Petrology and Structure of the Pre-Tertiary Rocks of Lummi and Eliza Islands, Washington

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

University of Washington

1980

Approved by John T Whetten
(Chairperson of Supervisory Committee)

Program Authorized
to Offer Degree Geological Sciences

Date August 8, 1980

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Abstract

PETROLOGY AND STRUCTURE OF THE PRE-TERTIARY ROCKS OF LUMMI AND ELIZA ISLANDS, WASHINGTON

By Paul Richard Carroll

Chairperson of the Supervisory Committee: Professor John T. Whetten
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Exposed on Lummi Island are two groups of pre-Tertiary rocks everywhere in fault contact with each other: a 1300 meter thick section of turbidite sandstone and mudstone, and rocks largely of igneous affinity. The latter rocks consist of pillow lavas with associated radiolarian chert dated as Middle to early Late Jurassic, and, in a relatively small, isolated exposure, an intrusive complex containing rocks dated by Pb/U methods as 160 ± 3 my. This complex seems comparable in age and rock types to hypabyssal rocks of the Fidalgo Ophiolite of Brown (1977).

Radiolarian chert is interbedded with the sedimentary rocks at the base of the exposed section on Lummi, and was dated as Late Jurassic-Early Cretaceous. The section is indicative of channeled middle fan deposition (Walker and Mutti, 1973). The sandstones (Q-12 F-26 L-62) lack potassium feldspar and are dominated by volcanic lithic fragments.

A postulated structural history for the sedimentary rocks consists of 1) slight disruption of original bedding orientation, 2) development of cleavage subparallel to bedding, 3) the de-

velopment of the majority of the veins, faults, kink bands and metamorphic minerals seen, 4) deposition of Chuckanut Formation in early Tertiary time, and 5) rotation of cleavage parallel to strike, and folding of Chuckanut. In the Mesozoic rocks, beds presently dip moderately northeast, while cleavage dips approximately 10 degrees more steeply, and varies from absent to phyllitic. Phyllitic rocks are characterized by open to isoclinal folds to which the cleavage is axial planar; these rocks were brought to their present positions by faulting. The latest faulting seems dominantly strike-slip; in particular, a major fault zone terminating the sedimentary sequence halfway up the island shows evidence of strike-slip movement along east-west trending vertical planes. Danner (1977) and Muller (1977) have inferred such a fault, but show it as northeast trending. In contrast to the other San Juan Islands, pumpellyite is more abundant than prehnite on Lummi Island. Aragonite and lawsonite are characteristic south of the fault zone, but only minor lawsonite occurs north.

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ACKNOWLEDGEMENTS

In any wind at all, a canoe needs two people to assure progress in the desired direction. Therefore, the muscles of my field assistants (Jan Frederick, Andrea Stomberg, Eleanor Hutter, Kathy Lombardo, Ginna Crosby and John Winter) deserve the highest accolades. In addition, their cheerfulness, companionship and patience with or interest in my field work immeasurably brightened my days in the field. I offer them my fondest thanks.

Space does not exist to thank all the friends who have supsported me; I would hope they know I am very grateful. To Mark Brandon, though, must go a special note of thanks for continual assistance and enthusiasm concerning this thesis. I would also like to thank my committee members, Darrel Cowan, Joseph Vance and John Whetten for their part in the completion of this project, and for their continuing friendship towards me.

I am grateful to David Jones of the U.S. Geological Survey and Emile Pessagno, Jr. of the University of Texas for identifying radiolaria, and Robert Zartman of the U.S.G.S. for a Pb/U date. The U.S.G.S. also in part supported my research, as did an N.S.F. grant obtained by Cowan, Whetten and William Glassley. For this support, and that of my parents, I am very grateful.

I never would have overcome the feeling of flagrant trespass with which I began field work without the hospitality and access granted by the Baker Family and most especially by Mr. and Mrs. Lloyd Niedhamer of Lummi Island. That the Niedhamers became my

friends was one of the nicer things that happened on Lummi. I also appreciate the access I was granted to Eliza Island.

For nearly eight years now, it has been my good luck and pleasure to have enjoyed the friendship of John Whetten. If amnesia erased the memory of my Master's research and left the memories of laughter doing fieldwork with John, that would be fine with me.

CHAPTER I: INTRODUCTION

BACKGROUND AND STATEMENT OF THE THESIS PROBLEM

Geology of the San Juan Islands

Geologic understanding of the San Juan Islands (Fig. 1) has had a long evolution, beginning with the landmark work of McLellan (1927), and progressing dramatically in recent years through the efforts of numerous people, especially Danner (1966), Vance (1975, 1977), Whetten (1975), Whetten and others (1978), Cowan and Whetten (1977), Glassley and others (1976), Brown (1977) and Brown and others (1979). Critical contributions in determining the ages of the complexly deformed rocks exposed in the Islands have finally led to a moderate amount of agreement on the general geologic history of the area (cf. Vance (1977) and Whetten and others (1978)).

Generally, those two papers describe a series of southeast-dipping thrust faults which stack, in order of descending structural position, first (structurally highest), two or three Jura-Cretaceous but geologically distinctive (and thrust-bounded) "units" or "terranes", second, a complexly imbricated group of rocks ranging in age from possible Pre-Cambrian through Jurassic, containing volcanic, sedimentary, and metaplutonic (greenschist facies) rocks, third, a Triassic sedimentary formation, and structurally lowest, an Upper Jurassic-Lower Cretaceous sedimentary formation. The last two formations share neither the moderately high P/T metamorphism nor the intense deformation characteristic of the overlying rocks. To the north, the extensive, essentially

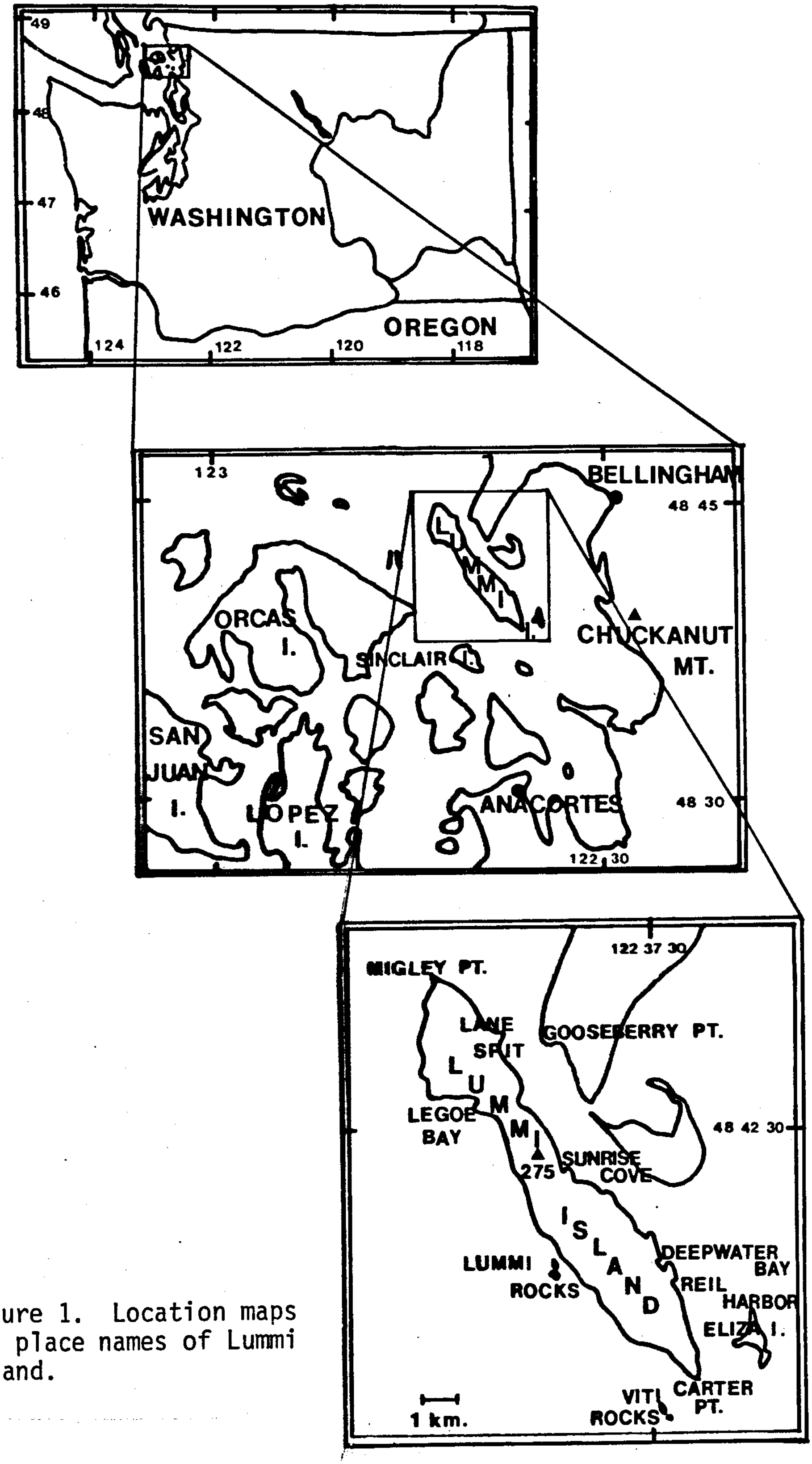


Figure 1. Location maps and place names of Lummi Island.

unmetamorphosed Upper Cretaceous Nanaimo Formation is in fault contact with the afore-mentioned sequence. It should be stressed that questions remain and differences of interpretation exist even at the level of this general synthesis.

Problems in Differentiating Coeval Mesozoic Rocks

Of particular concern to this thesis are disputed or tentative interpretations and correlations in the Jura-Cretaceous rocks. Vance (1975) stated:

> Understanding of the Mesozoic stratigraphy of the San Juan Islands is hampered by the absence of fossils in several of the key units, leading to uncertainty as to their age, as well as by controversy as to their structural relations and the possibility that rather different rock units may be of the same age.

Since that was written, the ages have been obtained by Whetten and others (1978), but the possibility "that rather different rock units may be of the same age" has been made a certainty, and the question remains as to how different these "rather different" rocks are. For instance, Vance (1977) groups the sedimentary rocks on southern Lummi Island with the Fidalgo Ophiolite of Brown (1977) while Whetten and others (1978) considered them to be part of a thrust sheet structurally higher than and separate from the ophiolite. Since then, in part due to data presented in this thesis, Whetten and others (1980) would group them in the Lopez terrane, a thrust sheet structurally below the ophiolite. I believe the questions remain because of a lack of detailed knowledge of the structural and metamorphic histories of these rocks, the sedimentology of the clastic rocks, and the geochemistry of the volcanic units.

Moreover, the problem also exists on a more regional scale. To the northwest, Vancouver Island is said to have rocks of similar age (Muller, 1977) exhibiting very different post-depositional histories (the Pacific Rim Complex (Muller, 1973, Page, 1974) and the Leech River Schist (Fairchild, 1979)), while to the east in the North Cascades, the Nooksack Group of Misch (1966) is again of Jura-Cretaceous age, and yet has different metamorphic minerals (Misch, 1966) than the Lummi Island sequence, with which all of the above rocks have been correlated by Muller (1977).

Correlations presently being suggested seem to principally express age equivalence and perhaps superficial lithologic similarities. Whether there are more significant similarities or differences can be resolved only by detailed work similar to that of Fairchild (1979) and Johnson (1979). Secondly, the post-depositional histories of these rocks may be as important for our understanding of Mesozoic and post-Mesozoic tectonics in the Northwest as the tenuous stratigraphic correlations presently being suggested.

Choice, Scope and Methods of Thesis Research

My thesis is an attempt at a detailed chatacterization of one of these Mesozoic "units". Lummi Island was chosen because it boasted both a thick (1300 m.), relatively well-exposed and undeformed sedimentary sequence, and a geographic position between the North Cascades and the main San Juan Islands. This intermediate position lends it strategic importance in comparing the geology of the two areas. Previous mapping of Lummi Island by McLellan (1927) in reconnaissance and more thoroughly by Calkin (1959) provided a background of information for my study.

In the present work, a more detailed and accurate description of the structural and metamorphic histories of the pre-Tertiary rocks on Lummi and nearby islands is presented, along with only a slightly more sophisticated description of the conditions of formation of the sedimentary rocks. Only the structure of the Tertiary Chuckanut Formation on Lummi was studied, since that could be presumed to have some bearing on the pre-Tertiary rocks.

Approximately ten weeks of field work was completed during the summers of 1976 and 1977. The base maps were preliminary 1:24000 U.S.G.S. topographic sheets, but the continuous shoreline exposure encouraged collection of structural data at more nearly a 1:12000 scale. Consequently, not all measurements, especially bedding attitudes, appear on the geologic map (Fig. 2, back pocket). Field work was largely conducted by canoe, since shorelines along the east shore are generally too steep to permit walking. During this field work, approximately 200 hand samples were collected; thin sections of most of these were made and studied. Sixteen of these samples were analysed by x-ray diffraction, primarily to identify metamorphic minerals.

LOCATION AND ACCESS

Lummi Island is in northwestern Washington State, 13 km. west of the city of Bellingham, and represents the northeasternmost extent of the San Juan Archipelago (Fig. 1). A small ferry shuttles between Gooseberry Point, on the mainland, and Lummi. Unlike the area around Gooseberry Point, which is the Lummi Indian Reservation, Lummi Island is mostly privately owned. A good road system in the northern part makes access easy, but only one development exists in the more rugged southern half, so access by land farther south is limited to two Jeep trails on either side of the island, neither of which extends to the southern tip.

GEOGRAPHY

Lummi Island (approximately 21 $km.^2$) is narrow (14 km. long and generally 2-3 km. wide) and trends northwest. Geographically, it can be divided into two parts. The northern half is fairly flat, low farmland, largely blanketed by Quaternary deposits. Bedrock exposures are essentially limited to the shores, where they are excellent. The more rugged, forested southern half, subsequently referred to as "south Lummi", is an asymmetric, northwest-trending ridge which rises abruptly from the northern lowland, eventually reaching a maximum elevation of 507 m. The west face of this ridge is the steepest most extensive slope in the San Juan Archipelago. The eastern shore is steep and rocky, providing excellent, nearly continuous exposures, but the western shore is, for long stretches, composed of debris from the high cliffs.

The largest of the islands just offshore of Lummi is Eliza Island, composed of three bedrock knobs connected by low-lying glacial deposits. It is located east of the south tip of Lummi, and the others, Viti Rocks and Lummi Rocks, are just southwest and west of south Lummi, respectively (Fig. 1).

CHAPTER II: DESCRIPTION OF LITHOLOGIES

TYPES AND DISTRIBUTION OF ROCKS IN THE MAP AREA

Four groups of rocks occur on Lummi: 1) the Chuckanut Formation (McLellan, 1927), a Tertiary sandstone sequence; 2) a Jura-Cretaceous sandstone-mudstone sequence (folded, strongly cleaved rocks of similar lithology underlie Eliza Island and parts of south Lummi); 3) basaltic volcanic rocks and associated Middle to early Late Jurassic chert and 4) a Middle Jurassic igneous complex. Later in this paper the sedimentary rocks are divided structurally into domains, but in this section this grouping is used only to facilitate discussion of other regionally variable aspects of the sedimentary rocks, and simply indicates geographical areas (Fig. 3). Locations of all dated pre-Tertiary rocks are shown in figure 4.

The igneous complex and the Chuckanut are restricted to the northern half of the island, and the volcanic rocks and Jura-Cretaceous sedimentary rocks are largely confined to the north and south halves of the island, respectively. A zone in which all three pre-Tertiary rock types are mixed crops out at Sunrise Cove.

CHUCKANUT FORMATION

Lithologic Description

The Chuckanut Formation on Lummi is a sequence of coal-bearing, cross-bedded arkosic sandstone with conglomerate and minor mudstone interbeds. In outcrop, the conglomerate has a high percentage of well-rounded chert clasts, although fine-grained volcanic clasts

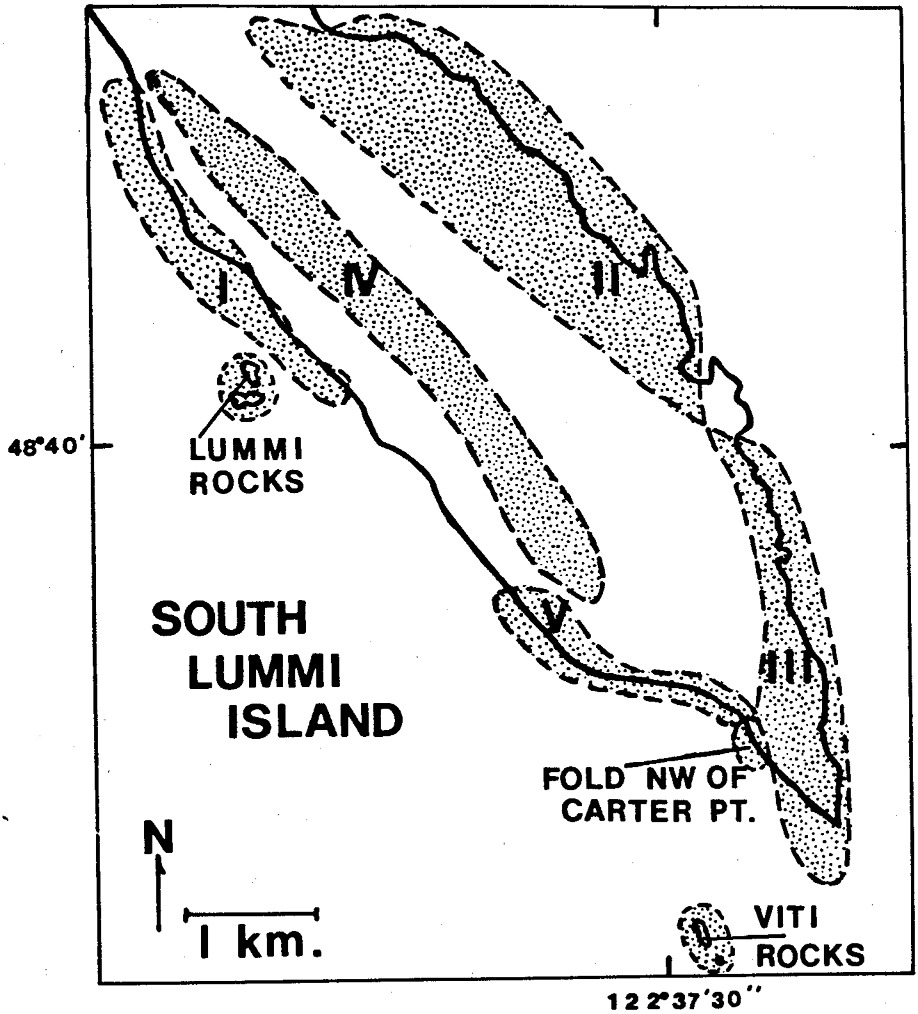


Figure 3. Location of structural domains, excluding Eliza Island.

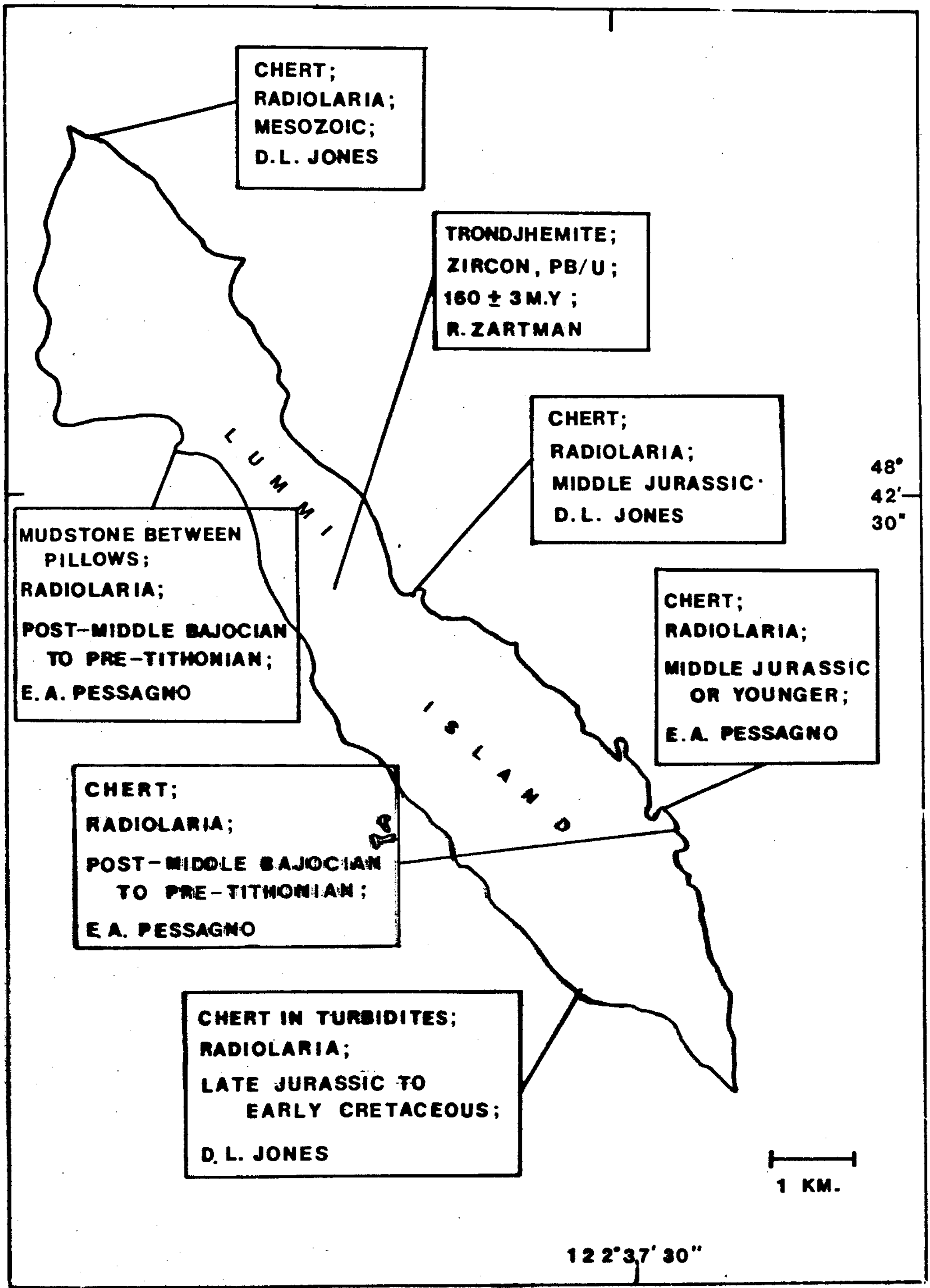


Figure 4. Location of all dated pre-Tertiary rocks on Lummi Island, with rock type dated; dated material; age; paleontologist/geochronologist.

are also present.

The contact of the Chuckanut with underlying volcanic rocks is an unconformity first noted by McLellan (1927). It is well exposed at Migley Point, and .2 km. farther east along the shore, and poorly exposed north of Lummi Point (also called Lane Spit). Bedding is subparallel to the unconformity. Pebbles (in contrast to overlying sandstone) fill depressions in the surface of the underlying volcanic rocks, and a basal conglomerate is developed which locally attains a thickness of three meters. Large (approximately .3 m. long) blocks of basalt are incorporated into the bottommost part of the basal conglomerate, but other clasts (generally cherty) show much better rounding and smaller size.

On a larger scale, the position of the outcrop of volcanic rocks at Legoe Bay is roughly as expected if the unconformity swings parallel to bedding around the synclinal structure of the Chuckanut.

SANDSTONE-MUDSTONE SEQUENCE ON SOUTH LUMMI

Lithologic Description

Southern Lummi is generally underlain by alternating sequences of 1) massive, thick sandstone beds, and 2) thin-bedded finer-grained sandstone with interbedded mudstone. These rocks are metamorphosed. They show cleavage of variable intensity, are veined, faulted and slightly boudinaged, and the sandstone is very indurated, greenish-gray on a fresh surface, weathering to a light brown.

The thin-bedded (generally less than 7 cm. thick) sandstone is generally fine-grained, and commonly shows normal grading, parallel lamination, climbing ripples, and/or cross-ripple lamination. Interbeds of mudstone of similar or greater thickness form sequences up to five meters thick.

The massive sandstone beds are up to three meters thick, separated by thin mudstone layers or sections of the above sequence. Typically they contain intraformational shale chips, either isolated or in discontinuous widely spaced layers within a bed. Other internal structures are infrequent, but include planar bands parallel to bedding that weather a lighter shade than the rest of the bed, occasional graded bedding, and, in one instance, a parallel-laminated sandstone bed. Generally, however, in beds thicker than 10 cm., internal structures are absent, except for wavy laminae at the top of the bed.

Sole marks are most frequent, but not abundant, in domain II (Fig. 3), and include flute and groove casts, some flame structures and load casts, and in one instance, roughly symmetric ripples of small amplitude (3 mm.). Channels were not observed.

Most of the massive sandstone beds are composed of medium sand-sized to very fine pebble-sized (5 mm.) clasts. Coarser clasts (up to 60 cm. in length) are abundant only very locally, are largely composed of sandstone and mudstone clasts, and show very poor sorting and rounding. These probably represent intraformational slump debris. Slumped bedding was noted at one locality, in a finer-grained, more thinly-bedded sequence.

Coalified plant debris, especially woody stems, are common on bedding surfaces everywhere except in the most strongly foliated rocks.

Facies Designations

The south Lummi sequence of sedimentary rocks is disrupted on an outcrop scale by faulting, and tracing beds laterally inland from the shoreline exposures is impossible. Therefore, a measured section was not attempted. A general description of turbidite facies present (exclusive of domain I) can be presented, using the work of Mutti and Ricci Lucchi (1972, English translation 1978). Although Walker and Mutti's (1973) work is also referred to, all lettered facies designations (A, B, C, D, E, F and G) are Mutti and Ricci Lucchi's.

The massive sandstone sequence described previously best compares to facies A and B, although the abundantly laminated facies B sandstones are not typical of Lummi. The beds in the massive sandstone sequence on Lummi are better typified by Walker and Mutti's organized pebbly sandstones (belonging to facies A) and especially their massive sandstones without dish structure (of facies B). The channeling that should be associated with either facies was not observed. Certainly the vertical stacking of the massive and thin-bedded sequences on Lummi also implies lateral facies variation, which, in a turbidite fan model, probably implies some channeling.

The thinner-bedded sequences on Lummi are best characterized by facies D. Facies E (similar to facies D), the chaotic facies F, and the hemipelagic and pelagic facies G were not observed on Lummi.

Facies Associations

This facies association most closely corresponds to Mutti and Ricci Lucchi's (1972) middle fan association--Walker and Mutti's (1973) middle fan channeled association. The lack of observed channeling on Lummi would, however, seem to argue for the outer fan association of the earlier work (called the "middle fan depositional lobe" association in the later work), except that those associations seem to demand more abundant pelitic material than is seen on Lummi. Discovery of channeling and thinning- and fining-upward sequences on Lummi would support the more proximal association, while thickening- and coarsening-upwards sequences and lack of channeling would support the more distal association.

Ichnofacies

In domain II, sand-filled, curving, single or, more generally, paired and parallel burrows are observed within and oblique to bedding surfaces (Plate I). Being sand filled, they are only obvious in mudstone. The burrows are slightly ellipsoidal, perhaps due to flattening during cleavage formation, and the longer axis of their

Plate I. Curving, parallel sand-filled burrows on a bedding surface in domain II, south Lummi Island. Penny for scale.

cross-sections ranges from 2 mm. to 1.5 cm. When paired, the burrows can be separated by up to 1 cm. The separation could be primary or due to slight boudinage associated with cleavage formation. Generally, the paired burrows are of similar size. In that they lie parallel to and also crosscut bedding surfaces, they seem similar to trace fossils associated with turbidite sedimentation described by Seilacher (1962).

In the same general area, a hexagonal net was observed in sharp convex or positive relief on an exposed surface of mudstone parallel to bedding. Whether this was actually an epirelief or a full relief (Seilacher, 1964) was not noted. The similarity to the trace fossil _Paleodictyon_ is strong (Plate II), especially in comparison with figured _Paleodictyon_ in Ksiazkiewicx (1970, his plate 4). If the Lummi trace was an epirelief, however, that is apparently unusual (Seilacher, 1977), and may indicate formation of the pattern in some other way. If the feature is _Paleodictyon_, this trace is diagnostic (Seilacher, 1964) of the _Nereites_ facies of Seilacher (1964,1967). This facies is described by Seilacher as characteristic of probable bathyal depths and associated with turbidite sedimentation. Limited data indicate that modern _Nereites_ facies trace fossils occur mainly at depths greater than 4000 m. (Bourne and Heezen, 1965).

Paleocurrent Directions

Measurable sole markings were scarce on Lummi, but paleocur-

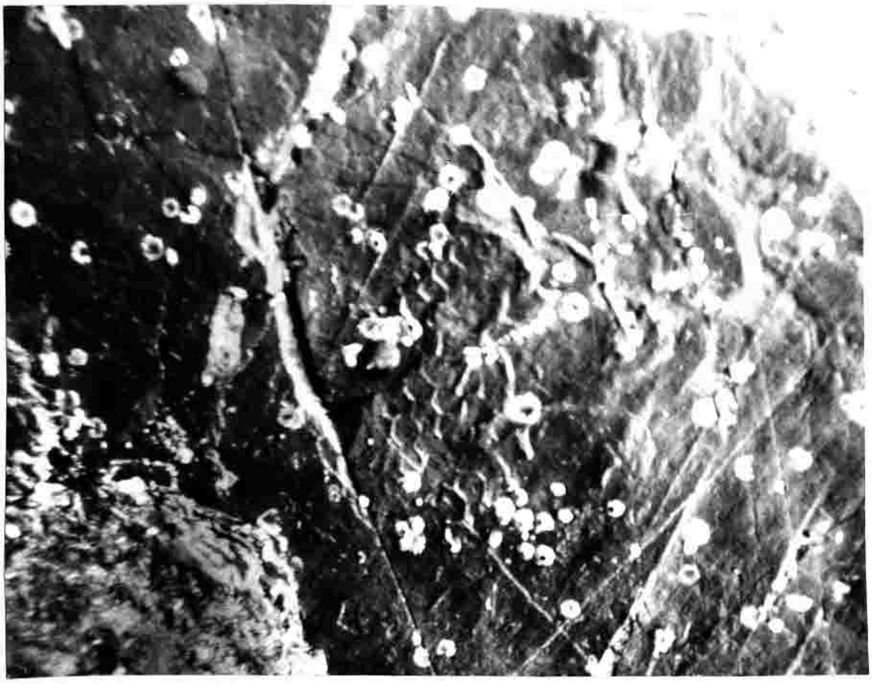


Plate II. Hexagonal net (possible Paleodictyon) in positive relief on a bedding surface of mudstone in domain II, south Lummi Island. Pictured hexagons average 7 mm. in diameter.

rent directions derived from them and from less reliable but more numerous cross-ripple laminations are shown in figure 5. To arrive at these directions, the paleocurrent indicators were only rotated around the strike of associated bedding; other rotations may have occurred, but have not been identified for south Lummi. Paleocurrent directions spread across more than 180°, from N 70 W to S 50 E.

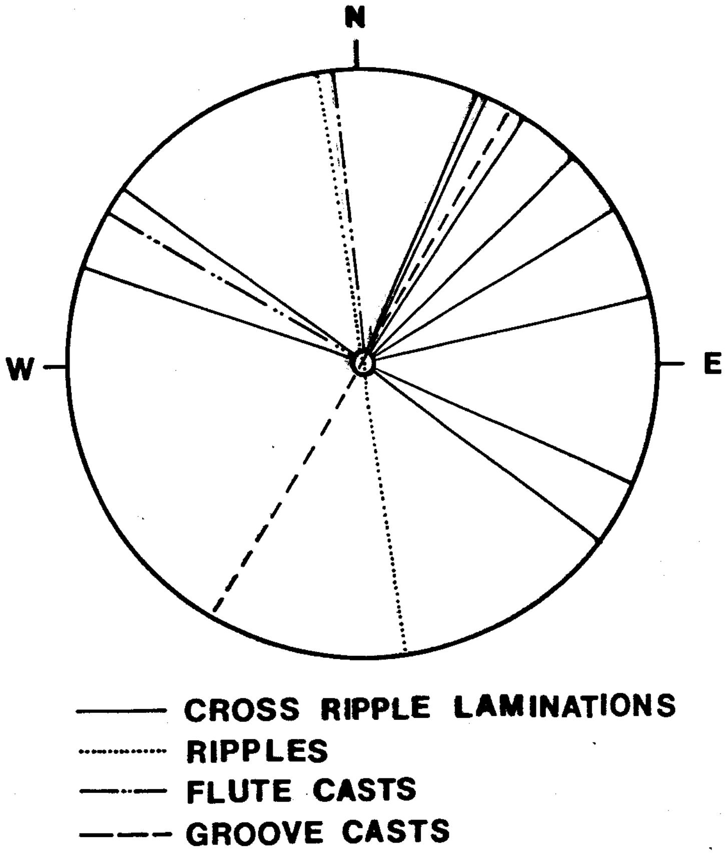


Figure 5. Paleocurrent directions. Each line is only one measurement; direction of transport only is indicated by diameters, while radii indicate both sense and direction of movement.

Detrital Mineralogy of Sandstone

Determination of the primary mineralogy of the sandstone is hampered by: lack of definition of clast boundaries; alteration of clasts to calcite, lawsonite or sericite; recrystallization of lithic clasts, especially volcanic fragments, to microcrystalline quartz, plagioclase and mica; and by difficulty in distinguishing whether low-grade metamorphic minerals (especially prehnite) within a detrital grain formed pre- or post-depositionally. Of 27 samples collected from domains I, II, III, and V (Fig. 3), only four could be point-counted with reasonable certainty (Table 1, Fig. 6).

The sandstone, averaging Q-12 F-26 L-62, is feldspatholithic sandstone, after Crook (1960). Although some chlorite occurs as clasts, and a very few occurrences of prehnite in sample 150 were thought to be interstitial and authigenic, the former was included in "matrix" and the latter called clastic. Matrix averages 8%; the sandstone would be classified as arenite. A plot of lithic clast types (Fig. 7) emphasizes the nearly complete dominance of clasts of volcanic derivation, specifically feldspathic clasts lacking obvious primary mafic minerals, perhaps indicative of an andesitic source terrane. Microcrystalline quartz identifiable as chert constituted less than a percent in each rock counted. Heavy minerals (including biotite) average 6% of the rock.

	Sample numbers			
CLAST TYPE	150	151	163	166
Minerals	Percentages			
monocrystalline plagioclase	18	22.5	19.5	16.5
polycrystalline plagioclase	5	3	2.5	1
total plagioclase	23	25.5	22	17.5
monocrystalline quartz	10.5	10.5	5.5	9
polycrystalline quartz	3	1	2	2
total quartz	13.5	11.5	7.5	11
epidote	1	1	1	1.5
biotite	1	1	0.5	0.2
chlorite, matrix or clastic	8	8	5.5	11
clinopyroxene	0.5	-	2.5	0.5
sphene	0.5	-	0.5	-
hornblende	0.5	-	2	1.5
unidentifiable clasts, now sericitic	1.0	3.5	3	1.5
prehnite	4.5 -- either clastic or authigenic	0.3 --not known if clastic or authigenic	1.5 -- clastic	2 -- clastic
Lithic Fragments				
microcrystalline quartz ± plagioclase	classed with "other lithics"	5	4	2
dark, fine sedimentary	4.5	4.5	7.5	5.5
metamorphic, foliated	1.5	-	0.5	0.5
feldspathic volcanic	29.5	32	32.5	34.5
cpx. + fldsp. volcanic	0.5	-	2	0.5
chloritic, probably volc.	0.5	2	-	0.5
plagioclase + hornblende	0.5	-	2	-
other lithic fragments	11	8.5	9	9.5

Table 1. Percentages of different clasts in sandstones from south Lummi Island, determined by point-counting 400 points in thin section.

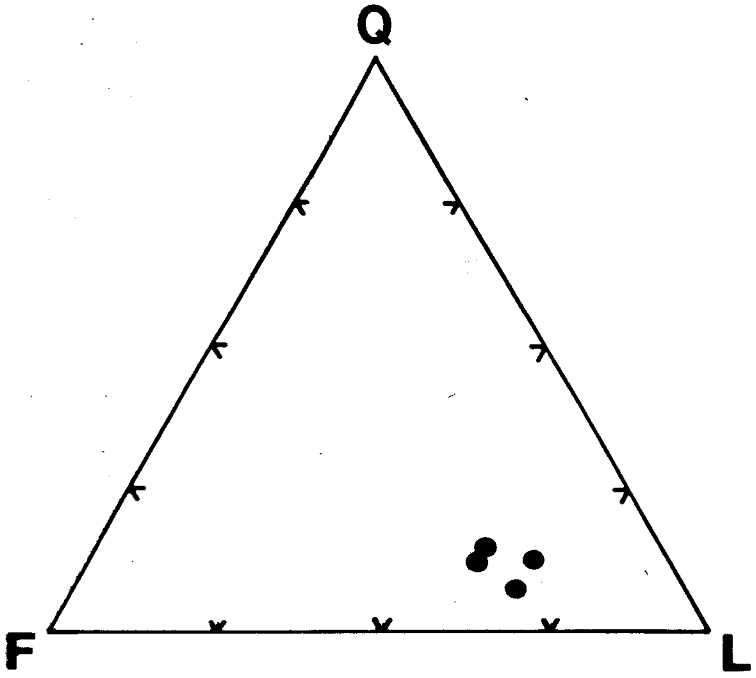


Figure 6. Q-F-L plot of sandstones point-counted in thin section. Q = mono- and polycrystalline quartz, F = mono- and polycrystalline plagioclase feldspar (no K-feldspar present), and L = all lithic fragments.

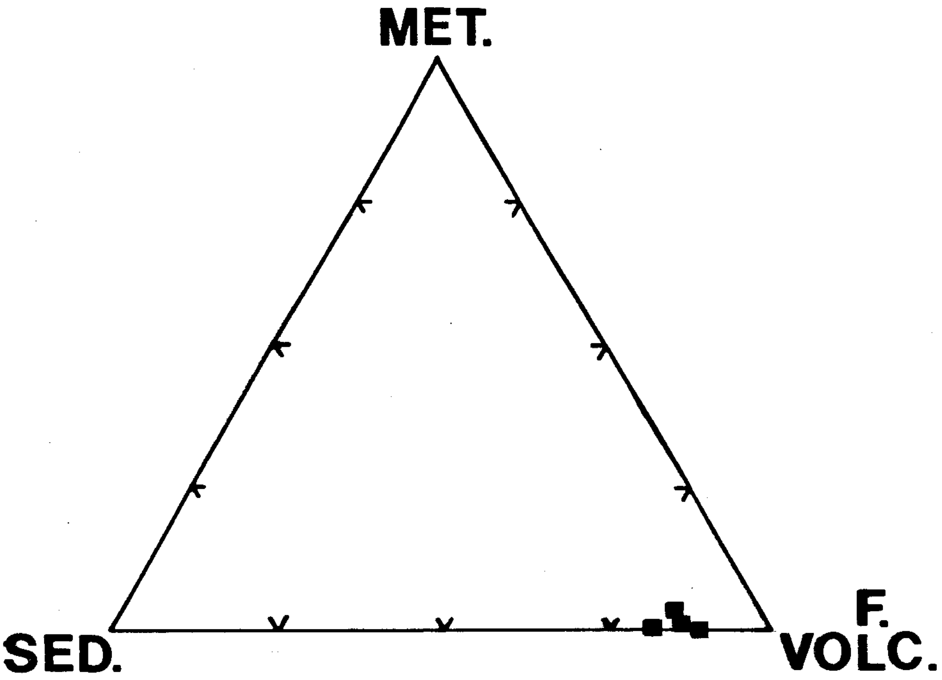


Figure 7. Plot of lithic clast types determined by point count in thin section. SED. = dark, fine-grained sedimentary rock fragments, MET. = foliated metamorphic rock fragments, and F. VOLC. = feldspathic volcanic rock fragments, lacking obvious primary mafic minerals.

Metamorphic Minerals

Veins in sandstone most commonly display quartz and pumpellyite, and commonly have aragonite, calcite, lawsonite, chlorite and sericite. Prehnite and plagioclase (albite) were only found in one sample. Datolite, a calcium-boron silicate associated with zeolites, prehnite and calcite in basic volcanic rocks (Deer and others, 1966) was found in three samples, all in domain II. Pumpellyite is generally colorless, or, rarely, weakly pleochroic. Atypically large (1 mm. long) and idiomorphic columnar to lathlike lawsonite crystals occurred in three samples. In two of these samples, they were clustered around the rims of clots of pumpellyite aggregates replacing sedimentary material. All other lawsonite in all lithologies on Eliza and Lummi Islands occurred as turbid, fibrous mats, such as was figured in Glassley and others (1976). Aragonite is inverted to calcite to varying extent. Pumpellyite and datolite are intergrown in one vein. One occurrence each of datolite, colorless pumpellyite, and euhedral lawsonite was confirmed by X-ray diffraction, using powdered veins in which each occurred alone with quartz. The identification of lawsonite, in its fibrous habit, was confirmed by X-raying one powdered vein in which it was particularly abundant.

The metamorphic assemblage in the sandstones consists of sericite and chlorite growing parallel to cleavage, lawsonite growing in detrital plagioclase, lithic fragments or quartz, and late replacement by calcite.

Age

Nearly at the base of the exposed sequence on Lummi (NW¼ SW¼ Section 36, T. 37 N, R. 1 E) is a 6 m. section of red and green chert which thins and becomes thinner-bedded north along strike until it finally grades into thin-bedded sandstone and mudstone. The upper contact appears conformable, while the lower contact is obscured. South along strike the chert is apparently faulted, as it abruptly terminates, reappears farther south at a lower elevation, and then disappears again. In this last exposure, the section is about 6 meters thick, thinner-bedded and more shaly at the top than at the base, and overlies mudstone-rich and underlies sandstone-rich sequences. Radiolaria from these cherts were dated as Late Jurassic-Early Cretaceous in age (D. L. Jones, pers. comm., 1979).

More Strongly Foliated Rocks of Similar Lithology

The strongly foliated rocks of Eliza Island and domain I, and occurring within domain V (Fig. 3), are in general more recrystallized than the sandstone and mudstone found elsewhere, but have essentially the same metamorphic minerals (lawsonite growing within clasts, sericite and chlorite growing within or parallel to cleavage), and aragonite, calcite, quartz, plagioclase, sericite, and in one case, lawsonite in veins. Plates III-VI show the development of cleavage and associated development of mica along that cleavage, plus flattening and recrystallization of clasts, especially volcanic lithic fragments, to microcrystalline mosaics of quartz and plagio-

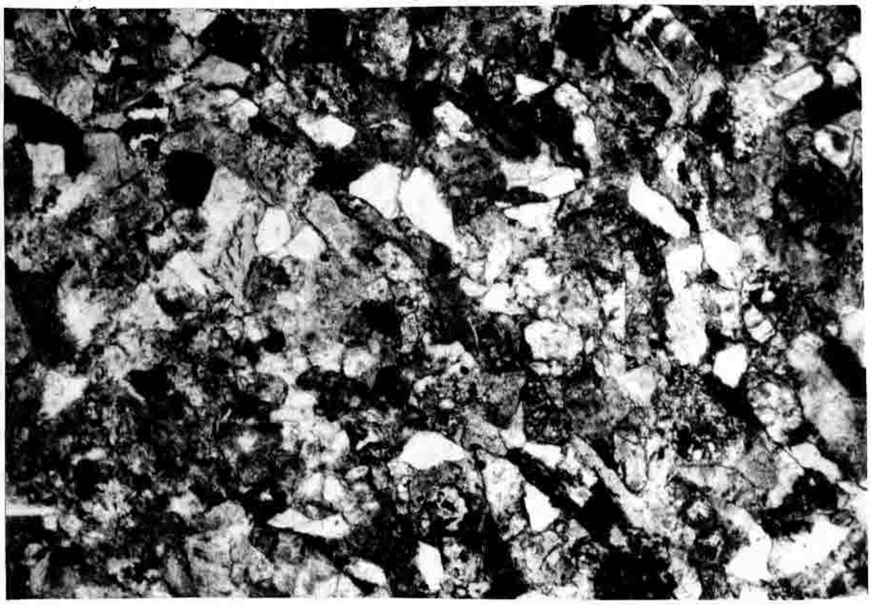


Plate III. Photomicrograph of sandstone from domain II lacking cleavage, or flattening of clasts. Plane light.

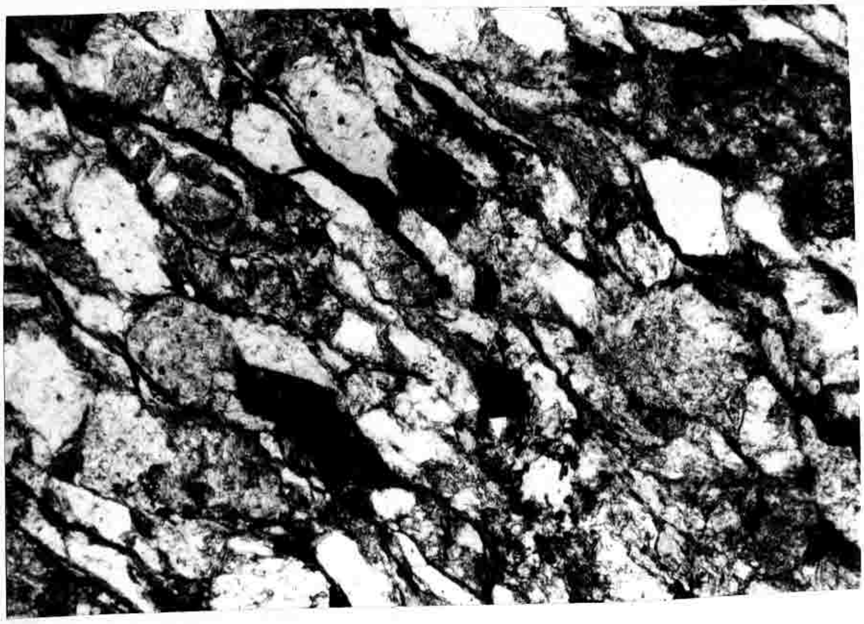


Plate IV. Photomicrograph of sandstone from domain III showing some flattening of clasts, moderate cleavage development. Plane light.

Plate V. Photomicrograph of sandstone from domain I showing strong cleavage, pronounced flattening of clasts. Sample 154, plane light.

Plate VI. Photomicrograph of sandstone from Eliza Island, north knob, showing very strong or phyllitic cleavage with extensive flattening and recrystallization of clasts. Sample 113q, plane light.

clase. Sample 154 is from domain I, and typifies these very foliated rocks, while 113q was collected on the north peninsula of Eliza Island, and represents the most extremely recrystallized rock seen in thin section. In it, porphyroclasts of relict quartz, plagioclase and epidote are the only phases not totally recrystallized and severely flattened. In rocks from Eliza Island, the cleavage is associated with a lineation defined by spindle-shaped clasts; in sections perpendicular to that lineation, micas are crenulated by the cleavage, whereas in sections parallel to the lineation, the micas parallel cleavage.

VOLCANIC ROCKS AND ASSOCIATED LITHOLOGIES ON LUMMI ISLAND, EXCEPTING SUNRISE

Lithologic Description

Rocks of this group occur in isolated outcrops throughout the northern half of the island, with only one outcrop occurring in the south, between Reil Harbor and Deepwater Bay. Generally they consist of aphanitic, green pillowed basalts or pillow breccias with occasional diabase, chert, and minor limestone and tuff. Unusual rocks are present at the Legoe Bay exposure, where nearly half the exposure is a sedimentary volcaniclastic breccia, with associated, apparently bedded argillite.

Primary Textures and Mineralogy of Volcanic Rocks

With the possible exception of the rocks at Legoe Bay, the volcanic rocks exposed at different localities on Lummi have primary textures and mineralogy similar to each other and typical of basalt. All that can be recognized of the primary mineral assemblage is plagioclase feldspar, augite and what must have been areas of glass near the edges of pillows. Quartz, present as small and poorly formed crystals, may be secondary in origin. Alteration makes the textures of the feldspars hard to see, but the lavas are generally intersertal to intergranular, and some of the more coarsely crystalline (2 mm.) rocks display subophitic texture. The pillowed lava from Legoe Bay features large amygdules and large clinopyroxene phenocrysts in a much finer martix of felted feldspar microlites and alteration minerals such as sphene and chlorite.

Toward the edges of pillows hyalopilitic texture is developed. In such areas chlorite pseudomorphs plagioclase phenocrysts up to 1.2 mm. in length. However, most plagioclase crystals are about .5 mm. long, while granular, isolated augite crystals are half that size; occasionally these minerals occur in clusters. Characteristically these crystals, especially the feldspar needles, are encased by a feathery radial growth of clinopyroxene (figured in Moorhouse, 1959, p. 167, fig. 95B), identified by X-ray diffraction as augite.

One sample of massive, unveined basalt from the Reil Harbor outcrop has rare earth element abundances and distribution most closely similar to those found in present-day mid-ocean ridge tholeiites (Vance and others, 1980).

Metamorphic Minerals in Volcanic Rocks and Associated Veins

Vein minerals from volcanic rocks near Reil Harbor show some differences from those near Migley Point (Table 2). The former consist of nearly ubiquitous aragonite, pumpellyite, chlorite and calcite (in part inverting from aragonite), and less common plagioclase (albite), sericite and quartz. Three samples had veins containing possible lawsonite, two contained datolite, and one had prehnite in association with pumpellyite and lawsonite. The prehnite is altered to calcite and may be altered to lawsonite.

Veins in the volcanics near Migley Point also typically show pumpellyite, chlorite and calcite, and less commonly sericite and quartz. Only one sample contained vein plagioclase, though, and none had datolite or aragonite. Moreover, epidote was present in 3 of the 6 rock samples, and stilpnomelane in two.

The volcanic rocks from the Migley Point and Reil Harbor outcrops show much the same metamorphic minerals that the veins did (Table 2). Recognizing that aragonite and datolite are not expected in rocks of this composition outside of veins, the significant differences are again that stilpnomelane and epidote are present in some of the Migley Point rocks and absent in the rocks of Reil Harbor.

The samples of volcanic rocks from Legoe Bay are few, but typically show the metamorphic minerals calcite, pumpellyite and chlorite. One rock of dubious origin is thoroughly altered to prehnite, with associated quartz, calcite, chlorite and sericite.

OUTCROP AND ROCK	NUMBER OF SAMPLES	QTZ.	ARAG.	CC.	LAWS.	PUMP.	PREHN.	CHLOR.	PLAG.	SERIC.	STILP.	DAT.	SPH.	EP.
Reil														
Volc.	17	3	-	-	-	5	-	15	-	1	-	-	10	-
Veins	18	8	15	16	3?	13	1	17	5	4	-	2	1	-
Migley														
Volc.	6	2	-	3	-	5	-	4	-	1	2	-	2	2
Veins	6	2	-	4	-	6	-	5	1	3	2	-	1	3

Table 2. The number of samples from the volcanic rocks of Migley Point and Reil Harbor in which various metamorphic minerals were identified in thin section.

Only one sample, apparently a metamorphosed tuff, was collected from the exposures near Lummi Point. It has no veins, and is thoroughly altered to chlorite, epidote and sericite.

Metamorphic Minerals in Associated Lithologies and their Veins

Chert, a few small pods of limestone, and, at one locality, a small outcrop of a breccia with clasts of chert and limestone in a black, graphitic, very fine-grained sedimentary matrix are associated with the volcanic rocks between Deepwater (or Inati) Bay and Reil Harbor. Metamorphic minerals found in all these rock types are consistent with those of the associated volcanic rocks, except that prehnite occurs more commonly, in veins in chert and as crystals growing in the black matrix of the breccia. The latter occurrence was confirmed by X-ray diffraction.

Cherts, "dirty" limestones and fine-grained sedimentary rocks also are associated with the volcanics near Migley Point. Stilpnomelane is present in all these rock types in contrast to its absence in similar lithologies occurring near Reil Harbor. One sample of fine-grained sedimentary rock from Legoe Bay has prehnite and chlorite, while others have chlorite or clays ± quartz.

Age

Two samples of chert associated with the volcanics near Reil Harbor were dated, one as Middle Jurassic or younger, and the other, post-middle Bajocian to pre-Tithonian, by Dr. Emile Pessagno (Whetten and others, 1978). The pillow basalts at Legoe Bay were dated more directly by retrieving radiolaria from black mudstone interstitial to the pillows. Pessagno also identified these radiolaria as post-middle Bajocian to pre-Tithonian (Whetten and others, 1978). Chert and tuff from the Migley and Lummi Points exposures contained relict radiolaria in thin section, but Dr. David Jones found the remains too recrystallized to date, other than noting their probable Mesozoic age (pers. comm., 1979).

ROCKS OF THE MIDDLE JURASSIC IGNEOUS COMPLEX ON LUMMI

This complex of igneous rocks crops out only in moderately poor exposures on a hill inland on Lummi ("275" in Fig. 1) and was first described by Calkin (1959). Three different rock types are exposed. Staining of the thin sections revealed no potassium feldspar in any of them.

Hornblende Gabbros

Fine to medium-grained hornblende gabbros comprise the principal rock type. Their mineral assemblage consists of amphibole (50-70%) and altered plagioclase, with a varying amount of an allotriomorphic opaque mineral, plus a minor pale brown mineral with low birefringence (chlorite?) and in one sample, less than one percent quartz. The amphiboles are generally hypidiomorphic, blue-green actinolitic hornblendes, although some uralite is present, and occur in connected clumps of highly variable shape. In two samples, large clinopyroxene (augite?) crystals are partly altered to aggregates of equigranular hornblende, or occasionally also to uralite. Anorthite content of the plagioclase was difficult to measure because of the generally extreme saussuritization, but four measurements (An 27, 30, 45, 65) were obtained using the A-normal method on a flat stage, and two more (An 59, 63) were taken on a 6-axis universal stage using the Rittman zone method. Apparently plagioclase of labradoritic composition has lost varying amounts of calcium due to alteration and now spans a variety of compositions.

Some of the hornblende gabbros display a foliation defined by thin, sometimes discontinuous laminae of hornblende and/or by preferred crystallographic orientation of the amphiboles. In these foliated gabbros, laminae of hornblende bow out around rounded aggregates of hornblende and minor uralite. It is possible that these aggregates are altered clinopyroxenes. In one sample, a well-laminated hornblende gabbro has been intruded along its foliation by a coarse-grained rock consisting mostly of plagioclase (up to a cm. long) and minor idiomorphic hornblende of similar size. Both rocks, and the foliation, are cut by another hornblende gabbro, also crudely foliated, in this case with its foliation parallel to its contact. The grain size of this gabbro also appears to become finer towards that contact. Both gabbros have the afore-mentioned amphibole aggregates. Both also have relatively unaltered mosaic plagioclase, but the older gabbro has, in addition, large irregular areas of nearly completely altered plagioclase. Anorthite contents (An 24, 51, 70) were measured on the universal stage for three crystals of the less altered plagioclase in the older rock.

Brown and others (1979) describe foliated hornblende gabbros similar to these belonging to the Fidalgo Ophiolite, exposed about 25 km. south of the exposure on Lummi. In addition to the foliation observed, they describe other apparent metamorphic characteristics of the rock, yet excellent exposures afford apparently unequivocal evidence of the intrusive character of the Fidalgo hornblende gabbros. Their interpretation may be valid for the Lummi gabbros also.

Trondhjemitic and Porphyritic Rock Types

Two other rock types occur in the Lummi exposure, both apparently also seen by Brown and others (1979, especially fig. 3) on Fidalgo Island, and interpreted by them to be also hypabyssal. On Lummi, a grey brown biotite-bearing porphyritic rock with plagioclase phenocrysts and about 20% quartz in the matrix was observed. Its relation to the hornblende gabbro is not clear. Both the gabbro and this porphyritic rock are intruded by a foliated biotite-bearing rock consisting mainly of normally zoned plagioclase (5 crystals averaged An 17 in cores (generally altered) and An 10 in rims (generally unaltered)) and quartz, in roughly equal amounts. The foliation in these trondhjemites is parallel to their contacts and consists of thin undulatory seams of microcrystalline quartz which wrap around large plagioclase crystals, and along which biotite, pumpellyite and epidote are concentrated. A parallel foliation defined by discontinuous undulatory seams of crudely foliated biotite is seen in thin section in the porphyritic rock where it contains trondjhemite veins. Whether the foliation exists farther from such veins is not known. In one sample, similar relations occur between the trondjhemite and an unusually fine-grained hornblendic rock, except that the foliation in the latter rock is defined by seams of foliated biotite and hornblende. Although relationships exposed on Lummi do not unequivocally prove the intrusive nature of either the porphyritic rock or the trondjhemite, that origin seems probable.

Metamorphic Minerals

Of 9 rocks sectioned from this complex, only one did not have prehnite in veins. Vein minerals seen were prehnite ± quartz ± plagioclase, and in one rock, prehnite, pumpellyite and quartz. Thorough alteration of the country rock to prehnite and/or pumpellyite occurred around some veins. Pumpellyite is found growing in feldspar, unassociated with veins, in the trondjhemitic rocks. Isolated anhedral epidote is a minor phase in the porphyritic and trondjhemitic rocks, but does not occur in the hornblendic rocks.

Age

Zircons separated from a a meter thick trondjhemitic layer, presumably a dike, in the hornblendic rocks were dated by Robert Zartman. Nearly concordant Pb/U ratios were obtained, and it is believed that these, and particularly the 206 Pb/238 U ratio, give the best estimate of the age (Whetten and others, 1980). The 206/238 ratio yields an age of 160 ± 3 my. Since this date was obtained from what is presumed to be a dike, it strictly is a minimum age for the hornblendic rocks, the bulk of the Lummi exposure. Similar ages were reported by Brown and others (1979) from similar intrusive rocks of the Fidalgo Ophiolite. Although these dated plagiogranitic rocks are demonstrably younger than the layered plutonic part of the complex, and do not involve magma produced by "fractionation of the same melt that crystallized layered gabbro" (Brown and others, 1979), Brown and others (1979) still assume the ages obtained date the complex as a whole.

ROCKS EXPOSED AT SUNRISE COVE

Lithologic Description and Age

Outcrops at Sunrise Cove expose a faulted, veined complex of breccias, monolithologic breccias, and smeared, mixed rocks, all showing some phaneritic texture, intercalated or intermixed more or less intimately with less disrupted areas of pillow breccias. On the northern tip of Echo Point (the north side of Sunrise Cove) a fault-bounded lens of mafic-rich sandstone occurs in the breccias. This complex seems bounded to the north (along the north shore of Echo Point) by a thin belt of less deformed rocks of two types: first, basaltic lavas, in part pillowed, with minor associated radiolarian chert dated by Dr. David Jones as Middle Jurassic in age, and second, cleaved sandstone-mudstone sequences similar to those of south Lummi, but striking almost due east-west and dipping steeply north. These two rock types appear to occur as interleaved lenses.

Description of Rocks in Thin Section

The rocks exposed at Sunrise Cove are severely altered, texturally and mineralogically, by cataclasis, extensive veining and spectacular (associated?) alteration of all relict phases (amphibole to chlorite and uralite, clinopyroxene to uralite, and plagioclase to pumpellyite, sericite and prehnite). Recognizable relict rock types include fine-grained (.5 mm.) hypidiomorphic epidotite, unfoliated coarse-grained (3 mm.) hornblende and plagioclase showing subophitic texture, and panidiomorphic-granular plagioclase and hornblende ± epidote. Vein minerals include prehnite, pumpellyite, chlorite, sericite, plagioclase and quartz, with the first two dominating. Calcite is occasionally found, and one occurrence of possible lawsonite was noted. Prehnite and especially pumpellyite form large areas of these rocks, presumably by alteration of plagioclase, since floating relicts of uralitized amphibole or clinopyroxene are found in these areas.

SUMMARY OF METAMORPHISM

The presence of aragonite, lawsonite and quartz, and associated prehnite and pumpellyite in the sedimentary rocks of south Lummi indicates metamorphism at a relatively high P/T (Glassley and others, 1976, Vance, 1977). The volcanic rocks near Reil Harbor have developed much the sam metamorphic assemblage. Aragonite is widespread in the rocks of south Lummi, occurring exclusively in veins, while calcite is the polymorph found in small limestone pods in chert associated with rocks having aragonite veins. It seems likely that this aragonite, at least, was not formed metastably from strained calcite, as has been suggested elsewhere in the San Juan Islands (Newton and others, 1969, Vance, 1977). However, lawsonite on Lummi seems more abundant than has been described in these other areas (Glassley and others, 1976, Vance, 1977), though the lawsonite on San Juan Island (Brandon, 1980) seems as abundant as that on Lummi. In contrast to other San Juan Islands (Glassley and others, 1976, Vance, 1977, Brandon, 1980) pumpellyite is more abundant than prehnite on south Lummi, and is a very typical mineral in all areas of Lummi. Prehnite is only locally abundant, and seems to be correlated with rocks showing pervasive internal shearing, or proximity to such rocks. Prehnite, in fact, seems a better candidate than aragonite on Lummi for metastable formation somehow related to strain (Vance, 1977). Lawsonite is never oviously foliated, either in veins or in flattened detrital clasts, and probably grew after the cleavage formation.

In contrast to the general metamorphic assemblage in south Lummi, rocks of the north half of the island lack aragonite, have only one possible occurrence of lawsonite, and instead typically bear epidote, stilpnomelane, prehnite, pumpellyite, and other low grade metamorphic minerals. The lack of minerals suggesting higher P/T metamorphism is striking, but interpreting the regional significance of this distribution is tenuous at this time. The difference is probably related to the fault zone on Lummi linked to the Vedder Discontinuity (Danner, 1977), discussed later in this paper.

CHAPTER III: STRUCTURE

METHOD OF STEREOGRAPHIC PROJECTION

All stereographic projections were performed using a computer program (Brandon, 1980) modified from Kamb (1959). This procedure expresses the density of the points plotted as statistical deviations from an expected density if the distribution were random. The actual population density is then expressed as standard deviations from this expected density, and ranges from zero-sigma upwards (negative sigma values are not possible). In all diagrams presented in this thesis, contours are at intervals of three sigma, the first contour being the three-sigma contour. Statistically significant overpopulation is taken to begin at the six-sigma level; the area more overpopulated than six-sigma is stippled on all diagrams. Only those stippled areas show significant concentrations of points, but points can most certainly exist outside the stippled area. In figures 17 and 19, the three-sigma contours are omitted for clarity. In all diagrams, the number of points plotted is given, or the points are actually plotted, and North is shown (East is clockwise; these are lower hemisphere, equal-area projections).

The computer program also derives the directions in which the maximum, minimum and intermediate population densities occur. Any average cited concerning a stereographic diagram is this calculated maximum density direction, and any beta-axis mentioned is the minimum density direction. (Any girdle plotted is the great circle to such a calculated minimum density pole.

BEDDING AND CLEAVAGE RELATIONSHIPS, AND RELATION TO FOLDING

Domains I-IV, South Lummi

Structural dissimilarities allow division of south Lummi Island into five principal domains (Table 3, Figs. 8 and 9). Four other areas are distinctive but are either small or offshore of Lummi (Table 3, Figs. 1 and 3). In general, bedding on south Lummi strikes northwest and dips moderately northeast, while cleavage (either slaty cleavage in mudstones or a flattening of clasts in sandstones) strikes subparallel to bedding, and dips more steeply. The sequence is right side up except in domain I and on Eliza Island, where there are overturned folds. Intensity of cleavage varies, being weakest where the bedding is least disrupted (domain II), and strongest when mesoscopic folding is present. Very generally, cleavage increases in intensity away from domain II--to the south and down-section to the west.

Average bedding and cleavage attitudes derived from stereonet analysis of the five domains (Figs. 8 and 9) exhibit the following four characteristics. First, cleavage attitudes are more uniform than bedding, in comparisons between the domains. Second, cleavage strikes (on average) subparallel to bedding and dips about ten degrees more steeply. Third, dips of both bedding and cleavage decrease west across the island--particularly from domains II and III to IV, and domain V could occupy an intermediate position in the

AREA	DEVELOPMENT OF CLEAVAGE (as seen in ountcrop)	CHARACTERISTIC ATTITUDES OF BEDDING AND CLEAVAGE	OTHER CHARACTERISTICS
Domain I	Very strongly developed axial planar cleavage in both sandstone and mudstone.	Generally strong westerly strike of both bedding and cleavage, which dip moderately north-northeast.	Tight, overturned folds. Thinner bedded sandstones than elsewhere on Lummi.
Domain II	Moderate to absent cleavage, observable only in mudstone.	Bedding strikes very uniformly, Cleavage consistently strikes east of associated bedding.	Sole marks, burrows, coalified woody plant remains are common.
Domain III	Moderate to strong cleavage, always developed in mudstone; some flattening usually seen in sandstone.	Bedding attitudes show more variation than in II; cleavage consistently strikes west of associated bedding.	Veining and faulting are common.
Domain IV	Similar to III.	Generally, the shallowest dips of both bedding and cleavage on Lummi.	
Domain V	Similar to III.	More westerly strike of bedding and cleavage than III, and more gentle dips.	Zones of very strongly flattened rock faulted against less foliated rock.
Lummi Rocks	Cleavage very weak to absent.	Bedding strikes north to northeast.	
Viti Rocks	Similar to III.	Bedding and cleavage dip west.	
Fold NW of Carter Pt.	Similar to III.	Bedding dips west, while cleavage dips east.	
Eliza I.	Very strongly deveolped axial plane cleavage in both sandstone and mudstone.	Bedding generally dips gently east; cleavage is more uniform, also gently east-dipping.	Open to tight overturned mesoscopic folds. More thinly and regularly bedded than most of Lummi.

Table 3. Distinguishing characteristics of structural domains on Lummi Island and vicinity.

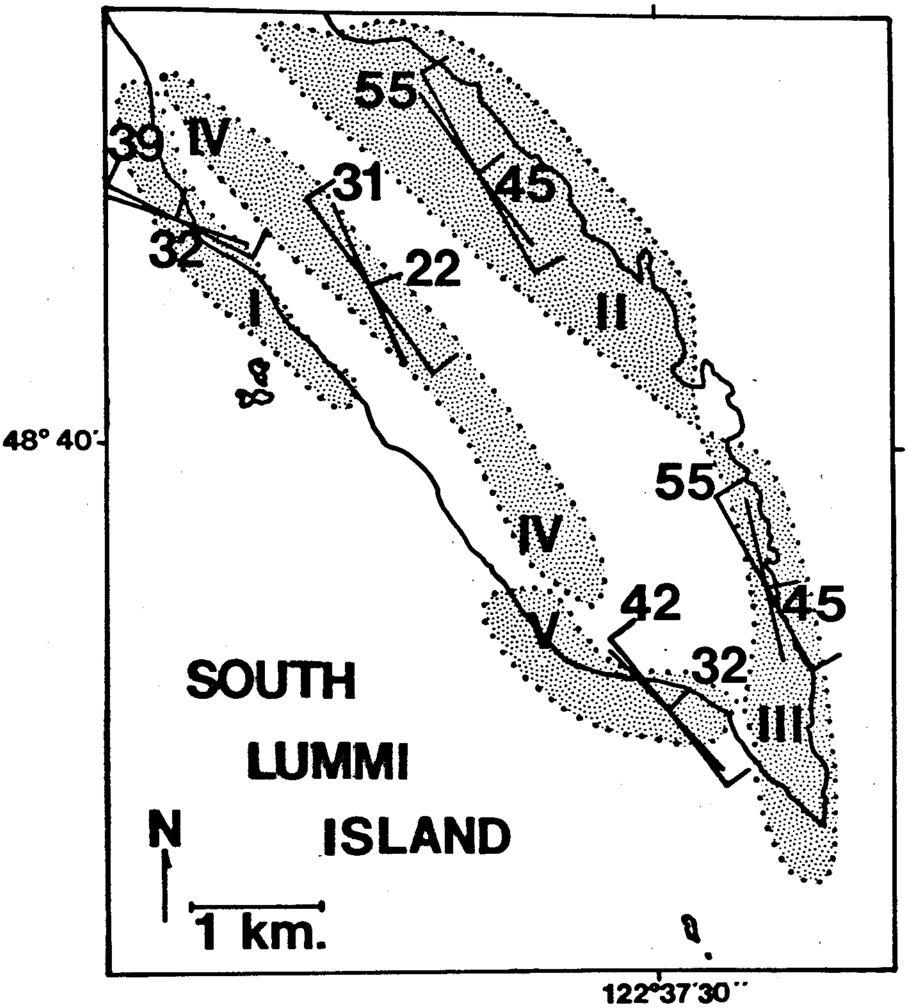


Figure 8. Average attitudes of bedding and cleavage in five structural domains on south Lummi Island. Attitudes are derived from stereographic plots of all attitudes within each domain (Fig. 9).

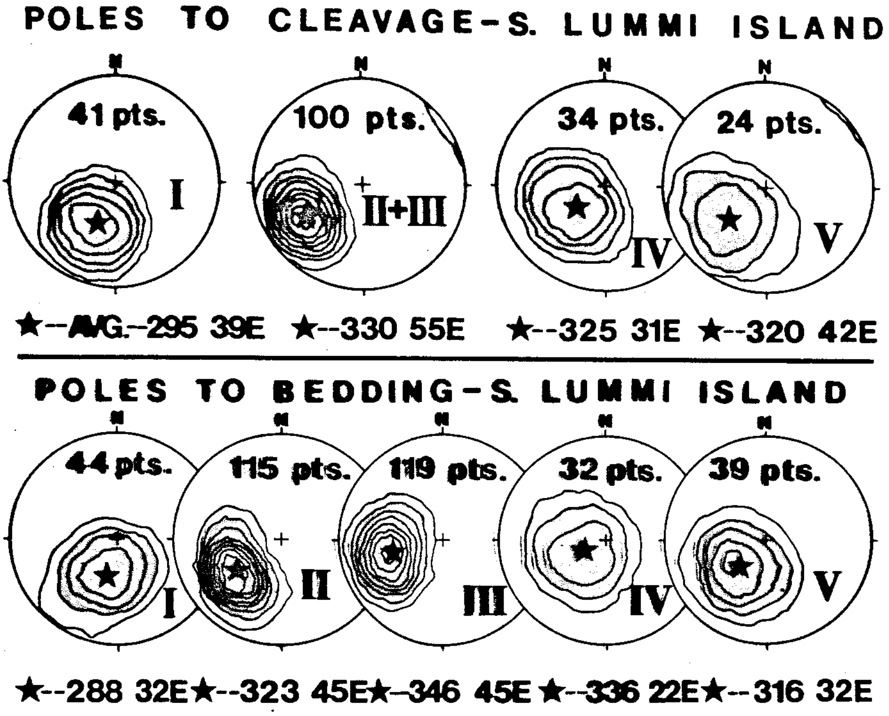


Figure 9. Stereographic plots of bedding and cleavage in five structural domains on south Lummi Island. The star indicates the average of the distribution for each plot, also given numerically as strike and dip below each diagram.

trend. The difference in dip between bedding and cleavage remains consistent at ten degrees, however. Fourth, domain I has an anomalously westerly strike of both bedding and cleavage, and does not fit the trend of westward-shallowing dips. Domain I shows tight folds to which the cleavage is axial planar. Interestingly, the strongly developed cleavage found in fault-bounded exposures in domain V has almost exactly the same average orientation (Fig. 10). Bedding attitudes were not numerous enough for comparison.

Bedding attitudes that deviate markedly from adjacent measurements (Fig. 2, most noticeably in domains II and III) are associated with a cleavage whose orientation is either similar to that of the average of the domain, or deviates from that average and thus more closely approximates the average relationship of bedding to cleavage found in the domain. This implies that rotation of bedding on a small scale occurred both before (by unknown mechanisms) and after (probably by faulting) the development of cleavage. The suggestion of pre-cleavage disruption of bedding is also supported by the observation previously made that, in comparing averages between domains, the orientation of cleavage shows more uniformity than that of bedding. In particular, the different average bedding attitudes of domains II and III (Fig. 8) relative to a more constant cleavage (average for II = N28W 57E, for III = N29W 55E) produce the clockwise (II) and counterclockwise (III) relationship of cleavage strike to bedding strike seen in figure 8. That this is not simply

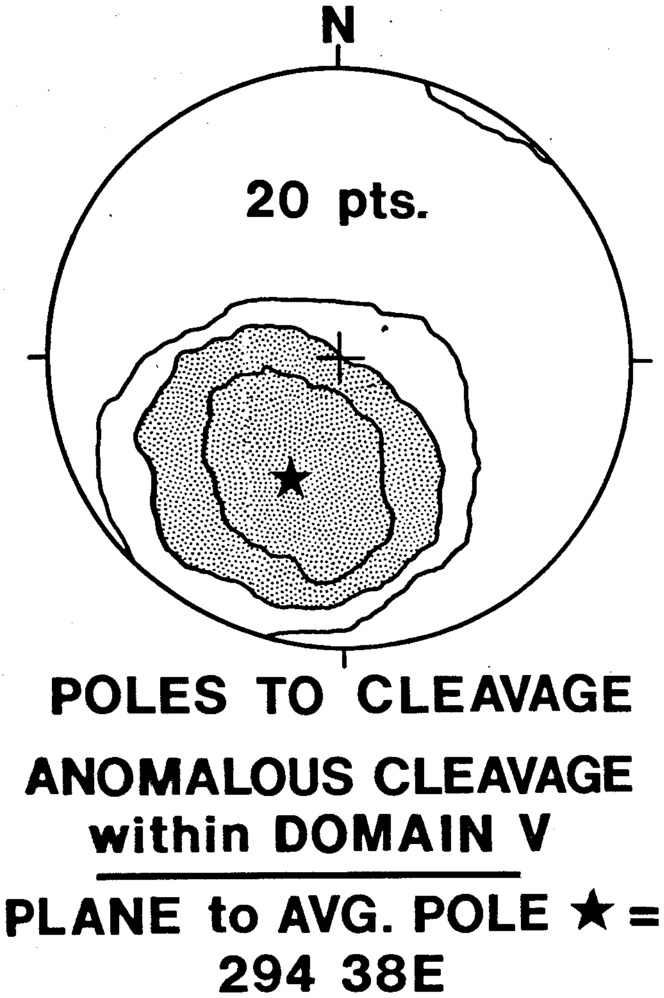


Figure 10. Stereographic plot of poles to very strong cleavage within domain V.

an artifact of averaging is shown by individual measurements of bedding and associated cleavage in the two domains. In domain II, 16 of 20 are of the clockwise relationship, and in domain III, 13 of 17 are counterclockwise. This strongly implies that domain II as a whole was rotated relative to domain III before cleavage formation.

Area Northwest of Carter Point, South Lummi

Northwest of Carter Point on Lummi is a small area of shoreline along which a northerly plunging anticline is exposed (Fig. 2). The fold terminates at a cataclastic zone shown as a northeast-trending fault, which, in outcrop, does not show any cleavage. Throughout this fold, the cleavage orientation remains constant and similar to that of domain III.

If a cleavage is axial planar to a fold, the pole to that cleavage should plot on the girdle of an S-pole diagram of the folded surface. The bedding attitudes of the hinge and west-dipping limb define a fairly tight girdle (Fig. 11) whose β-axis is N36W 17. The average cleavage of domain III does not fall on this girdle. All of Carter Point could be considered the east limb of this anticline, so to represent that half of the fold the next 10 attitudes south of the hinge along the shoreline were added to the diagram. These attitudes are more scattered than the former and do not lie along their girdle, but their addition to the diagram defines a new girdle (β-axis N19W 09) which nearly intersects the domain III cleavage. That cleavage still seems to dip less steeply than the appar-

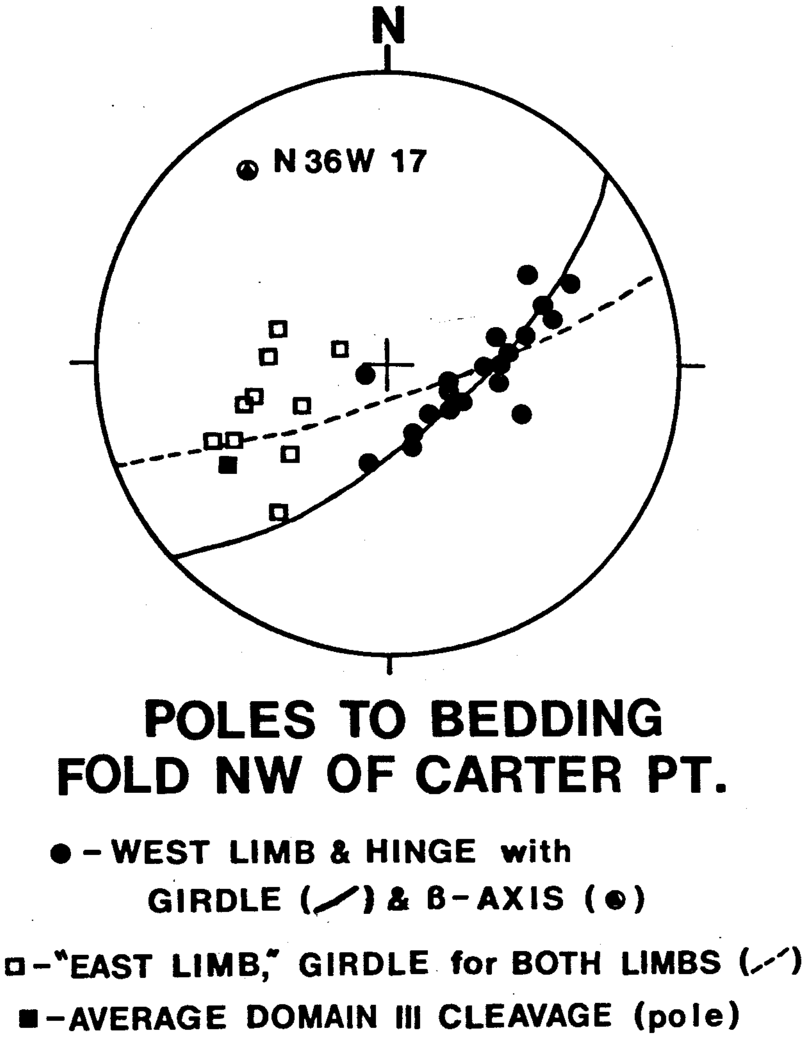


Figure 11. S-pole diagram of fold northwest of Carter Point.

ent plane of symmetry of the fold. In summary, the data are too limited to define a girdle with certainty, but all indications suggest that the cleavage is not exactly axial planar, but intriguingly close.

Viti Rocks

Moderate to steeply west-dipping beds are exposed on Viti Rocks (Fig. 1) with an associated cleavage dipping more steeply southwest. These west-dipping beds and those of the area northwest of Carter Point invite comparison, but the cleavages, though of similar strike, differ in dip direction. The cleavage might not originally have been uniformly oriented (if associated with folding, perhaps the cleavage fans divergently, although that was not observed in the fold northwest of Carter Point). Alternatively, rotation of the cleavage (in a domain II or III relationship to bedding--not that of the west limb of the afore-mentioned fold) might have occurred after cleavage formation. This last possibility is strengthened by the rotation of cleavage noted between the east shore of south Lummi and domain IV. South to southwest dips of bedding and cleavage observed in reconnaissance by the author on Sinclair Island, southwest of Lummi (Figs. 1 and 12) suggest that this rotation of cleavage could be regional in extent.

Lummi Rocks

Structurally, Lummi Rocks are anomalous only in that the beds

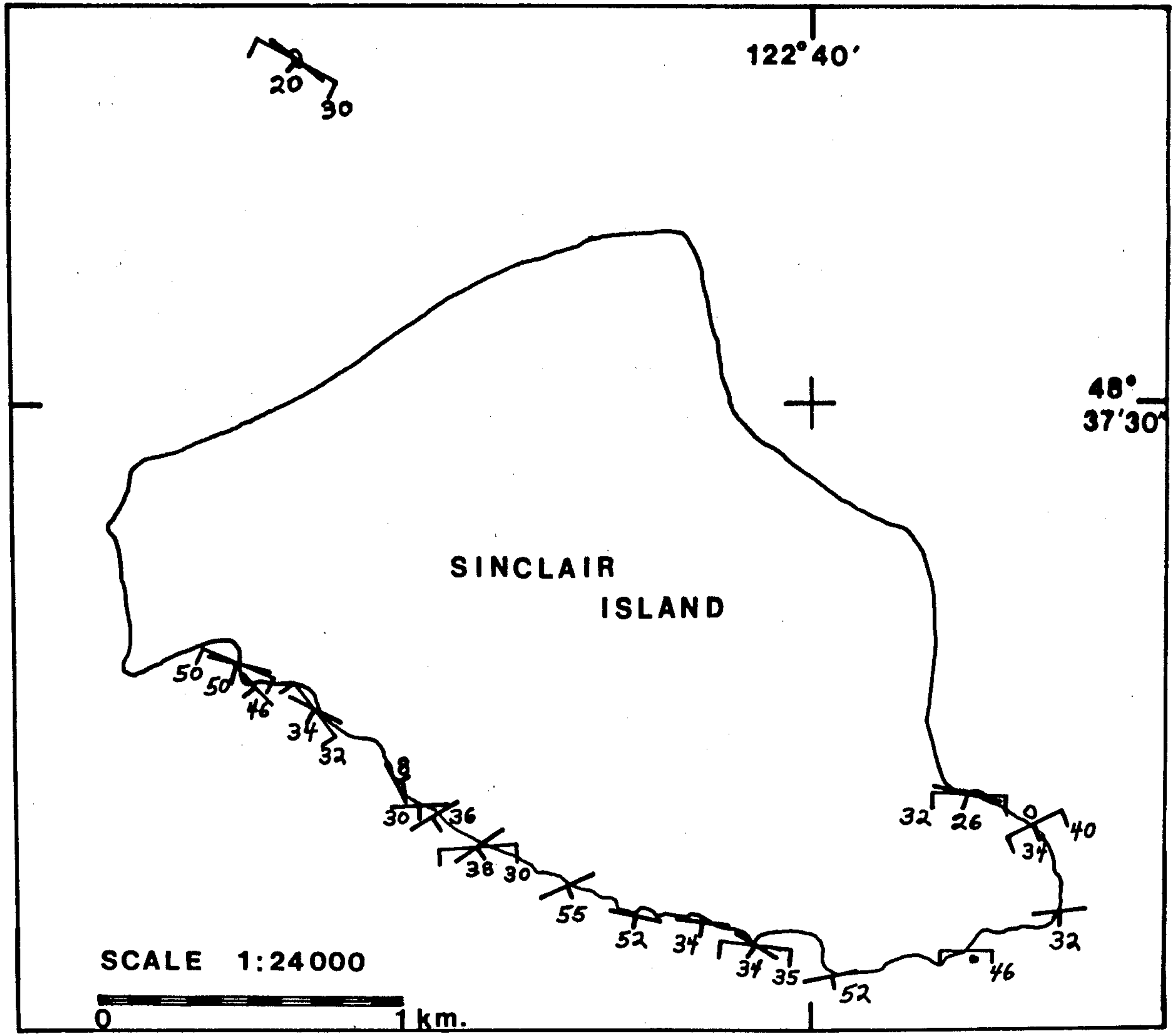
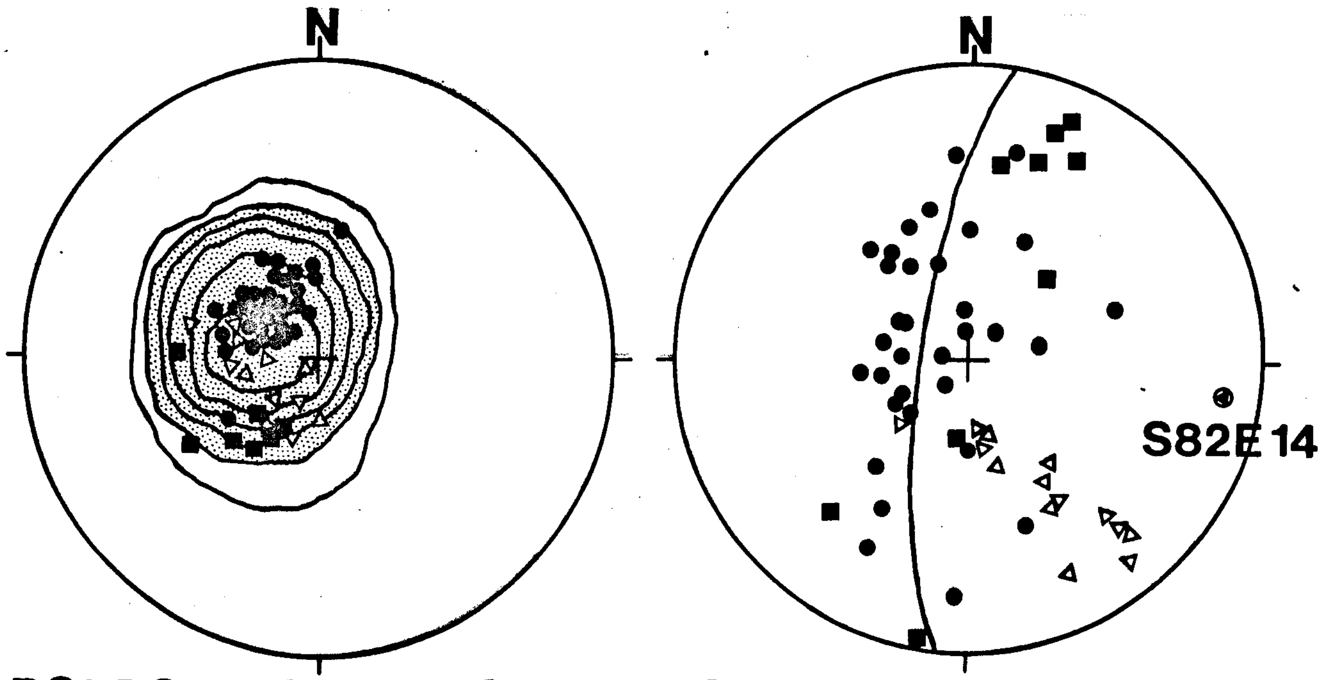


Figure 12. Bedding and cleavage attitudes in sedimentary rocks on Sinclair Island.

strike more to the northeast than is typical of south Lummi, appear to be gently warped, and have a nearly non-existent cleavage. This last is in sharp contrast to the nearby rocks of domain I. It is likely that a fault of unknown displacement, not necessarily large, separates Lummi Rocks from the main island.

Eliza Island

Shale and sandstone on Eliza Island are typified by a very strong cleavage that consistently dips shallowly east (Fig. 13). Very gentle antiformal warping of the cleavage across the island is indicated by the separation of attitudes (in figure 13) measured on each of the three knobs or peninsulas of the island. Folding is present on the north knob, but is well displayed only on the southeast knob, where the cleavage is axial planar to open to tight, overturned folds generally a meter or two in amplitude (Fig. 14). Bedding attitudes for the southeast, and probably also the north knob fall along a great circle whose pole (S82E 14) (Fig. 13) is roughly coincident with the average measured axis of folding (S70E 19) (Fig. 14). Bedding on the southwest knob (on which no folds are visible) is definitely discordant to this great circle and yet shares nearly the same cleavage orientation as the folded rocks. Some pre-folding, pre-cleavage rotation of bedding must have affected these rocks.

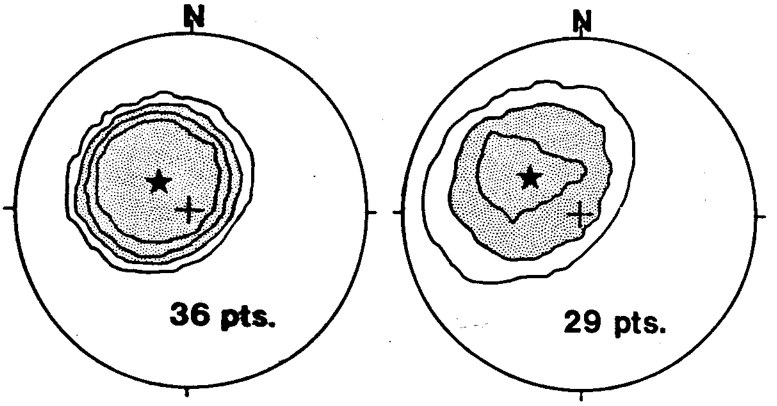


POLES to CLEAVAGE POLES to BEDDING

- ELIZA ISLAND -

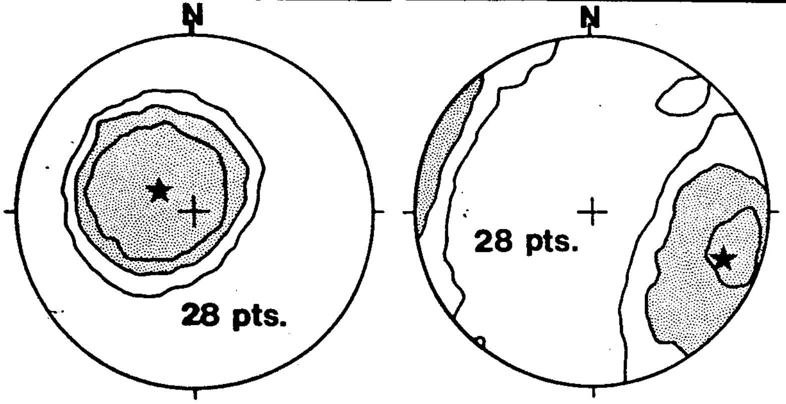
[■ - north Eliza ● - se. △ - sw.]
girdle & ß-axis (with attitude) plotted for se. bedding

Figure 13. Stereographic plots of poles to bedding and cleavage on Eliza Island.



CLEAVAGE (poles)
SE. ELIZA
PLANE to AVG. POLE ★=
N41E 20E

FAULTS (poles)
SE. ELIZA
PLANE to AVG. POLE ★=
N35E 32E



AXIAL PLANES of FOLDS
(poles) SE. ELIZA
PLANE to AVG. POLE ★=
N31E 20E

AXES of FOLDS
SE. ELIZA
AVG. AXIS ★ = S70E 19

Figure 14. Stereographic plots of fold axes and poles to cleavage, fault planes, and axial planes on southeast Eliza Island.

MESOSCOPIC FAULTING

South Lummi

South Lummi Island, especially domain III, is extensively faulted and veined, though most measureable offsets are less than a third of a meter. Roughly half the faults observable along the shoreline were measured, the choice having been made by flipping a coin. For such a large number of points, the stereonet pattern (Fig. 15) shows only a small and not strongly overpopulated area. The indicated prevalence of NE-ENE striking, steeply dipping faults could either be an artifact of measuring nearly randomly oriented faults along thin, long, northwest-oriented shorelines, or could possibly be a real preferred orientation. In either case, the most prominent characteristic of the distribution is its lack of preferred orientation.

Striations on slickensides were measured along only two segments of shoreline of south Lummi (Fig. 16). Unfortunately for such a small sampling area, the data appear to be domainal, in that slickensides and especially slickensided fault planes in area A are more strongly clustered and differ in orientation compared to those of area B. In area A (Fig. 16), slickensided fault planes strike east-west and dip vertically, on average, and slickensides plunge gently west-northwest. In contrast (Fig. 16), measured fault planes in area B, although more numerous, do not form a distribution that is significantly overpopulated, although most have moderate to steep dips (19 of 35 > 60°, 31 of 35 > 40°). Associated slickensides show

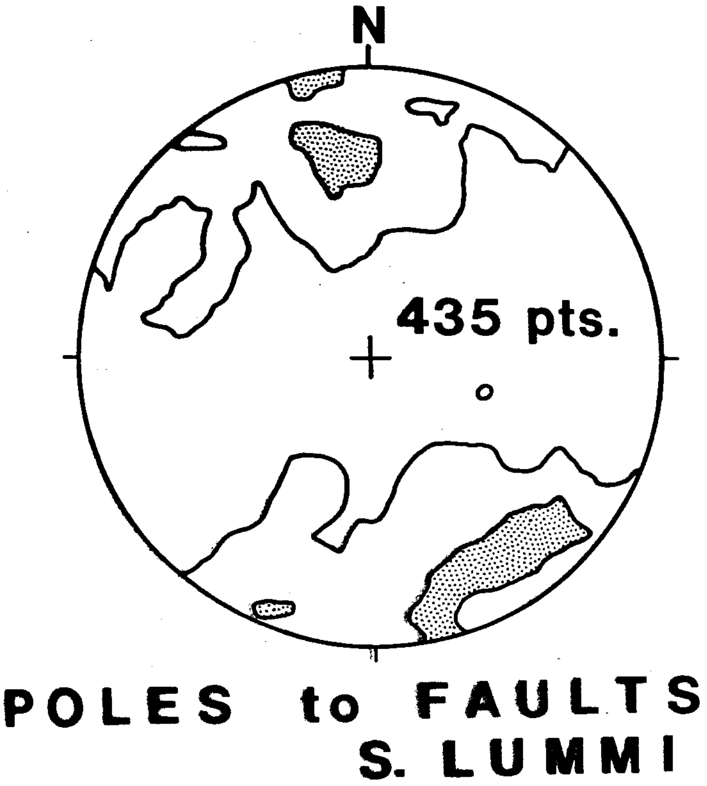
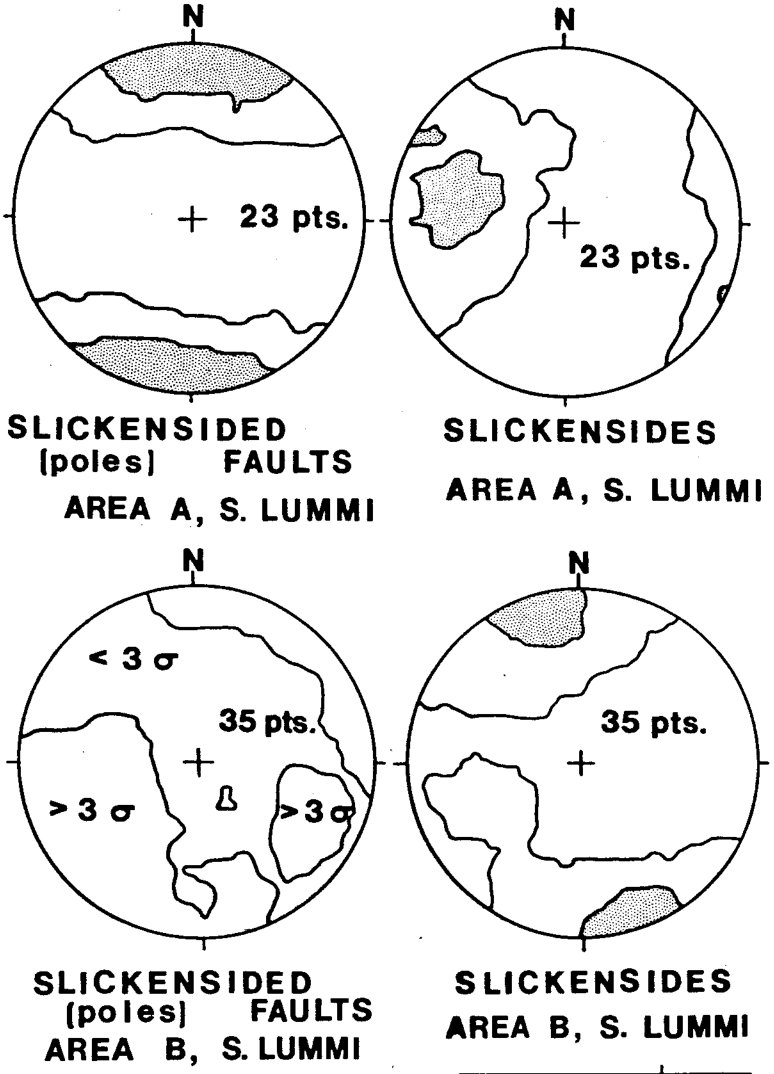


Figure 15. Stereographic plot of poles to fault planes on south Lummi Island.



SLICKENSIDED (poles) FAULTS AREA A, S. LUMMI

SLICKENSIDES AREA A, S. LUMMI

SLICKENSIDED (poles) FAULTS AREA B, S. LUMMI

SLICKENSIDES AREA B, S. LUMMI

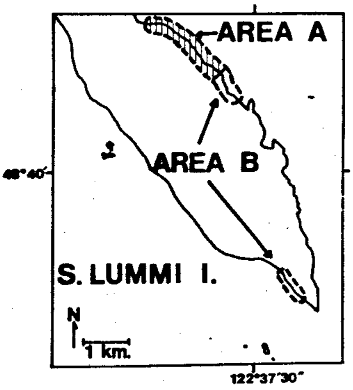


Figure 16. Stereographic plots of slickenside striations and slickensided fault planes on south Lummi Island, with map of sampled areas.

a statistically significant preferred orientation; they tend to be horizontal and trending NNW-SSE.

In all areas measured, then, steeply dipping faults have shallowly plunging slickensides, indicating that at least the latest movement on these faults had a dominant strike-slip component. In area A, moreover, that movement occurred along generally east-west striking vertical faults.

Eliza Island

The strongly foliated rocks of Eliza Island do not show the faulting that has affected the less foliated rocks of south Lummi. Faults on the southeast knob of Eliza (extensively veined) are subparallel to the axial planes of the folds (Fig. 14). Since some can actually be seen to develop along limbs of folds as the fold becomes tighter, this origin is suggested for the whole set of faults.

MACROSCOPIC FAULTS

McLellan (1927) first postulated a fault separating the north and south halves of Lummi at the level of Sunrise Cove. The abrupt changes in relief and geology support such an hypothesis. Furthermore, the sedimentary sequence of south Lummi strikes directly towards older hypabyssal rocks exposed on hill "275" and older chert associated with pillow basalts at Sunrise Cove. Lastly, rock types exposed in fairly coherent sections elsewhere on Lummi are mixed, together with lithologies not exposed locally, in exposures at Sunrise Cove. Especially south of the north shore of Echo Point, these rocks are cataclastic and extremely altered.

The southern contact of the sheared hypabyssal-volcanic rocks against the sedimentary sequence of south Lummi is well located south of Echo Point (Fig. 2), and the other most northern exposures of sedimentary rocks in domains I and II force this edge of the fault zone, if it is straight, to strike east-west to east-northeast. Prominent vertical gouge zones on Echo Point strike almost due east-west. These gouge zones and the vertical slickensided fault planes measured in area A south of Sunrise Cove (Fig. 16) support the suggestion of a generally east-west striking, vertically dipping fault zone at the latitude of Sunrise Cove. Striations on the slickensides measured in area A (Fig. 16) suggest that movement associated with this faulting was dominantly strike-slip.

This area of Lummi is a prominent element of the northeast-trending Vedder Discontinuity (Danner, 1977) or the Orcas Fault Belt (Muller, 1977), a strike-slip (Danner, 1977, Muller, 1977) or transform fault zone (Davis and others, 1978) showing left-lateral movement. My work suggests the latest movement in the fault zone on Lummi may have been strike-slip, but along planes striking east-northeast to due east, not northeast. On Lummi Island, at most a 2 km. segment of a 150 km.-long feature is exposed, so the deviation from a northeast strike may be insignificant on a regional scale. Alternatively, it could represent a period of faulting later than that forming the Vedder Discontinuity.

The fold northwest of Carter Point is terminated to the north by a cataclastic zone (brecciated quartz veins in a very fine-grained crudely foliated black matrix) 10 meters wide. On the opposite shore is a wider zone of pervasively faulted sandstone, terminated to the south by a 2 meter-wide, nearly vertical swath of black gouge with straight, parallel, slickensided walls striking N31E--nearly on strike with the cataclastic zone on the other shore and passing through an obvious saddle in the main ridge of Lummi. It seems likely that these features delineate one large fault zone. Striations on the above-mentioned slickensides plunge 34 degrees east, indicating the last movement had a significant strike-slip component.

A fault inferred to terminate the same fold to the west is only one of several ways to reconcile the discrepancy between the cleavage orientation within the fold and that of Viti Rocks.

Faults are inferred to separate areas of very strongly cleaved rocks from those on Lummi having a more normal cleavage. The dramatic difference in cleavage development between Lummi Rocks and domain I, occurring over a much shorter distance than seen elsewhere on Lummi leads me to infer a fault between the two areas. The tight folding and especially the change in cleavage orientation between domain I and the rest of Lummi seems to develop over a short enough distance, and to represent enough of a significant departure from the norm on Lummi to make the inference of a fault contact reasonable. The similarity of the rocks of Eliza Island to those of domain I lead me to suggest a fault also separates Eliza and the less foliated, unfolded rocks of Lummi. In support of these inferred faults, the contact between very strongly foliated and more normally foliated rocks in domain V is a well-exposed fault.

The volcanic rocks occurring between Reil Harbor and Deepwater Bay are structurally above the younger sedimentary rock sequence to the west. Rocks near the contact (not exposed) are strongly faulted and faulting is assumed to have juxtaposed the two rock types.

KINK BANDING

South Lummi and Eliza Island

Kink bands are pervasive and locally penetrative at outcrop scale on Eliza Island and many are seen in more strongly cleaved rocks on south Lummi. The observation that faults are much less common in these rocks suggests the possibility that both are responses to the same stress system. The orientation of stress axes responsible for kink bands were derived according to Gay and Weiss (1974).

A few reservations need to be introduced regarding this treatment of kink bands. First, the foliation actually being kinked was not measured for each measured kink band, especially on Lummi. Measurements were discarded unless the error was thought to be minimal, but error was still introduced. Secondly, a foliation can only be kinked by a compressive force at relatively small angles to the foliation. Thus, if the foliation is fairly uniform across an area, as it is on south Lummi or Eliza, a stress system whose maximum principal stress axis is at a large angle to the foliation will not be represented by kinking and obviously will not be detected by this analysis.

On south Lummi, the kinks plotted were produced by a stress field (Fig. 17) whose axis of maximum compression was horizontal and trending WNW-ESE. σ_2 and σ_3 plunge at moderate angles in opposite directions in a plane perpendicular to this axis. The horizontality of the maximum stress is compatible with the strike-slip sense of movement recorded by the slickensides of south Lummi. If that stress induced a strike-slip system of faulting, it may have also produced vertical faults striking either slightly south of west or slightly north of northwest. From figure 15, the plot of south Lummi fault planes, there is a concentration of steep to vertical faults striking slightly south of west.

The orientations of σ_2 and σ_3 are not those expected to produce strike-slip faulting. In Gay and Weiss' analysis, σ_2 is defined as the intersection of the kink band and cleavage, and the other two axes are then perpendicular to it and each other. They do not discuss whether a stress system whose σ_2 axis did not lie in the plane of the cleavage might still be able to kink that cleavage, which would lead to an incorrect estimation of the orientation of σ_2 and subsequent misplacement of σ_1 and σ_3. Possibly this might

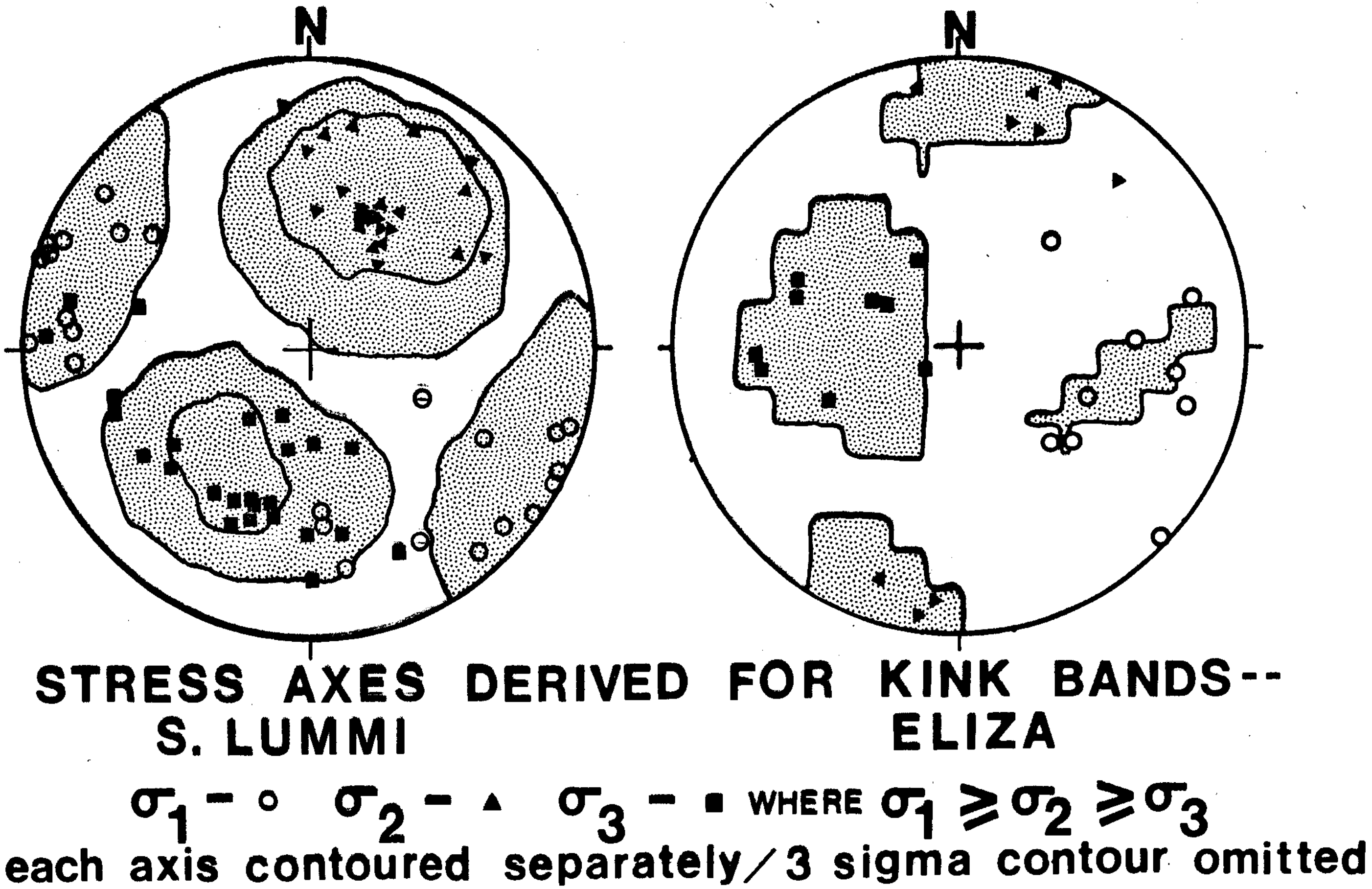


Figure 17. Stereographic plots of stress axes derived for kink bands on south Lummi and Eliza Islands.

account for the discrepancy, but σ_1 would also be affected, and I am already neck-deep in speculation.

Most kinks on Eliza are vertical, strike slightly east of north, and are regularly spaced several centimeters apart; some form a crenulation cleavage. Gay and Weiss' analysis is more suited to isolated kinks and those that have experienced small strains, but for comparison at least, the stress axes were derived and plotted (Fig. 17). σ_2 trends horizontally just east of north, with σ_1 and σ_3 plunging oppositely to each other and at moderate angles in the plane normal to σ_2.

The difference in orientation of these two stress systems has several possible explanations:

1) A 50° clockwise (post-kinking) rotation of Eliza relative to Lummi around a N66E 07 axis would bring the two systems into coincidence. If the Eliza cleavage (SE. knob) is "restored" to its Lummi precedent by this rotation it would be N81E 33N. This is closest to the cleavage in domain I (N65W 39N), which also is axial planar to tight folds and penetrative in both sandstone and mudstone. None of the south Lummi kinks plotted came from domain I, but over half were from the cleavage plotted in figure 10, which shows the same orientation as that of domain I.

2) The kinks were not formed in the same stress field.

3) The difference between the two orientations is not great, and might be the result of a single stress system whose σ_2 axis was

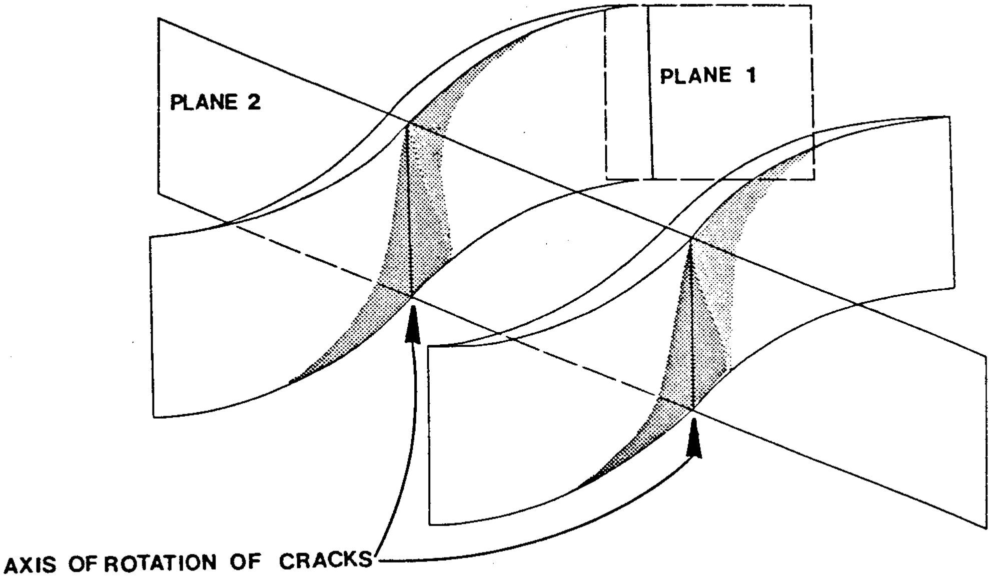


Figure 18. Diagram of sigmoidal extension cracks, showing planes measured ("1" and "2") in the field, and their intersection, identified as "axes of rotation of cracks".

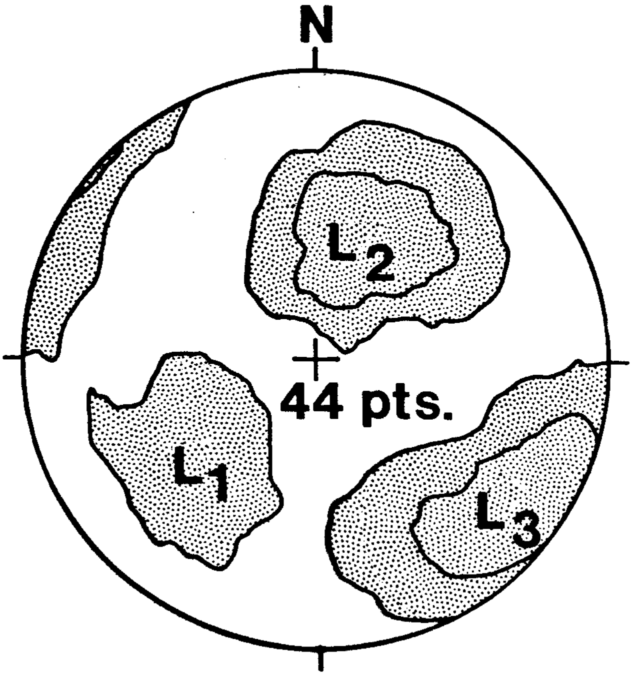


Figure 19. Stereographic plot of orthogonal reference axes for tails (plane 1) of extension cracks on south Lummi Island. L_3 = the normal to plane 1, L_2 = the axis of rotation of the cracks (the intersection of planes 1 and 2), and L_1 = the perpendicular to L_2 lying in plane 1. Each axis is contoured separately.

not coplanar with one or both cleavages, if it is possible to produce kinks in such a situation. Determination of the orientation of this stress system is not possible from these data.

EN ECHELON EXTENSION CRACKS

South Lummi

En echelon extension cracks, often sigmoidal, and not observed in conjugate sets (Beach's (1975) type 2 cracks?), are common on south Lummi. Two elements were measured in the field for each set of sigmoidal cracks: (1) the plane of the cracks' tails and (2) the plane containing each crack's axis of rotation (Fig. 18). Crack sets which were poorly developed, showed late disruption of the zone, or did not well expose the axis of rotation were not measured. From these measurements, three orthogonal lines (Fig. 19) lying within or perpendicular to the tails of each crack set were plotted for the south Lummi data (Fig. 19). Not enough cracks were measured on Eliza to produce a similar diagram.

The orientation of these lines is extremely similar to that of the stress axes derived for kink bands, and moreover L_1 is coincident with the pole to the average cleavage on south Lummi. Stress axes for kinks are constrained by the cleavage (very generally, σ_1 and σ_2 tend to be coplanar to the cleavage, and σ_3 tends to be normal). From my data, it seems that formation of the tails of extension cracks is also influenced by cleavage. The data suggest that extension cracks tend to form with their tails normal to cleavage and their axes of rotation within the plane of cleavage. The tendency of L_3 to form a girdle extending towards L_1 may mean rotation of the tails of the cracks has occurred around L_2, after formation of those tails.

FOLDING ON LUMMI ISLAND

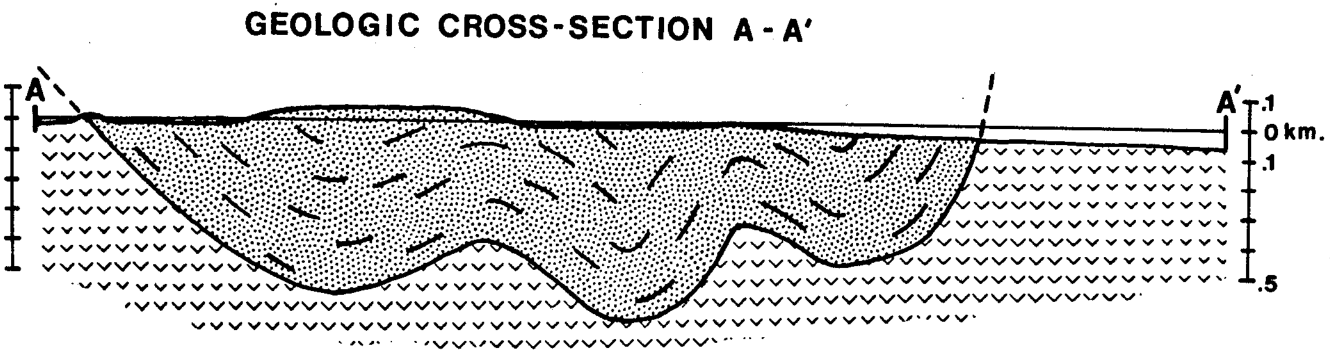
South Lummi

Outside of Eliza Island, mesoscopic folding does not seem to be significant, except in the strongly cleaved rocks of domain I. There the cleavage is axial planar to tight, similar, overturned folds clustered in two areas. These folds are separated by sections of relatively homoclinal, strongly cleaved beds, and may well be parasitic to larger folds. Only two plunges could be measured; both were northwesterly and shallow. One larger overturned open fold involving at least 5 meters of section in the SE¼ NE¼ SW¼ Section 22, T. 37 N, R. 1 E, has an orientation (axial plane N65W 30N, plunge N08E 26) similar to tighter folds elsewhere in domain I which have a very strong axial planar cleavage. This fold, however, folds a cleavage which is parallel to bedding and produces an axial planar cleavage--in sandstone, it is a crenulation cleavage; in mudstone, it appears slaty. Tentatively, the possibility exists that this more open fold allows observation of an early cleavage parallel or subparallel to bedding which has been transposed in tight to isoclinal folds elsewhere in domain I by the axial plane cleavage.

Over the rest of south Lummi occasional minor folds are sporadically observed in cherts, and in clastic rocks where they are typically associated with faulting. Three asymmetric folds were also seen in the clastic rocks that involved only a meter at most of section before they died out. The asymmetry was that of a Z-fold, looking north, which is not the expected asymmetry if the beds are the east limb of an anticline (which is what the cleavage to bedding relationship would suggest).

Northern Lummi Island, the Chuckanut Formation

In contrast to the older sedimentary rocks of south Lummi, the Tertiary Chuckanut Formation (McLellan, 1927) cropping out on the northern half of Lummi lacks any cleavage, has very few faults, and few if any veins. It is folded into macroscopic, open, plunging folds with sharper anticlinal than synclinal hinges. The axial surfaces are not well displayed, but are probably steeply dipping if not vertical. The Chuckanut as exposed on Lummi seems to be folded in a large synclinal structure with subsidiary folds having subparallel axes and generally steeper southern limbs (Fig. 20). As mapped, axes of folds plunge west or northwest gently, although the synclinal hinge at the southeast corner of the Chuckanut outcrop area plunges at approximately 50^{o}. An S-pole plot of Chuckanut bedding on Lummi yielded a girdle with a N63W 22 β-pole (Fig. 21). A girdle substantially similar to Lummi's was obtained, with a β-pole of N67W 22 (Fig. 20), by plotting bedding attitudes from folded



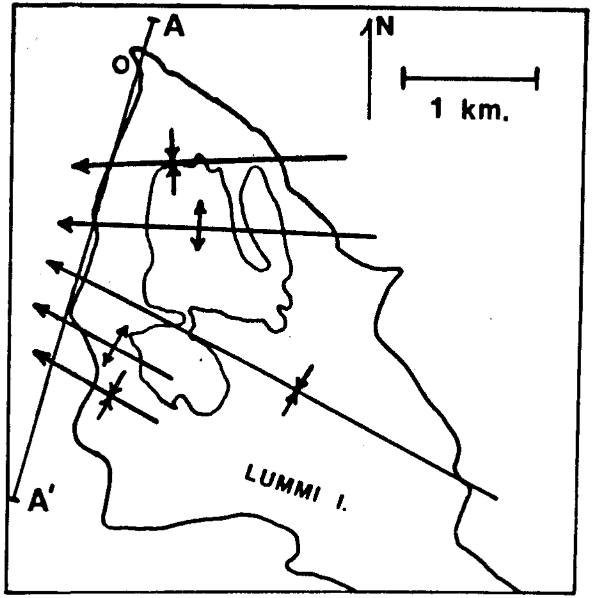


Figure 20. Geologic cross-section of folds in Chuckanut Formation, north Lummi Island.

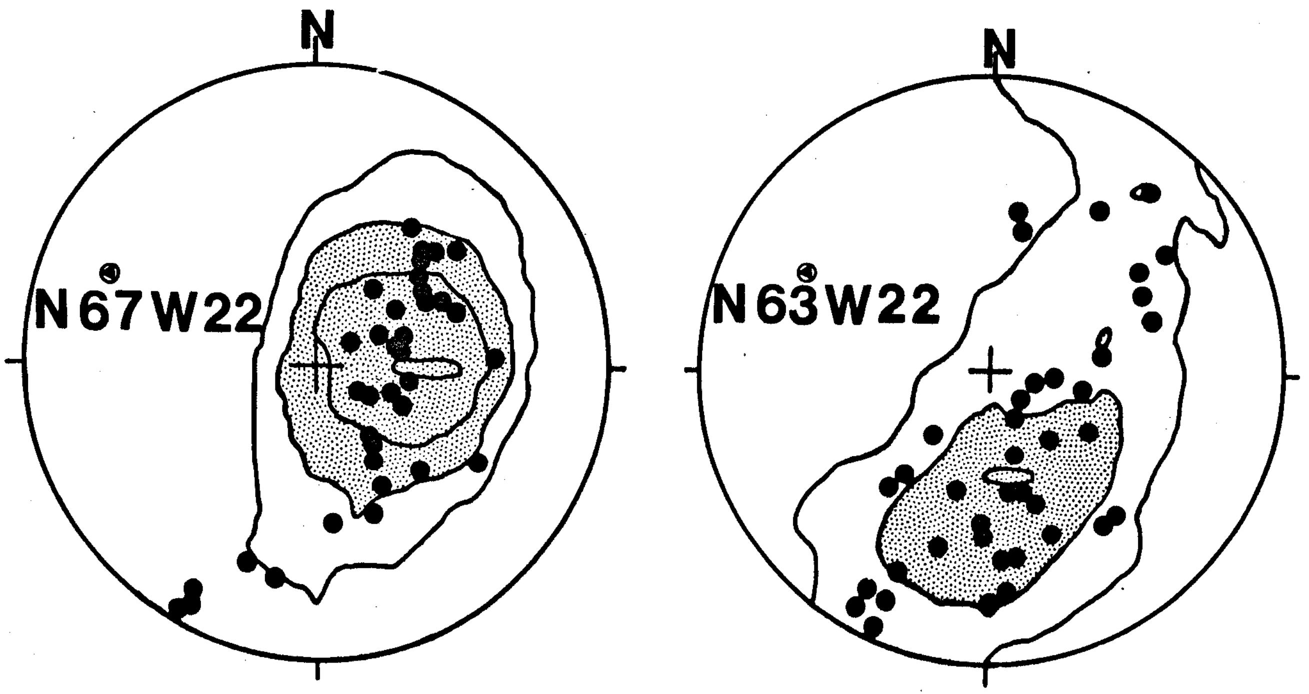


Figure 21. Stereographic plots of poles to Chuckanut bedding on Lummi Island, and near Bellingham on the mainland.

Chuckanut on the mainland east of Lummi (Easterbrook, 1976). The similarity of β-poles between the two areas is excellent, and implies no rotational movement of one area relative to the other since the time of Chuckanut folding, which is thought to be middle Eocene (Miller and Misch, 1963).

SUMMARY OF STRUCTURE

In summary, both Lummi and Eliza Islands have similar structural histories consisting of the sequence: 1) deposition of beds, 2) some disruption of bedding, 3) development of cleavage, 4) faulting and/or kinking, and 5) possible post-kinking rotation of Eliza relative to Lummi, and definite rotation of cleavage across Lummi. The cleavage on Lummi is roughly axial planar to one fold plunging gently north-northwest. On Eliza Island and in domain I on Lummi, development of cleavage is axial planar to open to tight folds. At least in domain I, the possibility of an earlier cleavage exists. The similarity of these folded rocks and their apparent discordance to structural orientations and style on Lummi suggest that they were once coherent and have arrived at their present positions by faulting. Kink bands on Lummi were formed by a horizontal maximum stress that is compatible with strike-slip faults striking east-west or northwest, which in turn are consistent with the gently plunging slickenside striations, and steeply to vertically dipping, east-west- or northwest-striking faults seen on Lummi. In particular, gently plunging slickenside striations associated with east-west vertical faults south of the inferred location of the northeast-trending Vedder Discontinuity (Danner, 1977, Muller, 1977) lend support to the interpretation that that structure is a strike-slip fault, but suggest that on Lummi, at least, it has a late episode of, or is formed by, east-west strike-slip faulting. The relatively unfaulted, unveined, and definitely uncleaved Chuckanut Formation implies that activity producing those features had largely stopped by the time Chuckanut was deposited. The alternative, that the Chuckanut on Lummi is far traveled, is not likely since extensive Chuckanut is found near Lummi on the mainland, south of the extension of the fault zone halfway up Lummi. Folding that affected the Chuckanut Formation may also be responsible for the rotation of cleavage seen on Lummi, since both rotations seem to take place around northwest axes.

CHAPTER IV: SUMMARY

1) The pre-Tertiary rocks on Lummi Island have been dated as Mesozoic. Hypabyssal rocks are 160 ± 3 my., basaltic volcanic rocks are associated with cherts dated as Middle Jurassic to early Late Jurassic, and interbedded cherts date the sedimentary sequence as Late Jurassic to Early Cretaceous. The hypabyssal rocks, at least, can be correlated with the Fidalgo Ophiolite as described by Brown and others (1979).

2) The metamorphic minerals aragonite, lawsonite and pumpellyite, in addition to prehnite, have been recognized and necessitate moderately high P/T metamorphism for the southern half of Lummi. Pumpellyite and stilpnomelane have been added to the known minerals occurring on the north half; there are no minerals commonly found there that demand high P/T metamorphism. Further work needs to be done to ascertain the significance of this difference.

3) The sedimentary sequence comprises the A, B and D facies of Mutti and Ricci Lucchi (1972) and probably is best described as a middle channeled fan association (Walker and Mutti, 1973).

4) Rocks of roughly similar lithology (perhaps more regularly and thinly bedded) occur on Eliza Island and domain I, and locally in domain V, but are distinguished by very well developed, nearly phyllitic cleavage axial planar to open to tight folds, and attitudes of bedding and cleavage that are not coincident with those found in less foliated rocks on Lummi. The amazingly similar

cleavage orientation of domain I to the spatially distant, fault-bounded occurrences in domain V supports the idea that all these rocks arrived at their present positions by faulting, and, moreover, constituted a coherent structural package at one time.

5) Stress axes derived for kink bands (Gay and Weiss, 1974) are characterized by a horizontal maximum stress which is compatible with late strike-slip faulting indicated by gently plunging slickenside striations on steeply dipping faults measured on Lummi. In particular, halfway up the island, strike-slip faulting along east-west vertical planes is the last movement indicated along what has previously been described as a dip-slip fault (McLellan, 1927, Calkin, 1959), or more recently as a major strike-slip but northeast-trending fault zone (Danner, 1977, Muller, 1977).

6) The Chuckanut Formation has relatively few faults or veins, and has no cleavage, indicating that activity accounting for those common features in the sedimentary sequence of south Lummi had ceased by the time of Chuckanut deposition. Folding affecting the Chuckanut may be responsible for the rotation of cleavage seen across Lummi. This folding of cleavage could possibly be documented on a more regional scale in the San Juan Islands.

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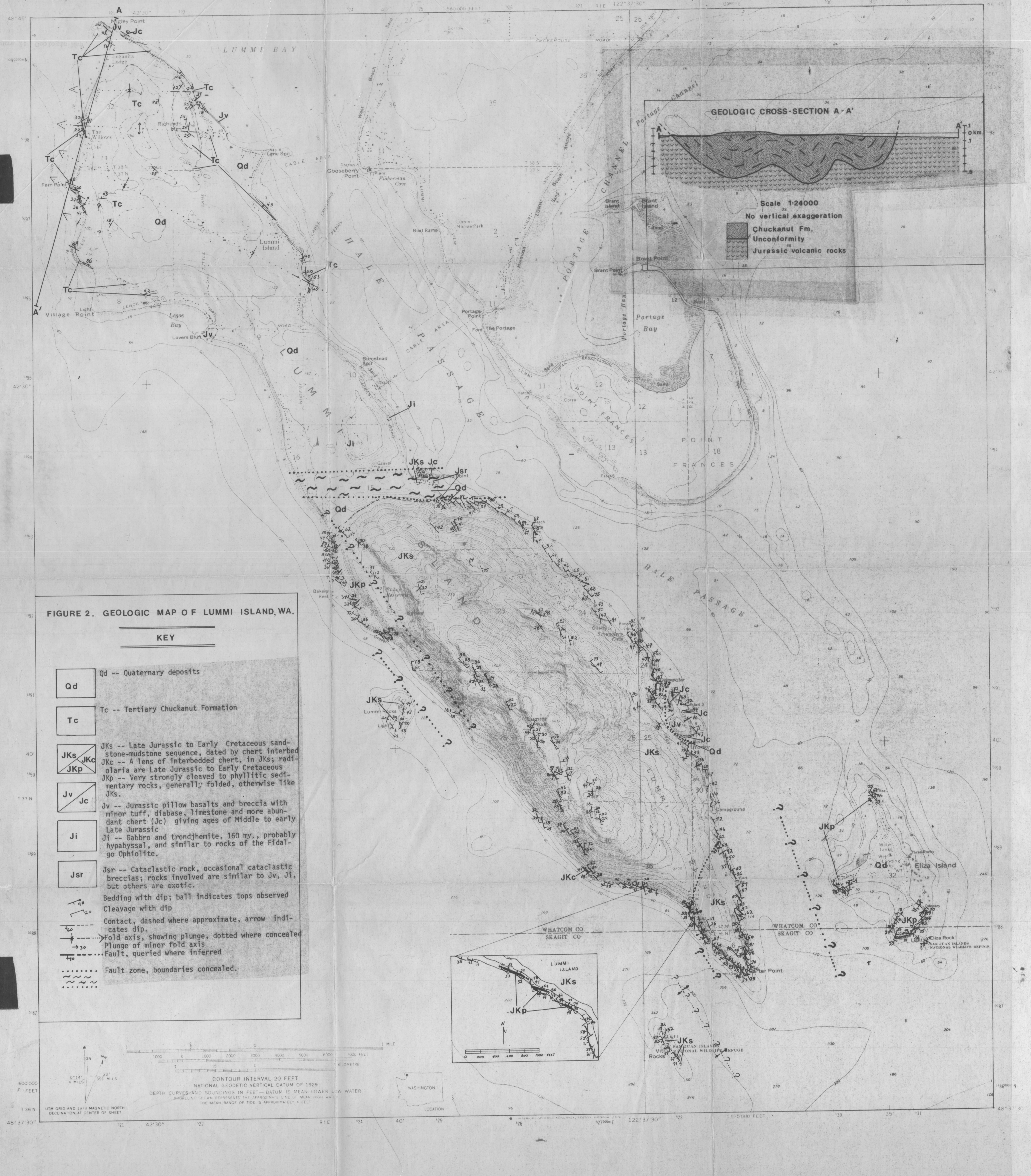

FIGURE 2. GEOLOGIC MAP OF LUMMI ISLAND, WA.

KEY

Qd -- Quaternary deposits

Tc -- Tertiary Chuckanut Formation

JKs -- Late Jurassic to Early Cretaceous sandstone-mudstone sequence, dated by chert interbed

JKc -- A lens of interbedded chert, in JKs; radiolaria are Late Jurassic to Early Cretaceous

JKp -- Very strongly cleaved to phyllitic sedimentary rocks, generally folded, otherwise like JKs.

Jv -- Jurassic pillow basalts and breccia with minor tuff, diabase, limestone and more abundant chert (Jc) giving ages of Middle to early Late Jurassic

Ji -- Gabbro and trondjhemite, 160 my., probably hypabyssal, and similar to rocks of the Fidalgo Ophiolite.

Jsr -- Cataclastic rock, occasional cataclastic breccias; rocks involved are similar to Jv, Ji, but others are exotic.

Bedding with dip; ball indicates tops observed

Cleavage with dip

Contact, dashed where approximate, arrow indicates dip.

Fold axis, showing plunge, dotted where concealed

Plunge of minor fold axis

Fault, queried where inferred

Fault zone, boundaries concealed.