1978; Brown *et al.* 1979; Brandon *et al.* 1988). Most workers agree that the ophiolitic sequence was intruded by Upper Jurassic intermediate plutonic and associated volcanic rocks that are probably island-arc generated (Brandon *et al.* 1988). Complex facies relationships, structural disruption, and discontinuous exposures make our understanding of the stratigraphy within the Fidalgo Complex fragmentary at best. Outlined below are several previously unrecognised stratigraphic and petrographic elements of the sedimentary and volcanic portion of the Fidalgo Complex.

Volcanic rocks of the Fidalgo Complex

Highly disrupted pillow basalts occur on southern Decatur Island, the Sperry Peninsula on Lopez Island, and numerous small islands in the vicinity (Fig. 3). These pillow basalts are probably related to the original ophiolitic portion of the Fidalgo Complex and therefore predate the intermediate plutonic suite (Brandon *et al.* 1988). These pillow basalts occur as a thick (>400 m) sequence of brown-weathering, highly fractured pillow basalt, flows and breccias that have minor interbeds of green – gray and light-gray bedded chert, black and red siliceous argillite, and light-brown-weathering fine-grained

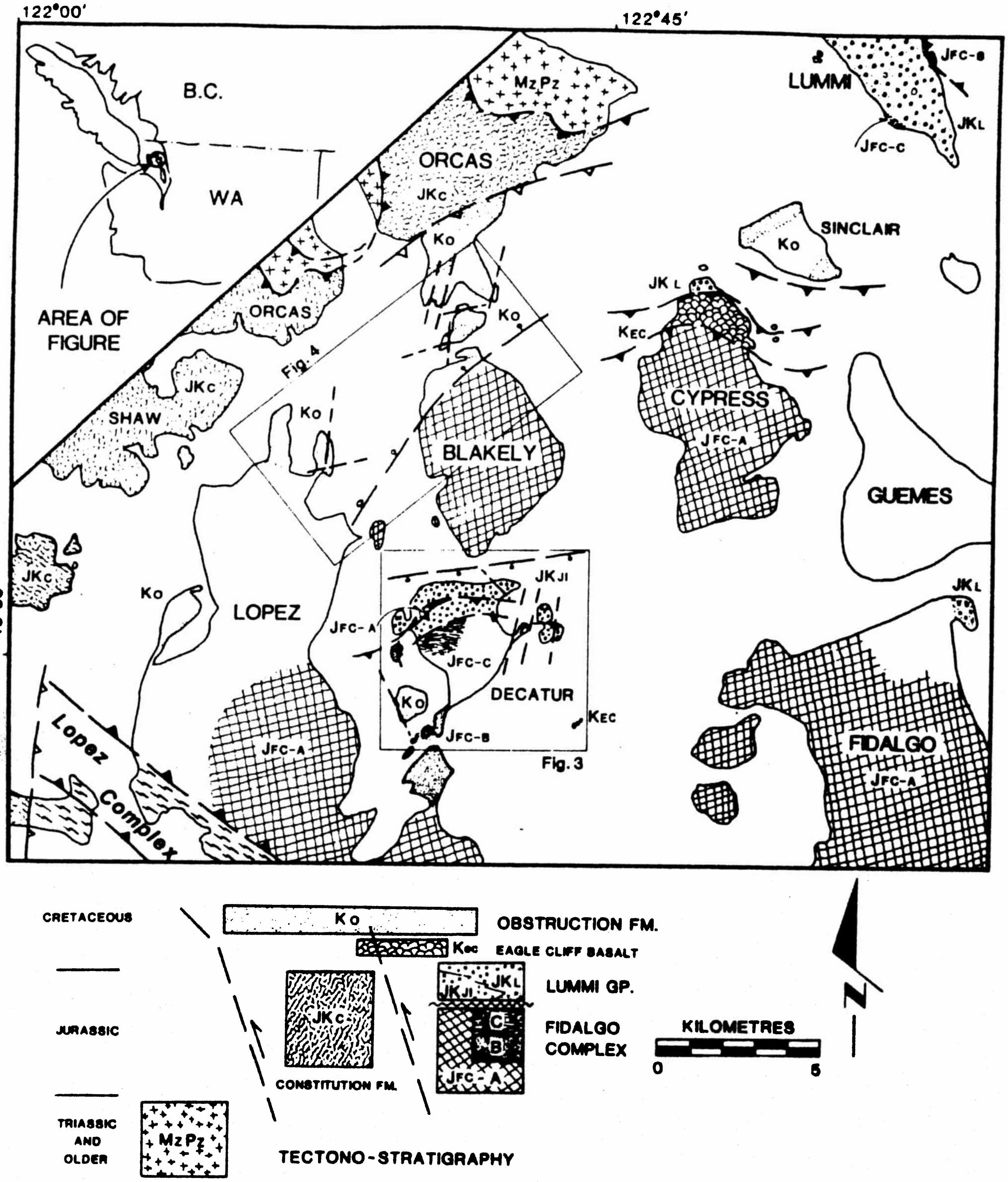

FIG. 2. Geologic map of the eastern San Juan Islands. MzPz—undifferentiated Paleozoic and Mesozoic terranes structurally low within nappes of San Juan Islands; includes Orcas chert and Turtleback Complex. JKc—Late Jurassic and (?)Early Cretaceous Constitution Formation; metagraywacke, chert and greenstone. JFC—Middle to Late Jurassic Fidalgo Complex, JFC-A: predominantly ultramafic and slightly younger intermediate intrusive rocks, also includes Fidalgo Complex undivided, JFC-B; predominantly pillow basalt, JFC-C; predominantly chert, argillite, and graywacke. JKL—Late Jurassic to (?)Early Cretaceous Lummi Group; sandstone, mudstone, and conglomerate, James Island Formation where designated (JKJI). KEC—middle Cretaceous basalt of Eagle Cliff; flattened pillow basalt and breccia with minor interpillow limestone. Ko—middle Cretaceous (?Cenomanian–Turonian) Obstruction Formation; sandstone, chert-pebble conglomerate, and shale. Lopez Complex comprises north-dipping, imbricated, lensoidal panels of all of the above lithologies and probably represents a wide fault zone.

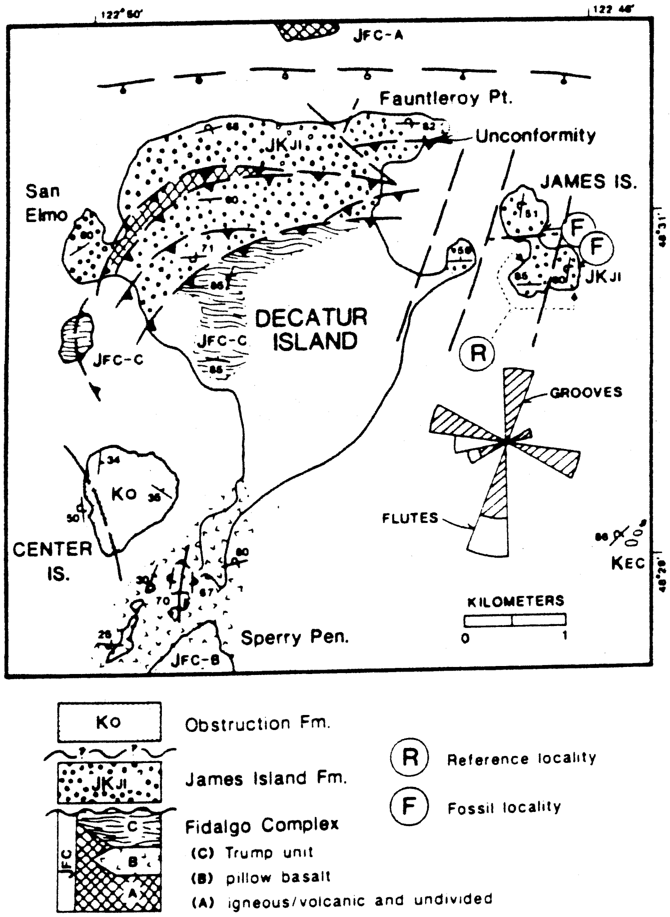

FIG. 3. Geologic map of the Decatur Island area. The paleocurrent rose diagram represents 24 measurements from the James Island Formation only. There is a postulated unconformity between the Fidalgo Complex and the Obstruction Formation. Reference and fossil localities are discussed in the text. See Fig. 2 for map location and explanation of KEC unit.

sandstone. Analyses of the basalts by Brandon *et al.* (1988) indicate that these are ocean-floor or ridge-generated basalts. Interbedded clastic sediments in the southern Decatur Island area, however, indicate proximity to an emerged landmass.

A thick sequence of breccia is spatially associated with the pillow basalts and the intrusive portion of the Fidalgo Complex. Exposures of these breccias are very good on the shores of Thatcher Bay on Blakely Island (Fig. 4) and on the western shores of Lopez Island in Lopez Sound (Fig. 2). These breccias are probably greater than 200 m thick and contain coarse, angular debris that consists primarily of mafic volcanic and mafic plutonic clasts that are very poorly sorted and nonstratified. A lack of intermediate plutonic debris differentiates these breccias from those described by Brown *et al.* (1979) to the east on Fidalgo Island, which may be younger.

Age

The age of the basaltic rocks and the breccias is constrained by radiolaria extracted from interbedded siliceous sedimentary rocks within the volcanics. On southern Decatur Island the most age-diagnostic radiolaria are Callovian or Oxfordian (see Appendix Table A1). Other localities yield less-age-specific radiolaria, but the ages fall within either the Late or Middle Jurassic (Fig. 5). Considering the maximum overlap, these pillow basalts are probably Oxfordian and older.

Sedimentary rocks of the Fidalgo Complex

The Trump unit, informally named for rocks on Trump Island (Fig. 4), is a highly disrupted sequence of siliceous sediments, argillite, medium-grained sandstone, and minor pillow basalt that makes up the youngest and stratigraphically highest portion of the Fidalgo Complex. No contact is exposed between the underlying volcanics and the Trump unit, but its stratigraphic position is inferred from its age. Minor fine-grained volcanic-rich sandstone interbedded within the underlying pillow basalt unit and within the Trump unit suggests stratigraphic continuity between these different units.

The stratigraphically lowest rocks of the Trump unit are pillow basalts overlain by about 50 m of fine- to medium-grained, volcanic-lithic to volcanic-arkosic sandstone. These clastic sediments are probably overlain by black argillites and siliceous sediments with minor thin-bedded sandstones. Locally, as on the southwest side of Trump Island, these predominantly fine-grained sediments are cut by diabase dikes. Stratigraphic relations within these sediments are only poorly known because of structural disruption. On northeastern Decatur Island (Fig. 3), black argillite, chert, and volcaniclastic sandstone occur directly below a well-displayed angular unconformity that separates these more "oceanic" sediments from the overlying submarine fan complex of the James Island Formation, described below.

Sandstones within the Trump unit are of two types, both of which had a juvenile arc source. The first suite is dominated by volcanic plagioclase, which is euhedral and commonly embayed, with minor volcanic lithics and volcanic quartz. Polycrystalline quartz and (or) chert are virtually absent. A second suite of sands is dominantly volcaniclastic, with minor amounts of chert; it is petrographically similar to the unconformably overlying James Island Formation and probably from a source similar to the first suite, although more diverse because of uplift (Fig. 6). The volcanic source seen in these sandstones may reflect erosion of a contemporaneous volcanic arc.

Age

Red siliceous argillite on southwest Trump Island has yielded both an early Tithonian assemblage of radiolaria (Whetten *et al.* 1978) and a late Tithonian assemblage (this report, see Appendix Table A1). Fossils in the overlying James Island Formation contain a late Tithonian *Buchia* species (Fig. 5). On Lummi Island, radiolaria extracted from siliceous sediments conformably below an undated turbidite sequence give a late Tithonian age (Appendix Table A1; Fig. 6). On Fidalgo Island, siliceous sediments, which overlie and are interbedded with the arc-related volcano-plutonic rocks, are Oxfordian and younger (Brandon *et al.* 1988). In summary, these ages indicate that the uppermost stratigraphic level of the Fidalgo Complex, consisting primarily of sedimentary rocks and minor volcanics, is restricted in age to Oxfordian through late Tithonian (Fig. 5). The age of the unconformity exposed on Decatur Island must be within the late Tithonian.

Interpretation—volcanics, breccias, and Trump unit

Geochemical data, intrusive relations, and radiometric age determinations clearly indicate that the Fidalgo Complex comprises an ophiolite that was intruded by arc-related igneous rocks with associated volcanics (Brown *et al.* 1979; Brandon *et al.* 1988). Radiolaria from chert interbedded with basalts with ocean-floor chemistry (Brandon *et al.* 1988) indicate an

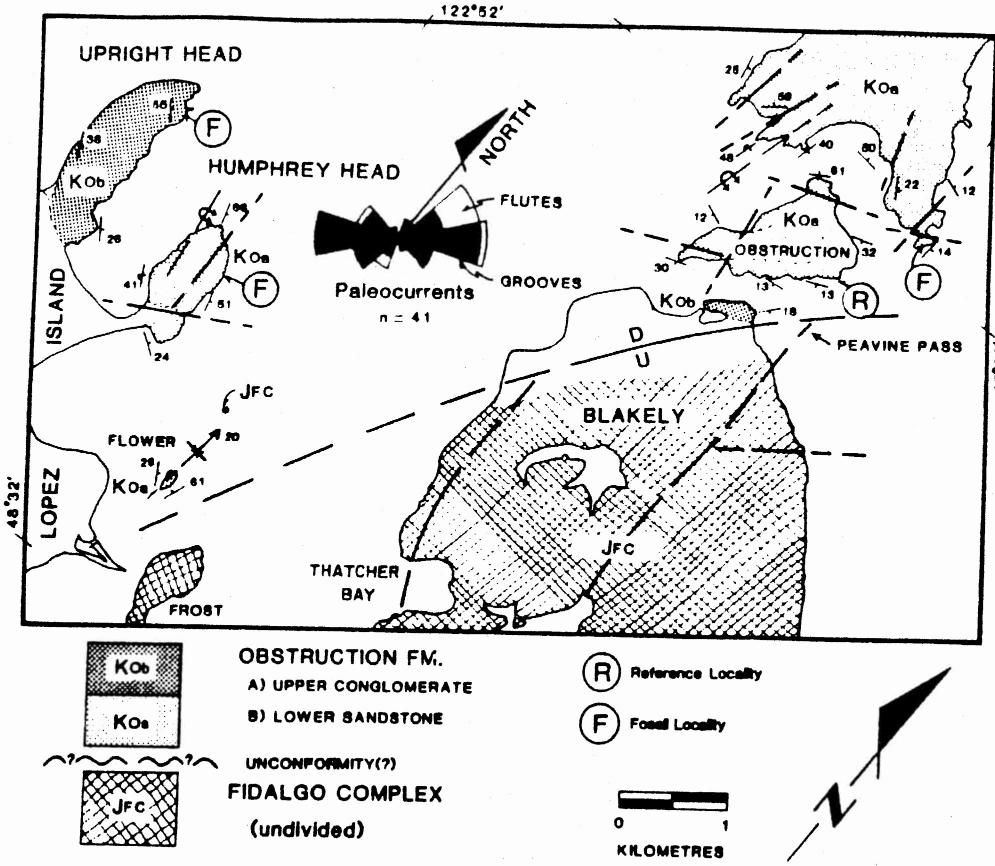

FIG. 4. Geologic map of the Obstruction Island area. Note that north is not straight up on the map. Paleocurrents are from the lower sandstone member of the Obstruction Formation. Mapping on Blakely Island by W. E. Glassely (unpublished data). See Fig. 2 for map location.

Oxfordian or older age for the ophiolite. Although minor, interbedded fine-grained, volcanic-rich sediments on southern Decatur Island suggest proximity to an arc, perhaps evidence for a back-arc origin for the original ophiolite.

The Trump unit sediments, with volcanically derived sandstones, were probably deposited in isolated and topographically complex basins adjacent to an active arc. The interbedded pelagic and clastic sediments as well as stratal discontinuity attest to basin comlexity. The underpinnings of this active arc are preserved in the intermediate–silicic volcano-plutonic suite of Fidalgo Island. Radiolaria and radiometric ages suggest that this arc, with its associated sediments, was active from Oxfordian through late Tithonian time.

Lummi Group

The Lummi Group, as defined here, is composed of well-bedded, volcanic-rich terrigenous sediments in numerous locations in the eastern San Juan Islands (Fig. 2). On southern Lummi Island, the Lummi Group occurs above a prominent stratigraphic break that separates siliceous sediments of the Fidalgo Complex below from the overlying well-bedded sandstones of the Lummi Group. The upper contact of the Lummi Group is nowhere exposed but is inferred to be an unconformity with the overlying Obstruction Formation. The Lummi Group is subdivided into a lower James Island Formation in the Decatur Island area only; elsewhere the Lummi Group remains undifferentiated (Fig. 5). Sediments within the Lummi Group have undergone prehnite-grade metamorphism but locally contain metamorphic aragonite and lawsonite (Carroll 1980; Brandon *et al.* 1988).

James Island Formation

The James Island Formation is a newly proposed name for a well-stratified yet disrupted sequence of thin- to thick-bedded sandstone, poorly stratified conglomerate, and mudstone that unconformably overlies the Fidalgo Complex. This unit is well exposed on James Island and Decatur Island, where it corresponds to the lower part of the Lummi Group. It is marked by distinct vertical and lateral facies changes, but three distinct stratigraphic units can be recognized (Fig. 7). A stratotype locality is designated as the entire southern to southwestern shoreline of James Island, where the three distinct facies can be seen (Fig. 3).

The lower sandstone unit (Fig. 7) is a thick (~400 m) sequence of medium- to thick-bedded turbiditic sandstone and minor conglomerate that overlies the Trump unit with an angular unconformity well exposed on Fauntleroy Point of Decatur Island (Fig. 3). The entire sequence generally coarsens upward. Poorly preserved graphitic plant fragments are common at the tops of some turbiditic beds; grooves and flutes, the most common sole marks, indicate a transport direction to the west (Fig. 3).

The middle conglomerate unit is a 200–400 m thick sequence of pebble to boulder conglomerates that thicken and become finer grained in a westerly direction, the transport direction. Boulder conglomerates with clasts up to 1 m in size are well exposed at the type area on James Island. Typically, the base of this conglomerate is gradational from the lower sandstone unit, but locally the contact is sharp; on the northwestern side of Decatur Island this unit has a scoured base with at least 10 m of relief. These conglomerates are organized into

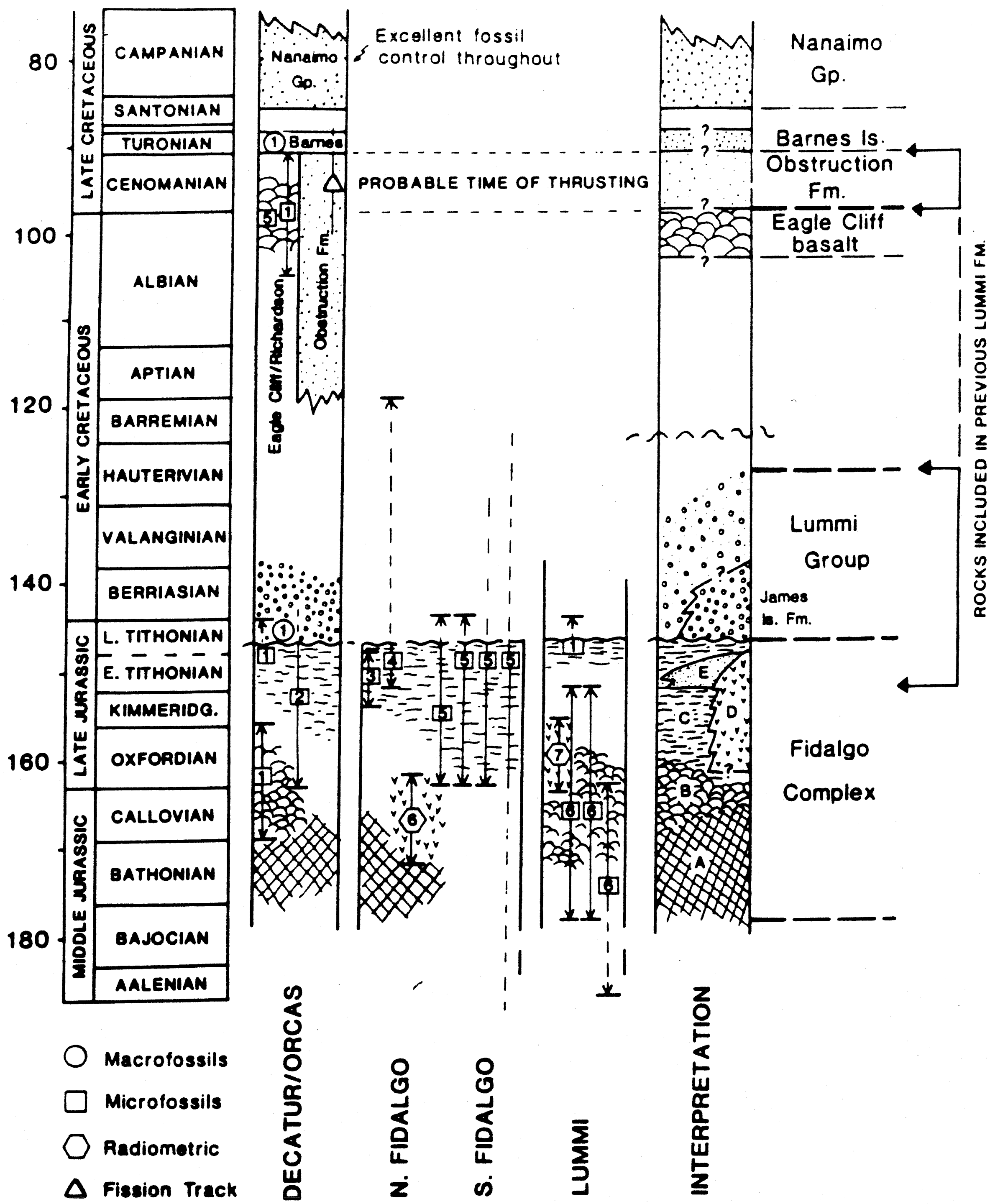

FIG. 5. Age control and stratigraphic position of units in the eastern San Juan Islands. Fossil data are in Appendix Table A1. Hexagons denote U–Pb concordant ages. Fission-track age is from this study (see Appendix Table A3). Errors in ages or calls shown by arrows. Original or modified original reference (reexamined radiolaria) given by number in symbol: (1) this report, (2) Brandon *et al.* (1988), (3) Gusey (1978), (4) Brown (1977*b*), (5) Carroll (1980), and (6) Whetten *et al.* (1978). Units in the Fidalgo Complex are schematically shown as follows: (A) ultramafic rocks, (B) pillow basalts, (C) pelagic sediments and minor volcanics, (D) tonalite intrusives and volcanics, and (E) graywacke. Time scale from Palmer (1983).

crudely graded, inversely graded, and (or) weakly stratified beds with minor interbeds of thin-bedded sandstone. Disorganized, matrix-supported boulder conglomerates and horizontally bedded conglomerates are much less common. Rare, tabular cross-stratified conglomerates are present in some of the finer grained units.

The upper mudstone unit, the uppermost unit recognized within the James Island Formation in the Decatur area, is a thick (500–600 m?) sequence of well-stratified black mudstone and irregular basalt blocks that sharply overlie the middle conglomerate unit. The contact between these units is well displayed on the southwest shore of James Island; the top of this unit is not exposed. The black mudstone contains laminae and thin beds of siltstone and fine-grained sandstone, medium- to

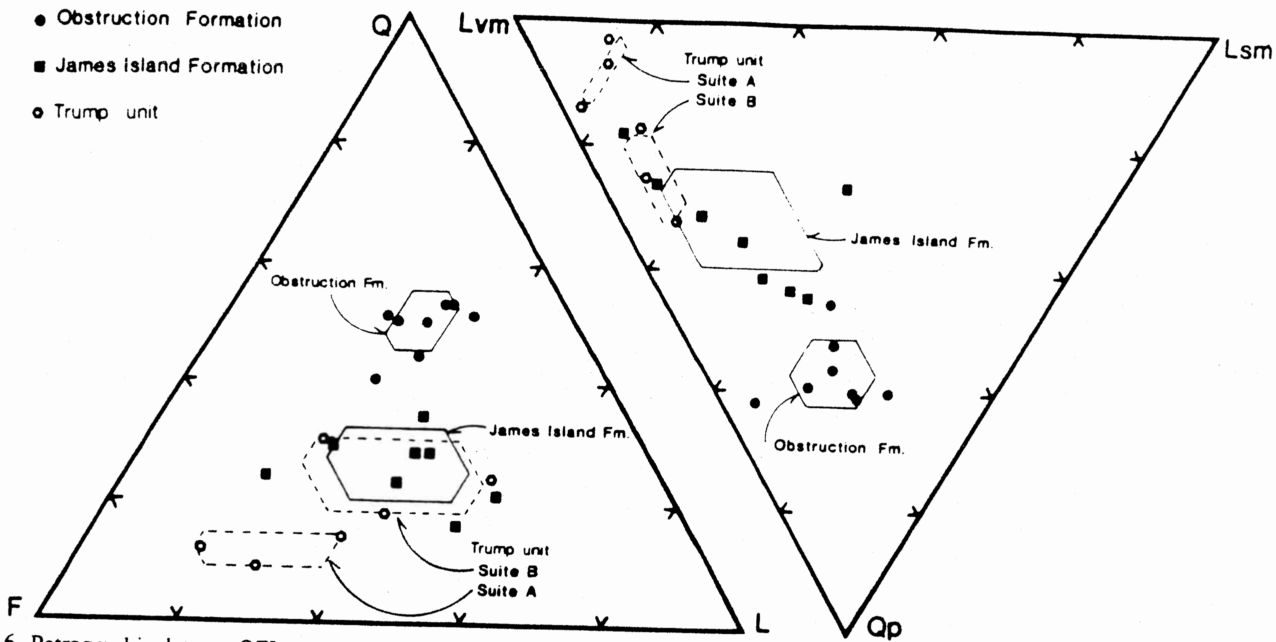

FIG. 6. Petrographic data on QFL and QpLvmLsm plots (see footnotes in Appendix Table A2 for explanation of parameters). Fields for each suite represent the standard deviation from the calculated mean of each group.

thin-bedded turbidites, and basalt-pebble mudstone beds. Two thin (<0.5 m) tuff beds occur near the base of this unit. Locally, large blocks of basalt, tens of metres in diameter, occur within the mudstone. Small-scale slump folds (metre scale), some delimited by limey concretions, are also present but are uncommon.

Depositional environments

The James Island Formation is interpreted as a progradational submarine-fan assemblage. The lower sandstone unit represents a midfan depositional setting, as evidenced by medium- to thick-bedded sandstones, minor conglomerates, beds with scoured bases, minor channelling, and complete Bouma sequences. The middle conglomerate unit is interpreted as a fan-channel conglomerate. Large clasts, which include ultramafic rocks of the underlying Fidalgo Complex, must have been derived from adjacent fault scarps that were responsible for uplifting basement material and shedding it into feeder canyons. The presence of this basement material, discussed fully below, attests to tectonic activity within the basin during sedimentation. The upper mudstone unit is interpreted as representing a slope facies because of its fine-grained nature, slumps, pebbly mudstones, and large blocks. These blocks probably fell from scarps that were exposed along the slope and presumably represent portions of the underlying Fidalgo Complex. The sharp contact between the slope facies and the channel facies probably represents rapid channel avulsion.

Age

The lower sandstone unit has several beds that contain fragments and whole shells of the bivalve *Buchia piochii* (Appendix Table A1), an index fossil for the late Tithonian (Jeletzky 1984). These fossils were recovered from two localities on eastern James Island. One bed contains hundreds of individuals; other *Buchia* species were not identified. All three units contain Jura-Cretaceous belemnites, and the upper mudstone unit contains poorly preserved *Orbiculiforma* radiolaria that are the same general age. An olistolith in a tectonic mélange

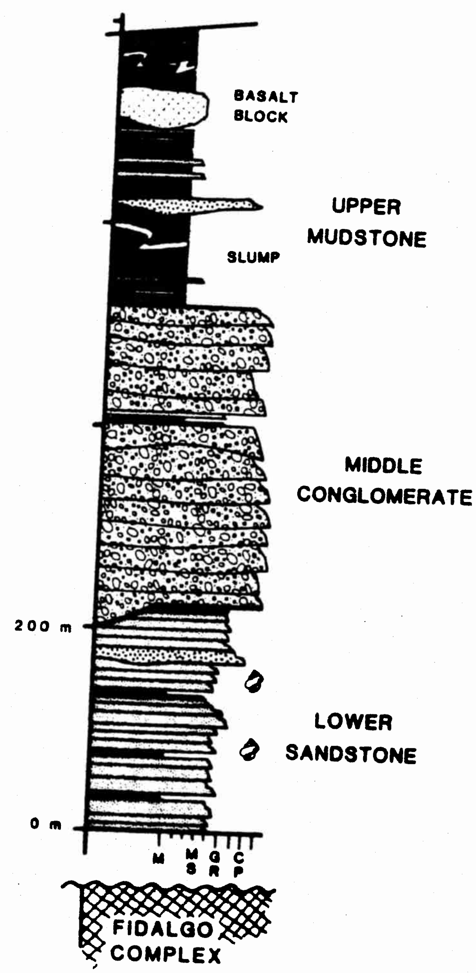

FIG. 7. Generalized stratigraphic section for the James Island Formation. Thickness of units is approximate, and bedded relationships are schematic. See text for a detailed description of lithologies. The top of the unit is cut by a fault. Grain-size scale: M, mudstone; MS, medium sand; GR, granule; and CP, coarse pebble. Fossil symbol refers to the stratigraphic location of *Buchia*.

within the Lopez Complex contains a Valanginian *Buchia* (Brandon *et al.* 1988). Although the affinity of these sediments is not clear, they may be part of the Lummi Group, as are many clastic units in the Lopez Complex. In sum, the James Island Formation is late Tithonian in age and younger (Valanginian?).

Provenance and source area

Sandstones from the lower sandstone unit were point counted according to the Gazzi–Dickenson method (Dickenson 1970; Ingersoll *et al.* 1984). Although the rocks were metamorphosed to prehnite–pumpellyite facies, recrystallization is minimal. Locally, these sediments contain metamorphic lawsonite and aragonite (Carroll 1980). The effects of metamorphism can be easily assessed so as to ascertain original detrital species.

The sandstones are chert-rich, volcanic-lithic sandstones (Appendix Table A2; Fig. 6). Among the volcanic grains, subequal proportions of lathwork, microlitic, and felsic textures are represented. Volcanic clasts span the compositional spectrum from mafic to silicic. The feldspar detritus, a substantial population of which is clearly volcanically derived, is overwhelmingly plagioclase rich. Metamorphic clasts are dominated by nonfoliated greenschist-facies metavolcanic fragments as well as by detrital serpentine. Accessory detrital minerals include epidote, hornblende, pyroxene, and prehnite.

The conglomerates of the James Island Formation contain two distinct although mixed clast populations. The first is coarse and angular ophiolitic debris that was probably locally derived. Pebble counts in the coarser beds and visual inspection of boulder beds indicate that the conglomerate is dominated by basalt (40%), gabbro (16%), and ultramafic debris (includes pyroxenite and serpentinite, 8%). This debris is clearly derived from the underlying Fidalgo Complex; minor (<5%) amounts of tonalite are presumably derived from the late-stage arc-related intrusives of the Fidalgo Complex. Rare clasts of massive sulfide up to 1 m in diameter are also presumably locally derived.

Mixed with this ophiolitic debris are smaller and more rounded clasts of volcanic and sedimentary rock fragments. This more mature fraction includes chert (15–50%), intermediate to felsic volcanics (5–10%), and argillite (5–10%). The total volume of this fraction depends on the amount of mixing with the ophiolitic debris; some beds are exclusively sedimentary and volcanic material, whereas others are almost exclusively composed of ophiolitic debris.

Chert clasts are predominantly light green to light gray and are rarely veined; many contain abundant radiolaria. More than 200 chert pebbles were processed, of which about 20% yielded radiolaria. The species identified restrict the age of the source terrane to the Middle to Late Jurassic (Bajocian to Tithonian; C. Blome, personal communication, 1985; See Appendix Table A1). This age range is consistent with the source being reworked siliceous sediments of the Fidalgo Complex or equivalent rocks. Older chert sequences, such as the Triassic – Lower Jurassic Orcas chert, could not be possible source terranes for the clastic chert within the James Island Formation.

The mixed ophiolitic and volcanic provenance seen in the conglomerates and the volcanic provenance seen in the sandstones indicate a volcanic source area that may have been built on older (Middle to Late Jurassic) oceanic crust, of which the Fidalgo Complex may represent a fragment. The well-worked nature of the volcanic debris and the volumetrically minor tuff beds suggest that volcanic activity may have occurred contemporaneously but was removed from the site of deposition.

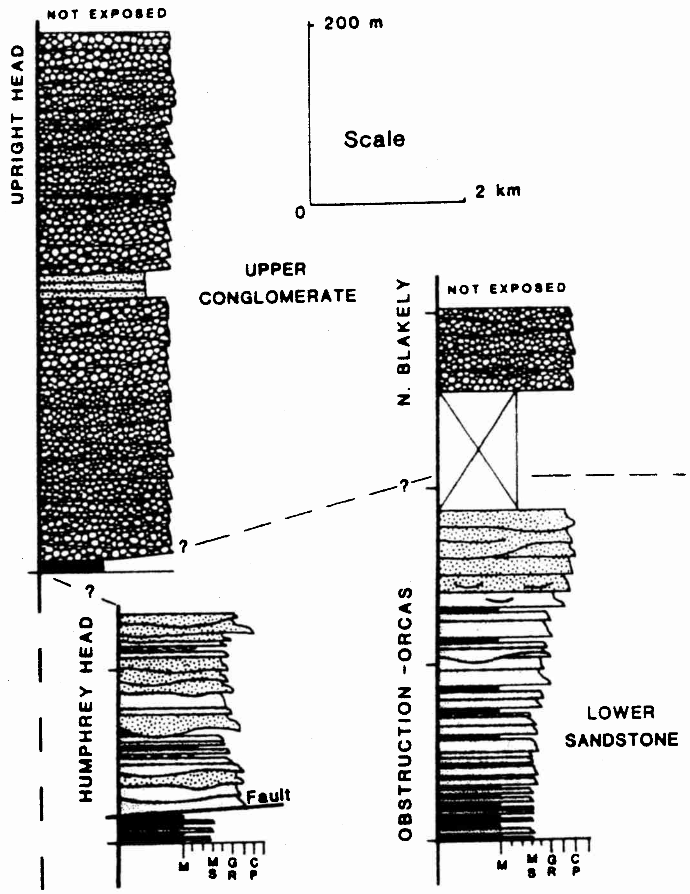

FIG. 8. Generalized stratigraphy of the Obstruction Formation. Sections are generalized from the areas shown to the left of each column. The contact between the lower sandstone and the upper conglomerate is not unequivocably exposed; its nature is described in the text. Same grain size scale as in Fig. 7.

Basalt of Eagle Cliff

Well-bedded, beautifully preserved, often flattened, green pillow basalts and breccias with minor interbedded black mudstone and pink tuffaceous limestone occur on northern Cypress Island (Eagle Cliff) and southeast of Decatur Island (Figs. 2, 3). This unit was referred to as the Eagle Cliff Porphyry by McLellan (1927); the name is partially resurrected because this unit is different from nearby basaltic units. These pillow basalts were considered part of the Fidalgo Complex until probable Albian–Cenomanian forams were recently recovered from northwest Cypress Island (Appendix Table A1). Lithologies and tentative biostratigraphy suggest that this unit is equivalent to the light rare-earth element (LREE)-enriched pillow basalts of the Richardson locality within the Lopez Complex (Brandon *et al.* 1988). Further dating and geochemical analysis of these basalts should verify the assumed equivalence of the basalts of Eagle Cliff to those within the Lopez Complex. Interbedded black mudstone – siltstone within these basalts suggest proximity to a clastic source during deposition.

Obstruction Formation

The Obstruction Formation is a newly proposed name for

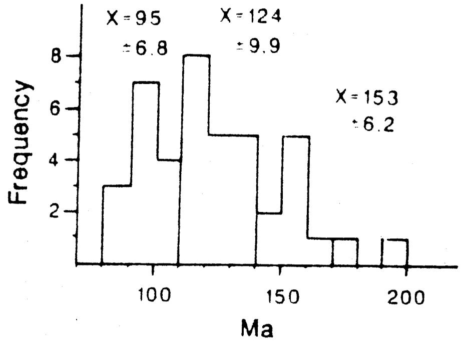

FIG. 9. Histogram showing 41 fission-track age determinations from one locality of the upper conglomerate unit of the Obstruction Formation. Outlined peaks have the calculated mean and standard deviation; these ages are approximate because peaks (which should have a Poisson distribution) overlap somewhat. See Appendix Table A3 for data and methods.

well-bedded sandstone and distinct chert-pebble conglomerate exposed on Obstruction Island, southeastern Orcas, northern Lopez, Sinclair, Flower, and Center islands (Figs. 2–4). Within the Obstruction Formation, two distinct units can be recognised: a widely distributed lower unit that is predominantly sandstone with minor conglomerate, and an upper unit that is almost exclusively well-rounded pebble conglomerate (Fig. 8). The contact between the Obstruction Formation and underlying units is not exposed and remains a major unsolved problem. The upper contact is also not exposed.

A single stratotype is impossible to define for the Obstruction Formation because either faulting or water prohibits the display of a continuous section through both the lower sandstone unit and the upper conglomeratic unit. The entire perimeter of Obstruction Island, especially the south shore, is designated as the type area (Fig. 4). Exposures of the upper conglomerate are displayed across Peavine Pass (south of Obstruction Island) at the northernmost head of Blakely Island (Fig. 4).

In the Obstruction Island area, the lower sandstone unit occurs as a 400 m thick, coarsening-upward and bed-thickening-upward sequence that represents progradation of a submarine-fan lobe (Fig. 8). The base of this unit is nowhere exposed. One hundred metres of medium- to coarse-grained, thin-bedded turbidites passes gradationally up into a 200 m thick sequence of medium- sand-grained to granule-grained, medium- to thick-bedded turbidites. This sequence is overlain by a 90–100 m thick facies of medium- to thick-bedded coarse-sandstone to pebble conglomerate in which beds are often thick and amalgamated. About 5 km to the southwest on Humphrey Head, a distinctly more proximal facies of thin- to thick-bedded, medium- to coarse-grained sandstone and pebble and cobble conglomerate with minor olive-green siltstone represents the lower sandstone unit. This facies change to the southwest, as well as well-defined scour and groove marks, suggests a paleotransport direction to the northeast (see paleocurrent data in Fig. 4).

The upper conglomerate unit of the Obstruction Formation is composed of about 800 m of well-rounded pebble conglomerate that is interpreted as overlying the lower sandstone unit (Fig. 8). This unit is well exposed on the small head on northern Blakely Island and on the entire perimeter of Upright Head on northern Lopez Island (Fig. 4). Poor exposures of similar lithologies on the west shore of Fisherman's Bay on western Lopez Island may be equivalent but are distinctly finer grained. The upper conglomerate is approximately 800 m thick on Upright Head and 100 m thick on northern Blakely Island; the top of the unit is not exposed. The base of the unit is exposed in a small roadcut in Odlin Park at the southwestern edge of Upright Head (Fig. 4). Here, cobble conglomerate rests above black shale and sandstone that are probably the upper part of the lower sandstone member. The upper conglomerate unit comprises almost exclusively well-rounded pebble and cobble conglomerate with only very minor coarse-sandstone interbeds. The conglomerate is predominantly clast supported and organized, with minor pebbly sandstone interbeds. Well-graded conglomerate beds, horizontal stratification, and stratigraphic continuity with the underlying turbiditic unit suggest that the upper conglomerate unit is the channelled portion of the same submarine-fan system represented by the lower sandstone unit. Together, both units within the Obstruction Formation define a coarsening-upward progradational submarine fan sequence.

Age

The age of the Obstruction Formation is constrained to the middle Cretaceous. The only fossils from the Obstruction Formation are long-ranging bivalves (Appendix Table A1). The Obstruction Formation lacks the structural attributes and metamorphic minerals seen in the Lummi Group and therefore is probably younger.

Fission-track age determination of detrital zircons provides the best control for the age of the Obstruction Formation. Figure 9 shows a summary of fission-track ages of 41 detrital zircons from a sample of the upper conglomerate unit of the Obstruction Formation. Data from this sample show several peaks that correspond to the uplift (crustal blocks were uplifted and cooled through a temperature of about 200 ± 30°C; see references contained in Johnson *et al.* (1986)) of different source terranes that supplied sediment to the Obstruction Formation basin (Fig. 9; Appendix Table A3). The youngest peak at 95 ± 6.8 Ma represents a maximum age of deposition for the Obstruction Formation. The abundance of first-cycle volcanics suggests that these may be volcanic zircons; therefore, the peak very closely represents the age of deposition. The next oldest peak at 123 ± 9.9 Ma represents the Early Cretaceous uplift of an unknown source to the Obstruction Formation sediments. Probable overlap between this peak and the young peak suggests that the 95 Ma peak may be slightly older. A Late Jurassic peak (Fig. 9; 152 ± 8.0 Ma) probably represents partial contribution of sediment from the Decatur terrane, which shows uplift ages of this time (Johnson *et al.* 1986). This probable contribution of sediments from the Decatur terrane reinforces the postulated depositional tie to the overlying Obstruction Formation. Fission-track data from Johnson *et al.* (1986) also suggest that the uplift of blocks that fed the Obstruction Formation was middle Cretaceous and older.

Upper Turonian strata on Barnes Island (north of Orcas Island) lack the pervasive cleavage and folding seen in the Obstruction Formation. The spatial proximity and relatively undeformed nature of the Barnes Island strata may place a younger age limit on the deposition and deformation of the Obstruction Formation, but the possibility of juxtaposition of these two units by large-scale horizontal transport cannot be neglected. In sum, the age constraints of the Obstruction Formation suggest a Cenomanian–Turonian depositional age.

Provenance of the Obstruction Formation

Unlike the Lummi Group sandstones, the Obstruction Formation sandstones do not contain metamorphic lawsonite–prehnite–aragonite. Instead, there is evidence that these minerals occur as detrital grains. Carbonate, clay, and white mica constitute the matrix of all the Obstruction Formation sandstones examined. The lack of diagnostic metamorphic minerals in the Obstruction Formation probably indicates that this unit did not suffer the high-pressure, low-temperature metamorphism characteristic of underlying terranes in the San Juan Islands. However, if this unit was metamorphosed, the lack of lawsonite + prehnite may be ascribed to high CO_2 pressures (Brandon 1980), but calcite (not aragonite) is the only carbonate present. The simplest interpretation is that the Obstruction Formation has not been subjected to high-pressure metamorphism like the underlying terranes in the San Juan Islands.

Point counts of the sandstones of the lower sandstone unit (Fig. 6; Appendix Table A2) indicate that these sandstones contain up to 45% polycrystalline quartz, mostly chert; coarser samples have a higher percentage of chert. Feldspar (average, 20%) is exclusively plagioclase, which commonly displays albite twins and sericitic alteration. Lithic fragments, excluding chert, constitute about 30% of the framework. The lithic clasts are dominated by intermediate and felsic volcanics, but minor sedimentary and metamorphic clasts are present. Metamorphic clasts are dominated by nonschistose metavolcanic–plutonic clasts with greenschist-facies minerals. Quartz tectonites and schistose quartz–biotite fragments are rare. In order of decreasing abundance, detrital epidote, biotite, hornblende, prehnite, muscovite, and pumpellyite are all common accessory minerals.

The Obstruction Formation sandstones are easily distinguished from those of the James Island Formation by (*i*) a distinctly higher percentage of chert, much of which is metachert; (*ii*) a lack of metamorphic lawsonite, prehnite, and aragonite; and (*iii*) common detrital epidote and hornblende. Volcanic clasts are common to both but diagnostic of neither. Detrital serpentine, pyroxene, and mafic volcanic clasts occur in the James Island Formation sandstones but are rare in the Obstruction Formation sandstones.

The conglomerates are rich in black to gray, veined chert and metachert. Dominantly chert-pebble conglomerates of the lower sandstone unit give way to a greater percentage of volcanic and sedimentary clasts in the upper conglomerate unit. Distinctive or unusual clasts seen in outcrop and (or) thin section include (*i*) chert-pebble conglomerate clasts, (*ii*) porphyritic dacite clasts, (*iii*) foliated metadiorite clasts, (*iv*) bull quartz, and (*v*) lawsonite-bearing quartz tectonite clasts (seen in thin section). The chert-pebble conglomerate clasts may represent cannibalization of the underlying sandstone member. The lawsonite-bearing clasts suggest that, in part, the source contained sub-blueschist-facies metamorphic rocks similar to metamorphic rocks in the San Juan Islands.

The chert clasts are lithologically similar to and probably age correlative with the structurally lower but spatially adjacent Triassic–Jurassic Orcas chert. Radiolarians obtained from these chert pebbles at two localities are very poorly to totally recrystallized, but those recognised are Early Jurassic (?Pliensbachian or Toarcian) and Middle Jurassic (probably Bajocian; see Appendix Table A1). The greater abundance, the poorer preservation, the older source age, the darker color, and the veining distinguish the Obstruction Formation chert pebbles from the chert pebbles of the James Island Formation.

The remaining detrital component of the clastics in the Obstruction Formation was also probably derived from lithologies similar to those of structurally lower terranes in the San Juan Islands. The volcanic component could have been derived from an active source or from numerous volcanic-rich sequences in most of these terranes. The heterogeneous, greenschist- to lower-amphibolite-facies, volcano-plutonic Turtleback Complex could have been a major sediment contributor to the Obstruction Formation, as originally suggested by Vance (1975) because of common detrital epidote. The paucity of K-feldspar in the sediments may be explained if the source were an albitized plutonic suite such as the Turtleback Complex. Alternatively, the Fidalgo Complex could have supplied much or some of this detritus, an interpretation supported by the presence of detrital zircon about 150 Ma in age. The provenance of the Obstruction Formation being structurally lower in the San Juan Islands is compatible with the lithologies that occur there. More elaborate and complicated source-area candidates are possible but are not warranted from the data.

Structure

At least four periods of deformation affected the rocks included in this report; this resulted in complex structure, especially in the older rocks. The James Island Formation and the unconformably overlying Obstruction Formation have grossly different structural attributes, an observation that suggests the Fidalgo Complex and the Lummi Group were affected by a significant middle Cretaceous deformational event prior to the deposition of the Obstruction Formation.

Fidalgo Complex

Stratigraphic relations in the Trump unit are difficult to resolve because multiple deformations resulted in an extremely chaotic distribution of lithologic units (Fig. 3). In outcrop, rocks of this unit are highly disrupted, locally showing coherent mesoscopic folds. Large, overturned synformal packages of pillow basalt (southern Decatur Island, Fig. 3) attest to the complexity of deformation in which overturned panels of contrasting lithologic units are juxtaposed. Similar overturned panels of the overlying James Formation are present on northern Decatur Island. Because these overturned panels involve thick packages of volcanic rocks, tectonic processes, rather than soft-sediment deformation, appear to be responsible for the overturning.

The angular unconformity that separates the Fidalgo Complex from the overlying James Island Formation indicates that part of the deformation (D_1) of the Fidalgo Complex occurred during the Tithonian. This deformation resulted in uplift of the Fidalgo Complex, which ultimately became a sediment source. Deformation may have continued during deposition of the James Island Formation. These early structures, however, are masked by at least two later deformations.

Lummi Group (James Island Formation only)

Rocks of the James Island Formation occur in east–west-trending, steeply dipping, thrust-bound panels in which overturned sections are common (D_2) (Fig. 3). Mesoscopic folds are generally not seen in the field, but these panels probably represent the limbs of tight to isoclinal folds with faulted hinges (Fig. 10). No cleavage developed in these rocks. Inferred south-dipping thrust faults, which separate these panels, are rarely exposed; their presence is indicated by east–west-trending panels of repeated stratigraphy in the

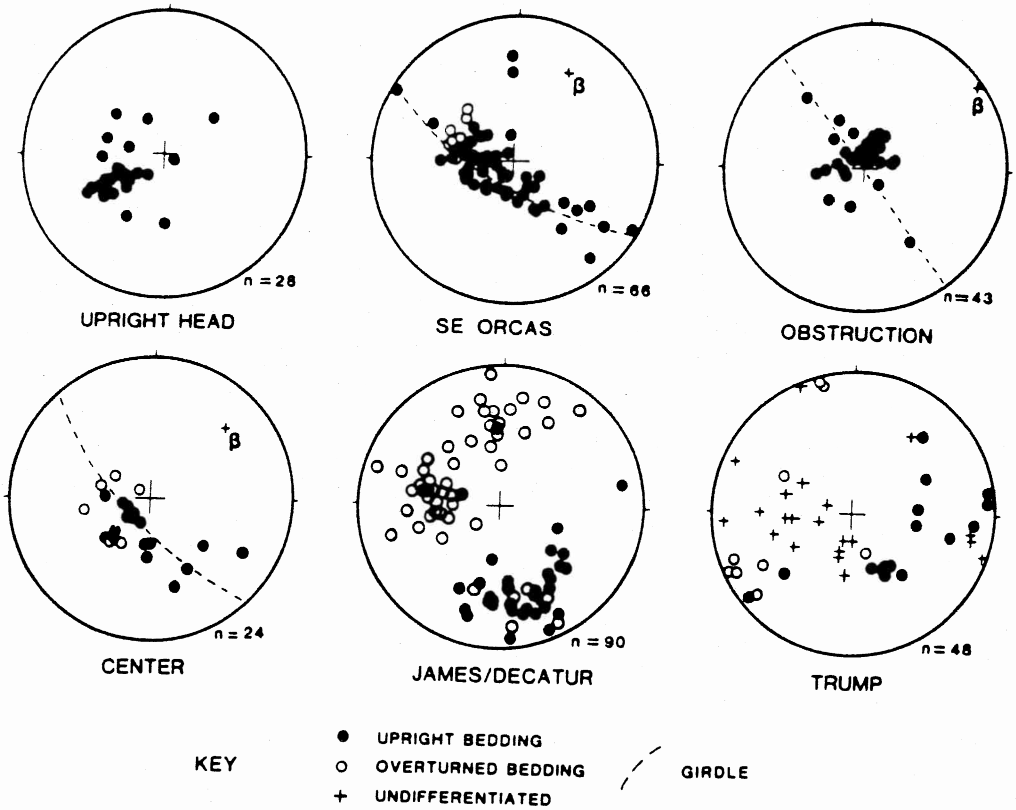

FIG. 10. Plots for poles to bedding for several units in the study area. Upright Head, southeast Orcas, Obstruction, and Center Island plots are all from the Obstruction Formation. James/Decatur represents measurements taken within the James Island Formation. The Trump plot represents measurements taken on volcanics and sedimentary rocks of the Fidalgo Complex.

Decatur area (Fig. 3).

The thrust faults on Decatur Island are cut by later high-angle faults (D_3), which disrupted structural continuity (Fig. 4). A series of small-scale, nearly vertical, northeast-striking faults on northern Decatur Island have horizontal slickensides and minor dextral separation between units. These small dextral offsets are parallel to an inferred larger system in the vicinity of James Island (Fig. 4). These latter structures (D_3) may be related to the same event that deformed the Obstruction Formation.

Obstruction Formation

The Obstruction Formation is structurally the most coherent of all the units in the area. It is a well-layered sequence that has been folded into large-scale, northwestwardly asymmetric, tight folds that have broad, gently warped eastern limbs and tightly overturned western limbs (D_3) (Fig. 4). Mesoscopic parasitic folds are common in the field. A nearly bedding-parallel foliation, nearly axial planar to large folds, developed throughout the study area in response to folding. The foliation is best displayed in mudstones, but locally sandstones and conglomerates are foliated also. A second foliation, only rarely seen in outcrop, developed in response to later open folding with north-trending fold axes (D_4). This deformation may be a manifestation of Tertiary folding recorded in the nearby Chuckanut Formation. The primary folding of the Obstruction Formation is probably a result of the involvement of this unit in the well-documented early Late Cretaceous thrusting that affected the San Juan Islands and North Cascades (Misch 1966; Brandon *et al.* 1988). The northwest vergence of the folds in the Obstruction Formation is broadly consistent with the favored direction of nappe emplacement (Misch 1966; Brandon and Cowan 1985).

It is important to note that although the bulk of the Obstruction Formation is in the northern portion of the field area, removed from the James Island Formation and Fidalgo Complex, on Center Islnd the unit sits amidst both James Island Formation and Fidalgo Complex with a structural disposition identical to that of Obstruction Formation rocks elsewhere (Fig. 10, compare first three plots). For this reason, comparisons in structure can be made. Center Island (Fig. 6) is spatially surrounded by pillow basalt and siliceous sediments of the Fidalgo Complex. In this locality, the Obstruction Formation could rest either depositionally or structurally (thrust fault) above the disrupted Fidalgo Complex. Either case could be argued effectively because the base of the Obstruction Island Formation is not exposed in this important area; the critical outcrops are under water.

Structural summary

Basement uplift and associated deformation of the Fidalgo Complex occurred during the Late Jurassic, as evidenced by an angular unconformity, basement-derived sedimentary debris, and fission-track uplift ages (Johnson *et al.* 1986). Deformation and lawsonite–prehnite-grade metamorphism probably occurred prior to the deposition of the Obstruction Formation. The deformation and metamorphism were probably coincident with sub-blueschist-grade metamorphism of the structurally lower terranes in the San Juan Islands (Brandon *et al.* 1988). Deformation and northwest-trending folding of the Obstruction Formation probably occurred after metamorphism of the lower terranes and may record late-stage thrusting. Superimposed on these structures are later open folds similar to those in the lower Tertiary Chuckanut Formation.

Discussion and tectonic implications

The upper Mesozoic clastic rocks of the San Juan Islands tell of tectonism and associated terrane interaction. The arc-proximal sedimentation of the Lummi Group on the Fidalgo Complex commenced in the Tithonian and possibly continued to at least the Valanginian (Fig. 11*a*). Similarities in the stratigraphy of the Lummi Group – Fidalgo Complex and the lower Great Valley Group – Coast Range Ophiolite were pointed out by Garver (1986). Because the stratigraphy of the Decatur terrane is different than that of coeval units in the northwest, a model using tectonic transport along the North American margin must be entertained so that stratigraphically dissimilar units can be juxtaposed immediately prior to thrusting.

The Decatur terrane, the upper Albian pillow basalts on southern Lopez Island, and structurally lower terranes in the San Juan Islands were subjected to high-pressure, low-temperature metamorphism after the late Albian. In order for these terranes to be imbricated, they must have been spatially adjacent. The writer and other workers (Brandon *et al.* 1988) favor a transpressional regime for this juxtaposition (Fig. 11*b*). This transpression shuffled various terranes, including the Decatur terrane, the Constitution terrane, the Orcas – Deadman Bay terrane, the Garrison terrane, and the Turtleback terrane (Brandon *et al.* 1988). This transpressive "orogen" may have also affected terranes in the North Cascades, where we see grossly similar lithologies but also important differences. For example, the Oxfordian or Kimmeridgian to Valanginian Nooksack Group (Misch 1966) is generally coeval with the Lummi Group. The stratigraphy and provenance of the Nooksack Group, however, are fundamentally different. The Nooksack Group is composed of volcanic graywackes that are mostly andesitic in composition, chert clasts are rare to absent in much of the section, and the Nooksack Group sits depositionally on a Middle Jurassic silicic volcanic unit called the Wells Creek Volcanics (Misch 1966). Facies within the Nooksack Group are both shallow marine (with abundant fauna) and turbiditic. Therefore, we have different coeval units that were both juxtaposed in a regional middle Cretaceous collisional event (Misch 1966). A transpressive shuffling of units along the margin of North America best explains this disparity (Fig. 11*b*).

The middle Cretaceous or early Late Cretaceous thrusting in the San Juan Islands and in the North Cascades (Fig. 11*c*) has been recognised by many workers (Misch 1966; Brandon *et al.* 1988). The thrusting imparted a high-pressure, low-temperature metamorphism on all units involved and was probably caused by rapid structural burial (Brandon *et al.* 1988). Many workers maintain that the timing of this event is constrained by the youngest rocks involved (upper Albian pillow basalts on Lopez) and the first occurrence of diagnostic metamorphic clasts in the adjacent Nanaimo Group (upper Santonian to Maastrichtian).

Evidence presented in this paper suggests that the Obstruction Formation and the upper Turonian strata on Barnes Island record the uplift of metamorphosed terranes in the San Juan Islands and that therefore the uplift is slightly older than originally thought. The Obstruction Formation, whose age is probably Cenomanian – Turonian, contains detritus from terranes in the San Juan Islands, as well as detrital prehnite and a lawsonite-bearing quartz tectonite clast. Younger strata, such as recently recognised upper Turonian sandstone and conglomerate of Barnes Island, have a provenance similar to that of the Obstruction Formation strata, although the former contain a greater percentage of volcanic clasts and plutonic clasts; chert-clast content is still quite high. A lack of cleavage and of mesoscopic folding in the Barnes Island rocks suggests that they may have been deposited after the cleavage-forming deformation of the Obstruction Formation, but they may have suffered different structural histories and then later been juxtaposed.

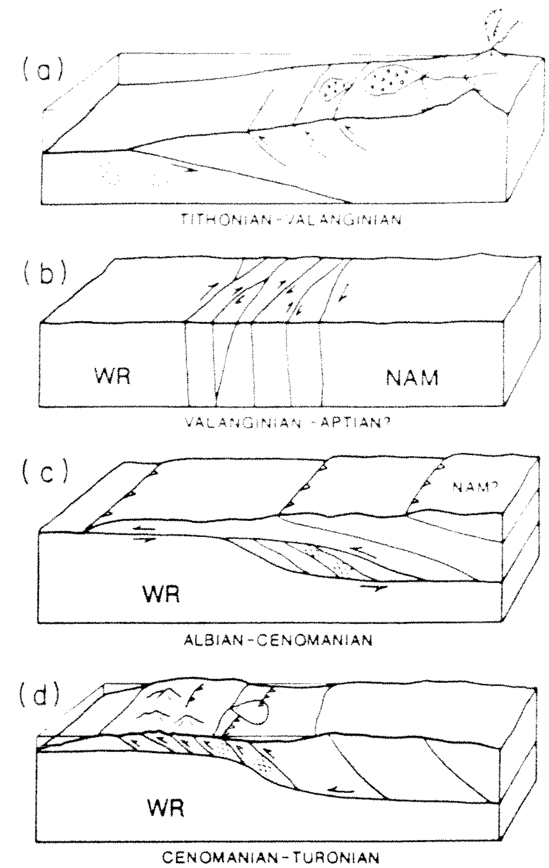

FIG. 11. Schematic representation of the tectonic setting of the units and events described in this paper. Cross-hatched area represents the Decatur terrane. "WR" and "NAM" denote Wrangellia and North America, respectively. Relative scale and orientation are not implied. See text for discussion.

Although folded and cleaved, the Obstruction Formation does not contain metamorphic lawsonite – prehnite – aragonite, as discussed. The deformation of the Obstruction Formation may have been caused by internal imbrication within the San Juan terranes during the last stages of thrusting but *after* these terranes were brought to upper structural levels by continued thrusting and erosion (Fig. 11*d*). This model requires that the structural burial, metamorphism (3–5 kbar (1 kbar = 100 MPa) Brandon *et al.* 1988), and subsequent uplift of terranes in the San Juan Islands were extremely rapid events that must have occurred between the latest Albian and the late Turonian. The duration of this event was even shorter if the Obstruction Formation is Cenomanian in age.

Facies, provenance, and sediment-dispersal patterns in even younger rocks of the Nanaimo Group (upper Santonian to Maastrichtian, or upper Turonian to Maastrichtian if Barnes Island is included), however, suggest deposition within a strike-slip basin (Pacht 1984). If so, an important transition from foreland basin deposition to strike-slip basin deposition is recorded somewhere in the lower portion of the Nanaimo Group.

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Appendix 1

Table A1. New paleontologic data for the eastern San Juan Islands

Unit/Lithology	Location/Sample No.[a]	Fauna	Assigned age (Identifying paleontologist)
Barnes Island			
Mudstone	Barnes north	Ammonites *Reesitites minimus*	Late Turonian (P. D. Ward, personal communication, 1985)
Obstruction Formation			
Chert clasts in upper conglomerate	Lopez—Upright Head USGS MR 6480	Radiolarians Poorly preserved nassellarians	Mesozoic: Triassic or younger (C. D. Blome, personal communication, 1985)
Chert clasts in lower unit	Lopez—Humphrey Head USGS DR 086	Radiolarians *Archaeodictyomitra* sp. *Pantanellium* sp. *Trillus* sp. ?*Tripocyclia* sp.	Early Jurassic: Pliensbachian or Toarcian; Middle Jurassic: probably Bajocian (C. D. Blome, personal communication, 1985)
Siltstone in lower unit	Lopez—Humphrey Head UW B3419	Pelecypods *Nucula* sp. *Pholladamya* gen. et sp. indet. *Gastropod* gen. et sp. indet.	Long ranging (V. S. Mallory, personal communication, 1985; P. D. Ward, personal communication, 1985)
Basalt of Eagle Cliff			
Pink interpillow limestone	Cypress—north, below Eagle cliff USGS MS 7111	Foraminifers Indeterminate forams, similar to those of Richardson locality	?Late Albian to mid-Cenomanian but extremely tenuous (W. V. Sliter, personal communication, 1987)
James Island Formation			
Upper unit	James Island	Radiolarians *Orbiculiforma* sp.	Jura-Cretaceous (C. D. Blome, personal communication, 1985)
Chert pebbles in middle conglomerate	James Island USGS MR 6477 USGS DR 0088	Radiolarians Poorly preserved *Hsuum pessagno*	Mid-Jurassic: Bajocian; to Late Jurassic (C. D. Blome, personal communication, 1985)
Clast in middle conglomerate	James Island UW B 3422	Ammonites Phylloceritid type ammonite	Mesozoic (P. D. Ward, personal communication, 1985)
Limestone clast in middle conglomerate	James Island UW B 3421	Pelecypods *Buchia piochii*	Late Tithonian (see Jeletzky 1984) (V. S. Mallory, personal communication, 1985)
Within all three units	James Island UW B 3632	Belemnites *Belemnite* gen. et sp. indet. (abundant)	Jura-Cretaceous (P. D. Ward, personal communication, 1985)
Lower sandstone unit	James Island, northeast UW B 4057	Pelecypods *Buchia piochii*	Late Tithonian (see Jeletzky 1984) (V. S. Mallory, personal communication, 1985)
Lower sandstone unit	James Island, southeast UW B 3420	Pelecypods *Buchia piochii*	Late Tithonian (see Jeletzky 1984) (V. S. Mallory, personal communication, 1985)
Fidalgo Complex			
Bedded chert below clastics (upper sedimentary unit)	Lummi Island, southwest USGS DR 0084	Radiolarians *Hsuum* (?)*mclaughlini* Pessagno and Blome *H. obispoensis* Pessagno *Mirifusus* (?)*baileyi* Pessagno *Parvicingula* sp.	Late Jurassic: late Tithonian (C. D. Blome, personal communication, 1985)
Red siliceous argillite in upper sedimentary unit	Trump Island USGS MR 6475	Radiolarians *Parvicingula excelsa* Pessagno and Blome *Parvicingula colemani* Pessagno and Blome *Ristola hsui* (Pessagno) *Turanta flexa* Pessagno and Blome	Late Jurassic: (late Tithonian) (C. D. Blome, personal communication, 1985)

Table A1 (*concluded*)

Unit/Lithology	Location/Sample No.[a]	Fauna	Assigned age (Identifying paleontologist)
Chert from upper sedimentary unit	Decatur Island USGS 6478 USGS 6479 USGS 0087	Radiolarians Poorly preserved nassellarians	Mesozoic: Triassic or younger (C. D. Blome, personal communication, 1985)
Interpillow chert (pillow basalt)	Decatur Island, south USGS 0089	Radiolarians *Archaeodictyomitra* sp. *Hsuum* sp. *Pantanellium* sp. *Pseudocrucella* sp.	Middle to Late Jurassic: Callovian or Oxfordian (C. D. Blome, personal communication, 1985)
Red argillite and chert in pillow basalt	Decatur Island USGS 0090	Radiolarians *Emiluvia* sp. Nassellarians	Mesozoic: ?Middle or Late Jurassic (C. D. Blome, personal communication, 1985)

[a]UW, University of Washington, Burke Museum collection number; USGS, United States Geological Survey collection number.

Table A2. Petrographic data

Sample	QFL (%)					M				QpLvmLsm (%)			LmLvLs (%)			Mx
	Q	Qm	F	L	Lt	(%)	P/F	Lv/L	Qp/Q	Qp	Lvm	Lsm	Lm	Lv	Ls	(%)
Trump unit																
JG84.62	14	12	50	36	38	9	1.0	0.88	0.18	7	83	10	2	88	9	8
JG85.85	9	8	65	26	27	3	1.0	0.88	0.10	3	85	12	7	88	5	17
JG85.71	12	10	71	16	19	5	1.0	0.96	0.26	14	83	3	0	96	3	13
JG85.54	31	18	46	24	36	4	1.0	0.88	0.41	32	60	8	0	88	12	14
JG85.56b	24	13	24	52	62	7	1.0	0.88	0.44	17	73	10	1	88	11	9
JG85.81	19	6	43	38	50	2	1.0	0.92	0.67	25	68	6	0	92	8	11
James Island Formation																
JG84.211a	28	10	33	38	56	4	1.0	0.69	0.63	26	39	35	0	53	47	18
JG84.211b	22	18	26	53	70	3	1.0	0.81	0.84	26	66	8	8	81	11	7
JG84.s1	35	10	29	36	60	2	0.97	0.67	0.70	41	43	16	5	67	28	12
JG84.s3	29	9	44	26	47	6	0.89	0.63	0.70	44	35	21	0	63	37	5
JG84.s2	23	7	39	38	54	5	0.90	0.78	0.70	31	57	12	3	78	18	6
JG84.371	29	7	32	40	61	6	1.0	0.70	0.74	35	49	16	6	70	24	13
JG84.106	16	5	33	50	61	3	1.0	0.79	0.68	18	75	7	13	79	8	20
JG84.317	24	10	56	20	34	9	0.90	0.62	0.60	43	38	18	6	62	32	13
Obstruction Formation																
JG84.297d	44	11	25	30	64	4	1.0	0.57	0.75	52	27	20	23	57	20	23
JG84.231b	51	15	27	22	58	6	1.0	0.50	0.70	61	19	19	15	50	35	19
JG85.231a	50	13	25	25	61	6	1.0	0.42	0.73	60	20	20	26	49	25	12
JG84.193	51	10	21	28	69	2	1.0	0.57	0.81	59	27	15	9	57	34	16
JG84.s4	53	9	18	29	73	12	1.0	0.52	0.84	62	33	5	36	52	12	12
JG84.187d	51	8	14	35	78	3	1.0	0.54	0.85	56	25	19	7	54	39	14
JG84.231c	40	17	33	27	49	3	1.0	0.58	0.56	45	31	24	3	56	41	13
JG84.188	53	8	17	30	75	4	1.0	0.37	0.84	60	15	25	0	37	63	17
JG84.304	17	5	47	35	47	5	1.0	0.46	0.70	26	41	33	24	46	30	12

NOTES: Petrographic analysis of medium- to coarse-grained sandstones. Three hundred points per stained thin section were counted according to the Gazzi–Dickinson method (Dickinson 1970). Format, abbreviations, and techniques follow those of Ingersoll (1983) and Ingersoll *et al.* (1984).

Q = Qm + Qp, where Q = total quartzose grains, Qm = monocrystalline quartz grains, and Qp = polycrystalline quartz grains.

F = P + K, where F = total feldspar grains, P = plagioclase feldspar grains, and K = potassium feldspar grains.

Lt = L + Qp, where Lt = total aphanitic lithic grains, and L = total unstable aphanitic lithic grains, excluding Qp.

L = Lm + Lv + Ls, where Lm = metamorphic aphanitic lithic grains, Lv = volcanic–hypabyssal aphanitic lithic grains, and Ls = sedimentary aphanitic lithic grains.

L = Lvm + Lsm, where Lvm is volcanic–hypabyssal and metavolcanic aphanitic lithic grains, and Lsm = sedimentary and metasedimentary aphanitic lithic grains.

M = miscellaneous grains (e.g., heavy minerals) and mica as a percentage of total framework.

Mx = matrix percentage of total count.

Table A3. Fission-track age determination

No.	Fossil[a]	Induced[b]	Age
1	479	181	81
2	333	110	95
3	914	191	150
4	468	98	151
5	413	133	98
6	843	194	136
7	469	155	95
8	647	217	94
9	588	190	97
10	472	120	124
11	445	111	126
12	285	77	116
13	235	59	125
14	781	148	165
15	284	76	117
16	413	138	94
17	826	145	178
18	251	72	110
19	207	73	89
20	599	127	148
21	615	127	152
22	404	126	101
23	668	155	135
24	320	126	81
25	525	107	154
26	483	148	103
27	789	126	196
28	889	177	158
29	472	110	135
30	182	51	112
31	344	103	105
32	751	186	127
33	468	130	113
34	618	166	117
35	520	122	134
36	496	141	110
37	236	51	145
38	333	75	140
39	244	81	95
40	404	103	123
41	457	145	100

NOTES: Fission-track age determination on a sample from eastern Upright Head of northern Lopez Island (Obstruction Formation) followed the standard procedure outlined by Johnson *et al.* (1986). The fluence was calculated by C. W. Naeser by determining track density in mica that was irradiated against NBS glass standard SRM 612 and the Fish Canyon Tuff. The fluence was 1.06 ($\times 10^{15}$ neutron/cm^2 $\pm$ 2%).

[a]Fossil tracks counted on a zircon grain.

[b]Tracks counted on the external detector after irradiation.