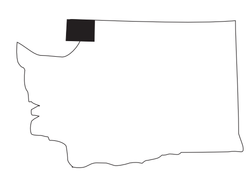
NATURAL RESOURCES

Geologic Map of the Bellingham 1:100,000 Quadrangle, Washington

by Thomas J. Lapen

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Open File Report 2000-5
December 2000



Location of quadrangle

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands

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Printed on recycled paper
Printed in the United States of America

Contents

FIGURES

TABLES

PLATES

Geologic Map of the Bellingham 1:100,000 Quadrangle, Washington

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INTRODUCTION

The Bellingham 1:100,000-scale quadrangle is one of fifteen 1:100,000-scale quadrangles that comprise the northwest quadrant of Washington State (Fig. 1). This map is one of several completed 1:100,000 geologic maps in the northwest quadrant compiled and mapped by the Washington Division of Geology and Earth Resources (DGER) and the U.S. Geological Survey (USGS). These maps are the principal sources of data for a 1:250,000-scale map of the northwest quadrant of Washington State (in progress). Several unpublished or in-progress 1:100,000-scale digital geologic maps compiled by DGER are also principal sources for the 1:250,000-scale geologic map (see below).

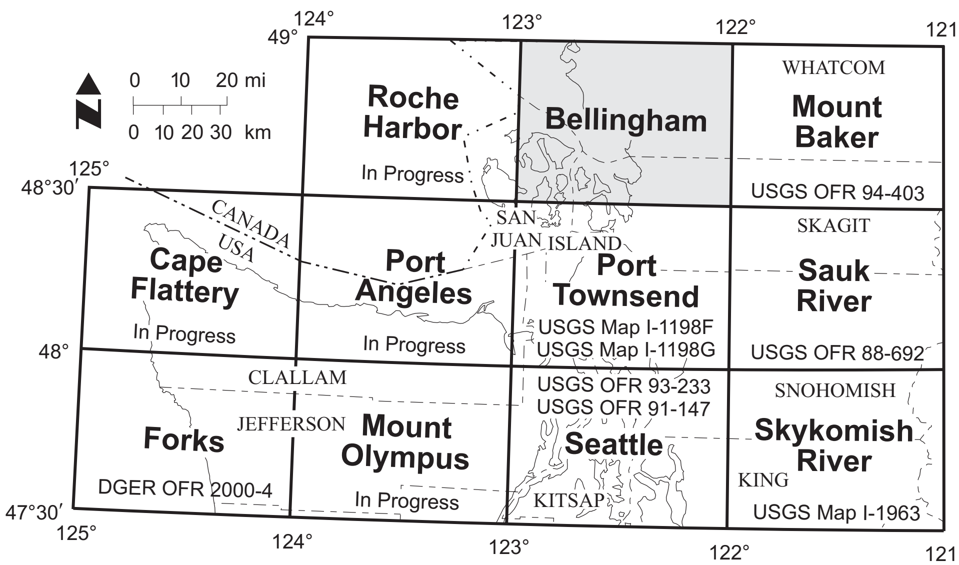


Figure 1. Location of 1:100,000-scale quadrangles, northwestern Washington. Dashed lines and Roman type indicate counties. Map numbers with the prefix DGER are Division of Geology and Earth Resources publications; those with the prefix USGS are U.S. Geological Survey maps and open-file reports (OFR), which can be purchased from: USGS ESIC, Rm. 135, 904 W. Riverside Ave., Spokane, WA 99201. For more information on USGS products, call (509) 368-3130 or fax (509) 368-3194; 1-888-ASK-USGS is toll free within the 509 area code.

As of completion of this report, 1:100,000-scale geologic maps in the northwest quadrant of Washington State released by DGER and the USGS as open-file reports or as geologic maps are:

Dragovich, J. D.; Norman, D. K., compilers, 1995, Geologic map of the west half of the Twisp 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 95-3, 63 p., 1 plate.

Frizzell, V. A., Jr.; Tabor, R. W.; Booth, D. B.; Ort, K. M.; Waitt, R. B., Jr., 1984, Preliminary geologic map of the Snoqualmie Pass 1:100,000 quadrangle, Washington: U.S. Geological Survey Open-File Report 84-693, 43 p., 1 plate, scale 1:100,000.

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text.

Stoffel, K. L.; McGroder, M. F., compilers, 1990, Geologic map of the Robinson Mtn. 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-5, 39 p., 1 plate.

Tabor, R. W.; Waitt, R. B., Jr.; Frizzell, V. A., Jr.; Swanson, D. A.; Byerly, G. R.; Bentley, R. D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1311, 1 sheet, scale 1:100,000, with 26 p. text.

Tabor, R. W.; Frizzell, V. A., Jr.; Whetten, J. T.; Waitt, R. B.; Swanson, D. A.; Byerly, G. R.; Booth, D. B.; Hetherington, M. J.; Zartman, R. E., 1987, Geologic map of the Chelan 30-minute by 60-minute quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1661, 1 sheet, scale 1:100,000, with 29 p. text.

Tabor, R. W.; Booth, D. B.; Vance, J. A.; Ford, A. B.; Ort, M. H., 1988, Preliminary geologic map of the Sauk River 30 by 60 minute quadrangle, Washington: U.S. Geological Survey Open-File Report 88-692, 50 p., 2 plates.

Tabor, R. W.; Frizzell, V. A., Jr.; Booth, D. B.; Waitt, R. B.; Whetten, J. T.; Zartman, R. E., 1993, Geologic map of the Skykomish River 30- by 60-minute quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1963, 1 sheet, scale 1:100,000, with 42 p. text.

Tabor, R. W.; Haugerud, R. A.; Booth, D. B.; Brown, E. H., 1994, Preliminary geologic map of the Mount Baker 30- by 60-minute quadrangle, Washington: U.S. Geological Survey Open-File Report 94-403, 55 p., 2 plates.

Whetten, J. T.; Carroll, P. I.; Gower, H. D.; Brown, E. H.; Pessl, Fred, Jr., 1988, Bedrock geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-G, 1 sheet, scale 1:100,000.

Yount, J. C., Minard, J. P., Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30- by 60-minute quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000.

Yount, J. C.; Minard, J. P.; Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30′ x 60′ quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000.

Unpublished digital geologic maps are available from DGER (see contact information below). These include in-progress maps slated to be released as open-file reports by DGER and USGS open-file reports and geologic maps reformatted to conform with the statewide unit symbology of DGER. In-progress maps are shown in Figure 1. Reformatted USGS maps available in digital form with minor or no modification include:

- Chelan quadrangle, reformatted by J. D. Dragovich;
- Sauk River quadrangle, reformatted by H. W. Schasse;
- Skykomish River and Snoqualmie Pass quadrangles, reformatted by J. D. Dragovich;
- Tacoma quadrangle, reformatted by T. J. Walsh;
- Mount Baker quadrangle, reformatted by D. K. Norman;
- Wenatchee quadrangle, reformatted by J. D. Dragovich, T. J. Walsh, and J. E. Schuster.

Maps that include updated data, combined bedrock and surficial geologic mapping into a single coverage, and reformatted symbology of USGS geologic maps and open-file reports include:

- Port Townsend quadrangle, compiled and reformatted by H. W. Schasse;
- Seattle quadrangle, compiled and reformatted by T. J. Walsh;
- Southwest corner of Robinson Mountain quadrangle, compiled by J. D. Dragovich.

These maps can be obtained in Arc/Info format on CD-ROM by sending requests to:

Washington Division of Geology and Earth Resources
PO Box 47007; Olympia, WA 98504-7007
phone: (360) 902-1450; *fax:* (360) 902-1785
e-mail: geology@wadnr.gov

Note: Currently Arc/Info cannot do subscripts. Therefore, in the digital versions of these maps, unit subscripts are indicated by letters and numbers in parentheses.

Method of Age Assignment

Ages of geologic units in the Bellingham 1:100,000-scale quadrangle were assigned following the flow chart in Figure 2. The geologic time scale used for age nomenclature was compiled by Palmer and Geissman in 1999 for the Geological Society of America. All reported ^{14}C ages are uncalibrated and shell ages are uncorrected for the marine reservoir effect. The term 'yr B.P.' refers to years before 1950. All known fossil and radiometric ages (excluding ^{14}C ages) and their references are listed in the Appendix. Sample locations are shown on Plate 1. All K/Ar age estimates cited were published after 1976 and are assumed to have used the decay constants adopted by the IUGS in 1976 (Dalrymple, 1979). ^{14}C radiometric age dates and localities in the Bellingham quadrangle and vicinity are being compiled by Dr. Donald J. Easterbrook and Doris J. Kovanen and will appear as an appendix in Kovanen's doctoral thesis (in progress, University of British Columbia, Vancouver, B.C.).

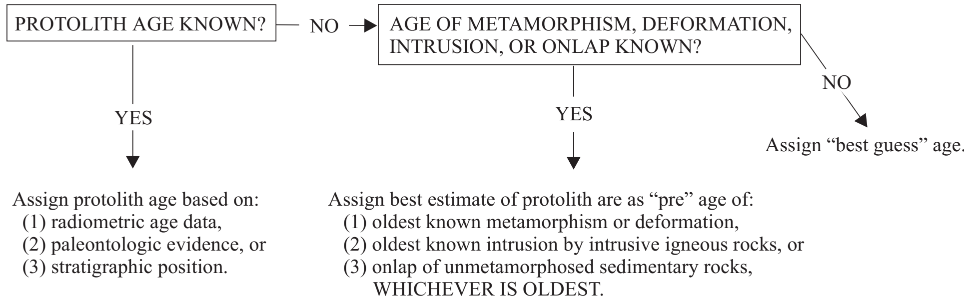


Figure 2. Flow chart for age assignment of geologic units. Unit descriptions include information on how the age was assigned.

Sources of Map Data

This map was compiled using published, unpublished, and original geologic mapping as sources of data (Fig. 3). Primary sources of data were used with little to moderate modification. Modification of the original geology from primary and non-primary sources was done in light of new field data and (or) inconsistencies between sources covering the same or nearby areas. Simplification of highly detailed, smaller-scale maps was necessary for many of the sources.

Primary sources of map data that cover large portions of the Bellingham quadrangle include unpublished mapping in the eastern San Juan Islands, namely the Blakely Island, Cypress Island, Anacortes North, Eliza Island, and Lummi Island 7.5-minute quadrangles by M. C. Blake, D. C. Engebretson, and R. F. Burmester of Western Washington University (in progress) and unpublished, in-progress mapping by R. A. Haugerud (USGS) in the Bellingham quadrangle. Geologic maps of Orcas and Shaw Islands by Vance (1975) and Whetten (1975) were a primary source of data, however, this report adopts Brandon and others (1988) interpretation that most lithologic packages on Orcas and Shaw Islands are in thrust contact. Also included as primary sources of data are the map of western Whatcom County by Easterbrook (1976a), the map of the Chuckanut Formation outcrop belt by Johnson (1982), maps of the Skagit River valley area by Dragovich and others (1998, 1999), maps of the Sumas and Black Mountain areas by Dragovich and others (1997a) and Moen (1962), and a map of the Twin Sisters Mountain area by Brown and others (1987). Other primary sources of map data are of limited extent in the Bellingham quadrangle.

GEOLOGIC SETTING

This report divides units into three general categories: (1) Quaternary deposits, subdivided into post-glacial deposits, glacial deposits, and interglacial deposits; (2) Tertiary rocks; and (3) pre-Tertiary rocks, subdivided into rocks of the Northwest Cascades system of Brown (1987), which is in turn subdivided into two geographic areas: (1) rocks of the northwest Cascade Range and (2) rocks of the San Juan Islands.

Quaternary deposits, exposed mainly in the Whatcom basin and Skagit River area, are composed mainly of material derived from the late Wisconsinan Fraser Glaciation. Deposits of the Fraser Glaciation are divided, from oldest to youngest, into four geologic-climate units: (1) Evans Creek Stade, (2) Vashon Stade, (3) Everson Interstade, and (4) Sumas Stade (Armstrong and others, 1965).

Tertiary rocks are extensive in the map area and consist of the Chuckanut and Huntingdon Formations. Deposition of these units was controlled by local uplifts and basins produced in a broad zone of strike-slip deformation (Johnson, 1982, 1985). Though the use of different formation names for these units implies they are unrelated, Mustard and Rouse (1994) conclude that the Huntingdon Formation is correlative to younger strata of the Chuckanut Formation. In this report, the term 'Huntingdon Formation' is used for sedimentary rocks on western Sumas Mountain, in agreement with Mustard and Rouse (1994), because most literature to date refers to these rocks as such (for example, Miller and Misch, 1963, and Dragovich and others, 1997a).

Pre-Tertiary rocks (excluding the Upper Cretaceous Nanaimo Group) constitute a structural system referred to as the Northwest Cascades system (NWCS) (Misch, 1966; Brown, 1987). This structural system is a thrust stack of mainly oceanic lithologic packages (or terranes) of varying age, structure, and metamorphic history (Brown and others, 1981; Brown, 1987). These packages were largely assembled in the mid-Cretaceous (Misch, 1966; Brown, 1987; Brandon and others, 1988; Tabor and others, 1994) and possibly also in the Late Jurassic (Haugerud and others, 1992, 1994). Eocene and later(?) deformation also disrupted and possibly juxtaposed many lithologic units of the NWCS (Haugerud and others, 1992; Dragovich and others 1997a; Haugerud, 1998).

The NWCS is divided into two geographic areas, the northwest Cascade Range and the San Juan Islands, because many previous studies refer to these areas when describing lithologic packages and tectonics. Similar geologic units in the two areas are likely correlative (for example, the Vedder Complex and the Garrison Schist, the Yellow Aster Complex and the Turtleback Complex, the Chilliwack Group and the East Sound Group, and the Elbow Lake Formation and the Orcas Chert) (Brown and Vance, 1987; Brandon, 1989; Ralph Haugerud, USGS, oral commun., 1999). Structural and kinematic connections between the two areas are proposed by Brandon and Cowan (1985) and Brown (1987), however, at present, the tectonic evolution of the NWCS remains an unsolved problem.

DESCRIPTIONS OF MAP UNITS

Quaternary Deposits

POST-GLACIAL DEPOSITS

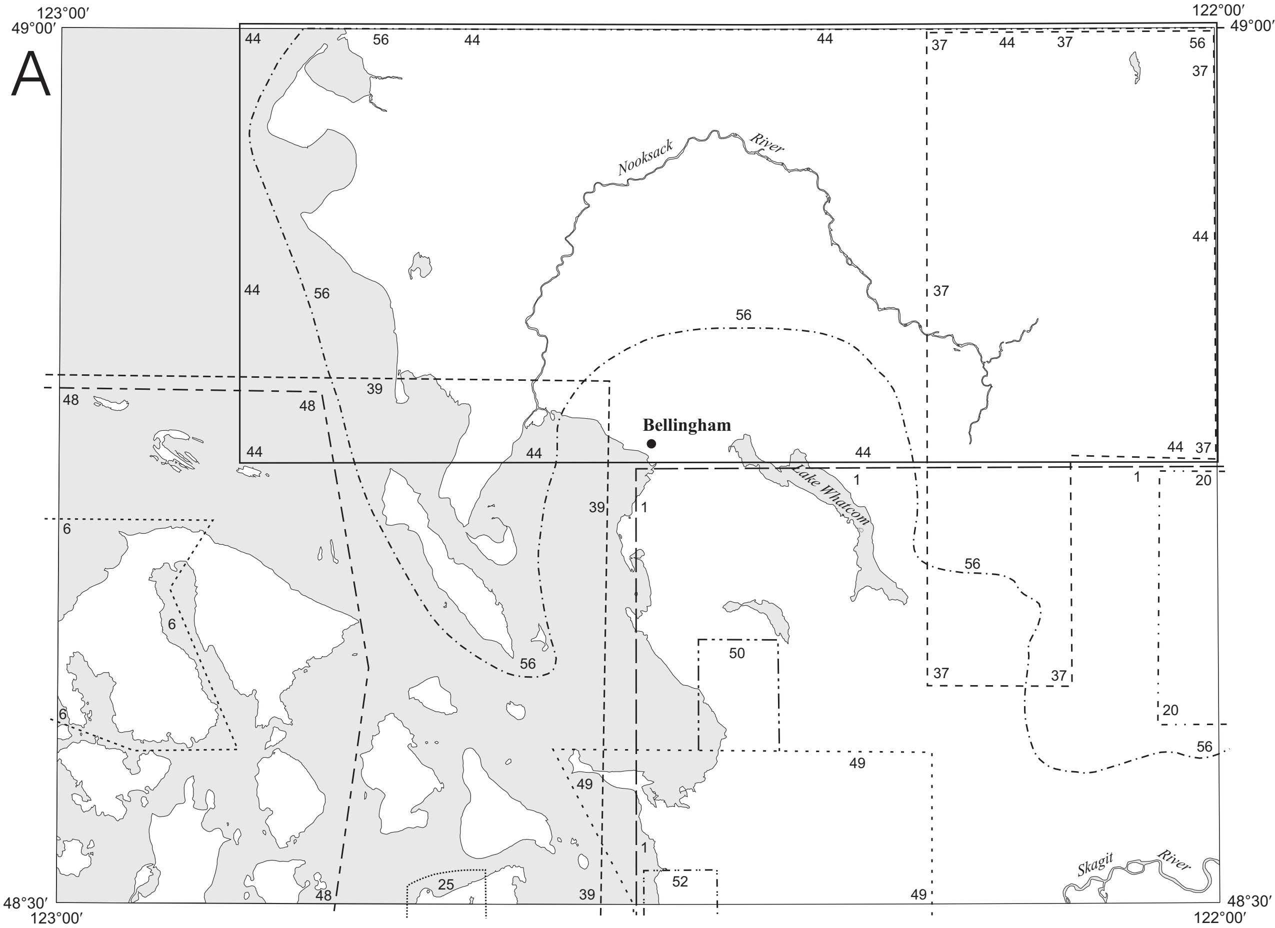
Qf **Artificial fill (Holocene)**—Composed of earth debris, demolition debris, and, locally, refuse disposed of as solid waste. Thickness is generally more than 2 m. Many wharves and structures, including industrial buildings, are built on unit Qf in Bellingham Bay. Smaller occurrences of unit Qf are near the city of Blaine and in Chuckanut Bay. (Description compiled from Washington Department of Ecology, 1977, 1978, and Dethier and others, 1996.)

Qa **Alluvium (Holocene)**—Well-sorted and stratified cobbly gravel, gravel, sandy gravel, gravelly sand, sand, silty sand, silt, clay, and peat (see unit Qp). Clasts are rounded to subrounded and consist of metamorphic, sedimentary, and igneous rocks derived from sources in the drainage basin of a particular river or stream and foreign material derived from reworked glacial deposits. Color is dependent on lithology and oxidation state but is generally some combination of gray and brown. Thicknesses range from a few meters to locally over 85 m. Deposits generally occur in stream and river channels, modern deltas, and modern flood plains. Unit Qa may locally include alluvial fans (unit Qaf) and older alluvium (unit Qoa). (Description compiled from Newcomb and others, 1949; Sceva, 1950; Washington Division of Water Resources, 1960; Easterbrook, 1971, 1976a; Dragovich and Grisamer, 1998; and Dragovich and others, 1998, 1999.)

Qb **Beach deposits (Holocene)**—Moderately to well-sorted coarse sand and gravel and, locally, sand, silt, and clay in tidal-flat deposits. Bedding is planar and channel cross-stratified and locally massive; locally includes very well sorted eolian back-beach sand dunes. Clasts are generally well rounded and sometimes crudely polished by wave action and mostly derived from reworked glacial deposits. Color is dependent upon dominant clast lithology. Thickness is highly variable but generally greater than 2.5 m. Unit Qb forms elongate spits near Drayton Harbor and Lummi Bay in the northwest part of the Bellingham quadrangle. (Description compiled from Easterbrook, 1971; Dethier and others, 1996; Dragovich and others, 1998; and Washington Department of Ecology, 1977, 1978.)

Qoa **Older alluvium (Holocene)**—Well-sorted and stratified cobbles, sand, silt, and lesser clay. Clasts are generally rounded to subrounded and consist of metamorphic, sedimentary, and igneous rocks derived from local sources such as bedrock and reworking of glacial deposits. Color is brown to gray, depending on oxidation state and composition. Thickness of the deposits is poorly constrained, however some exposures are at least 15 m thick, based on the height of erosional river terraces. Exposures of unit Qoa in the Bellingham quadrangle generally flank modern alluvial flood plains of the Skagit River and the south, middle, and north forks of the Nooksack River. Unit Qoa may locally contain primary and (or) reworked laharic material (units Qvl_k and Qvl_m) derived from Mount Baker and (or) Glacier Peak volcanoes. (Description compiled from Moen, 1962; Easterbrook, 1976a; Dragovich and Grisamer, 1998; and Dragovich and others, 1998, 1999.)

Qvl_m **Lahar of the Middle Fork Nooksack River (Holocene)**—Diamicton containing rounded to mostly angular boulders, gravel, sand, silt, clay, and woody debris, including logs. Mount Baker andesite is the predominant clast lithology; other clast types are likely derived from river alluvium and glacial deposits. Color in outcrop may be variations of red/brown (Fe-oxide), yellow/orange (sulfur staining), and gray/brown. Thickness may be greater than 13 m as determined from river bank exposures and subsurface (well data) interpretation. Exposures of unit Qvl_m occur near the north end of Van Zandt Dike but smaller exposures (too small to be mapped at this scale) occur in the Middle Fork Nooksack River valley in the vicinity of Clearwater Creek. ^{14}C ages obtained from wood in the deposit are 5,650 ±110 yr B.P., 5,710 ±110 yr B.P. (Kovanen, 1996), and 6000 yr B.P. (Hyde and Crandell, 1978). (Description compiled from Kovanen, 1996, and Dragovich and others, 1997a.)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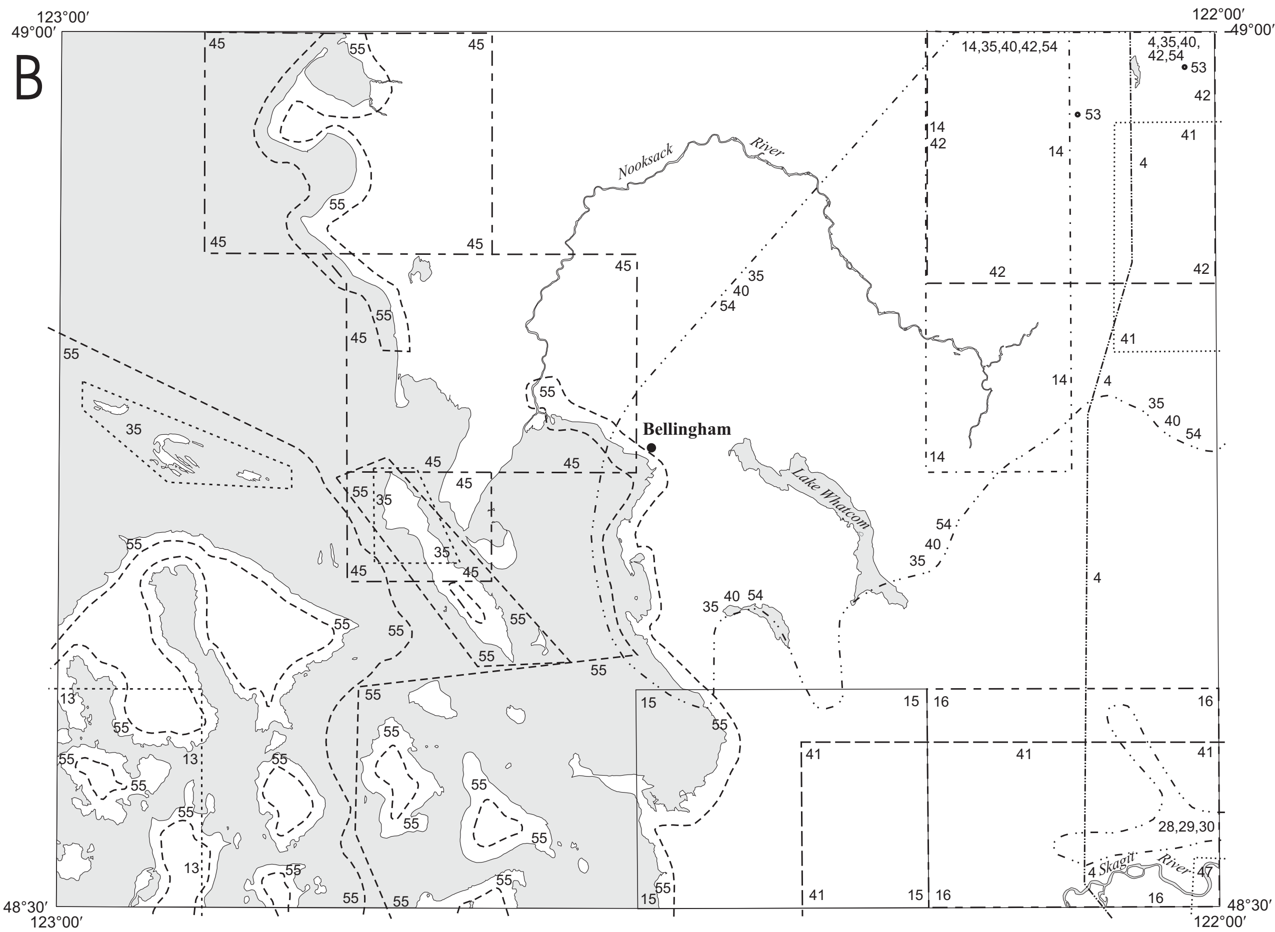
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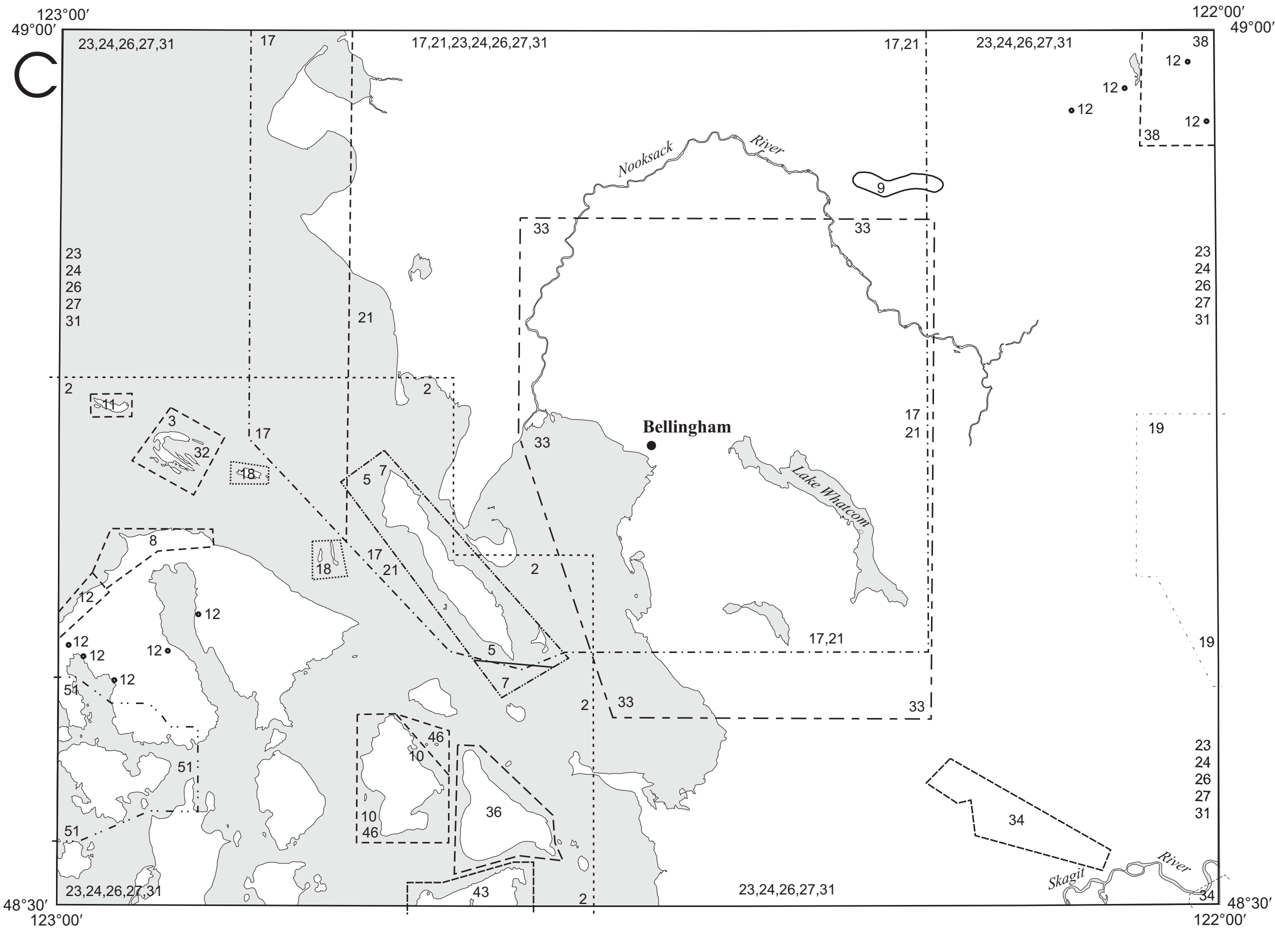

Figure 3. Index maps *(this and facing page)* showing sources of geologic data used in this compilation. Location of previous geologic map studies shown by various line types. Study numbers are located inside the line boundary. **, map coverage includes the entire Bellingham quadrangle; primary sources of geologic data are listed in **bold**.

1. Bechtel, Inc., 1979, 1:63,360
2. Brown and others, 1987, 1:100,000
3. Breitsprecher, 1962, 1:19,000
4. **Brown and others, 1987, 1:100,000**
5. Calkin, 1959, 1:63,000
6. Canton and Swarva, 1911, 1:31,680
7. **Carroll, 1980, 1:24,000**
8. Carsten, 1982, 1:22,000
9. Converse Davis Dixon and Associates, 1976, 1:4,800
10. Conway, 1971, 1:10,500
11. Dainty, 1981, 1:11,000
12. Danner, 1957, various scales
13. **Dethier and others, 1996, 1:24,000**
14. **Dragovich and others, 1997a, 1:24,000**
15. **Dragovich and others, 1998, 1:24,000**
16. **Dragovich and others, 1999, 1:24,000**
17. **Easterbrook, 1976a, 1:62,500**
18. Egemeier, 1981, 1:9,700
19. Frasse, 1981, 1:31,680
20. Gaudette, 1963, 1:50,688
21. U.S. Smelting Refining and Mining Company, 1958, 1:62,500
22. Gordy, 1988, 1:250,000**
23. Gower, 1978, 1:250,000**
24. Gower and others, 1985, 1:250,000**
25. Gusey, 1978, 1:12,000
26. Hall and Othberg, 1974, 1:250,000**
27. Haugerud, 1979, 1:250,000**
28. Heller, 1978, 1:63,360
29. Heller, 1979a, 1:62,500
30. Heller, 1979b, 1:62,500
31. Hopkins, 1966, 1:250,000**
32. Janbaz, 1972, 1:19,000
33. Jenkins, 1923, 1:84,000
34. Jenkins, 1924, 1:90,000
35. **Johnson, 1982, 1:50,000**
36. **Kahle and Olsen, 1995, 1:24,000**
37. Kovanen, 1996, 1:24,000
38. **Liszak, 1982, 1:15,000**
39. McLellan, 1927, 1:62,500
40. Miller and Misch, 1963, 1:169,000
41. Misch, 1977, 1:126,700
42. **Moen, 1962, 1:62,500**
43. Mulcahey, 1975, 1:42,000
44. Newcomb and others, 1949, 1:62,500
45. **Palmer, 1977, 1:24,000**
46. Raleigh, 1963, 1:144,820
47. Robertson, 1981, 1:15,840
48. **Russell, 1975, 1:70,000**
49. Sceva, 1950, 1:100,000
50. **Schmidt, 1972, 1:11,927**
51. Shelley, 1971, 1:56,320
52. Siegfried, 1978, 1:24,000
53. Smith, 1961, 2 plates, 1:3,000 and 1:4,800
54. Vonheeder, 1975, 1:62,500
55. Washington Department Ecology, 1978a,b, 1:24,000
56. Washington Division of Water Resources, 1960, 1:135,000

Qvl_k **Lahar (Kennedy Creek assemblage) (Holocene)**—Moderately to poorly sorted and locally poorly to nonstratified volcanic sand and gravel with local cobble gravel, silt, and clay. Consists of rounded pumiceous and (or) vesicular dacite clasts and crystal-lithic and dacite-rich sand; also contains lesser clasts from bedrock and glacial deposits to the east. Color, which is highly dependent on oxidation state and composition, is generally pale to dark yellowish brown, olive gray, or light to dark gray. Thickness is generally 10 to 20 m, based on well data. Chemical, age, and provenance data indicate that this unit was deposited by one or more large hyperconcentrated floods from the Glacier Peak volcano at about 5,100 to 5,500 yr B.P. and possibly again at ~1,800 yr B.P.

Outcrops of unit Qvl_k are common in the Skagit River valley and occur as flat terraces 10 to 20 m above the present river channel and flood plain. See Dragovich and others (1999, 2000) for a detailed discussion of unit Qvl_k. (Description compiled from Dethier and Whetten, 1981; Beget, 1982; David Dethier, written commun. to Dragovich, 1999; Dragovich and others, 1998, 1999; and Dragovich, oral commun., 2000.)

Qaf **Alluvial fan deposits (Holocene to latest Pleistocene)**—Poorly sorted, massive to poorly stratified diamicton consisting of clayey silty sandy gravel and gravelly sandy silt. Clasts are generally angular to rounded and consist of detritus derived from local sources and reworked glacial deposits. Deposits generally coarsen upslope along the fan surface. Color is dependent on lithology and oxidation state but is generally some combination of gray, brown, and olive-green. Thickness is variable but deposits generally thicken toward the head of the fan. Alluvial fans occur at the mouths of streams and disconformably overlie glacial deposits, but conformably overlie and interfinger with alluvium (unit Qa). Most alluvial fans are of debris-flow or debris-torrent origin and are locally modified by stream processes. (Description compiled from Easterbrook, 1976a; Dragovich and Grisamer, 1998; and Dragovich and others, 1998, 1999.)

Qls **Landslide deposits (Holocene to late Pleistocene)**—Poorly sorted to unsorted and unstratified diamicton consisting of angular to rounded boulders, cobbles, and gravel in a matrix of sand, silt, and (or) clay. Clast composition reflects source area. Deposits generally originated from deep-seated (bedrock) failures and shallow slumps and slides in Quaternary deposits. Deposits unconformably overlie bedrock and overlie and (or) interfinger with Quaternary geologic units. Landslide polygons include material transported downslope. The unstable scarp area may be included in the landslide polygon if smaller slumps and slides are present. No distinction is made between different mass-wasting processes and features on this map. (Description compiled from Washington Division of Water Resources, 1960; Moen, 1962; Easterbrook, 1976b; Heller, 1981; Carpenter, 1993; Schmidt, 1994; Engebretson and others, 1995, 1996; Kovanen, 1996; and Dragovich and others, 1998, 1999.)

Qp **Peat (Holocene to late Pleistocene)**—Poorly sorted, massive to poorly stratified silt and organic material ranging from leaf and plant litter and dark ooze to rooted stumps and logs. Color is usually brown to black. Thicknesses are variable but are generally less than 15 m. Material generally originated in abandoned channels, oxbow lakes, former river or stream channels, bogs associated with stagnant ice features (kettles), and depressions in glacial drift. Most peat deposits in the Bellingham quadrangle occur in the lowland areas of northwestern Whatcom County where they cover an estimated 10 percent of the land surface, the most of any county in the state. (Description compiled from Rigg, 1958; Easterbrook, 1976a; Cameron, 1989; and Dragovich and others, 1998, 1999.)

GLACIAL DEPOSITS

Fraser Glaciation, undivided

Qgd **Glacial deposits, undifferentiated (Pleistocene)**—May include any and all glacial deposits described below. Unit symbol Qgd is used where detailed field and map data are lacking and (or) differing interpretations of Quaternary glacial deposits are unreconcilable.

Qgo_{es} **Glacial outwash, Sumas Stade and (or) Everson Interstade (Pleistocene)**—Glacial outwash deposits of either Sumas Stade and (or) Everson Interstade (units Qgo_s and Qgo_e respectively). This symbol is used where no distinction can be made between these units. See the descriptions of units Qgo_s and Qgo_e below for details of the deposits.

Fraser Glaciation, Sumas Stade

Qgo_s **Glacial outwash, Sumas Stade (Pleistocene)**—Loose, moderately to well-sorted gravel with local boulders, sandy gravel, minor gravelly medium to coarse sand, and rare sand to silt. Clasts are generally subrounded to rounded and derived from the Coast Plutonic Complex in British Columbia and nearby sources. Bedding is massive to well-stratified; stratified sections are generally planar with bedding thickness ranging from a few centimeters to a few meters, depending on clast size; beds are rarely cross-stratified. Color is brown to gray, depending on oxidation state. Thickness is highly variable across the Bellingham quadrangle, ranging from 3 to 280 m, and is thickest in the Columbia Valley near Sumas Mountain. (See Dragovich and others, 1997b, for cross sections of the Columbia Valley area; Cameron, 1989, and Kahle, 1990, for subsurface data in the Sumas River area; and Sceva, 1950, and Dragovich and Grisamer, 1998, for subsurface data for the Samish River area.)

Age of unit Qgo_s, as determined by ^{14}C, is older than 10,000 yr B.P., the age of basal peat in abandoned Sumas outwash channels and kettles associated with Sumas ice (Easterbrook, 1962, 1969, 1976a, 1979; Easterbrook and Kovanen, 1998). Wood from Sumas drift in southwest British Columbia, inferred to be roughly coeval with Sumas outwash in northern Whatcom County, yielded ^{14}C ages of 11,700 to 10,950 yr B.P. (Armstrong and others, 1965; Clague, 1980; Armstrong, 1981). Outcrops of Sumas outwash are pervasive in the Columbia Valley and common in the Whatcom basin and Sumas River area. Sumas outwash is also common in the Bow and Alger 7.5-minute quadrangles in the Samish River area (Easterbrook, 1979; Dragovich and others, 1998) where a Sumas-age outwash channel is incised into glaciomarine drift of Everson age. (Description compiled from Moen, 1962; Easterbrook, 1976a; Cameron, 1989; Kahle, 1990; Dragovich and Grisamer, 1998; and Dragovich and others, 1997a,b, 1998, 1999.)

$Qgom_s$ **Marine deltaic outwash, Sumas Stade (Pleistocene)**—Loose, moderately to well-sorted cobbly gravel with local boulders and mixtures of sand and gravel with lesser silt and clay layers. Clasts are generally subrounded to rounded and derived from the Coast Plutonic Complex of British Columbia and local sources, including, but not limited to, andesite from Mount Baker, dunite of probable Twin Sisters origin, and phyllite and vein quartz from the Easton Metamorphic Suite and older glacial deposits. Color is some combination of brown and gray, depending on oxidation state. Thickness is 7 to 25 m. The unit is commonly thickly to thinly bedded and rarely nonbedded; large foreset beds (3–18 m high) are common and typically dip 15 to 35 degrees southeast to southwest and display numerous truncation surfaces. Topset beds are generally subhorizontal and consist of gravels with interbeds of sand and rarely silty sand and silt. Bottomset beds are composed of massive to laminated silty clay and clay and are overlain by foreset gravel and sand suggestive of southerly progradation of the delta front into the Skagit River valley.

Unit $Qgom_s$ has poor direct age control, however it can be inferred from ^{14}C dates of Sumas Stade deposits elsewhere (see the description of unit Qgo_s above). An outwash channel of the Sumas Stade is incised into uplifted marine terraces near Butler Hill (Easterbrook, 1979, 1992). These terraces are similar to the nearby marine terraces of Bay View Ridge, which emerged above sea level at 11,700 ±110 yr B.P. (^{14}C ages in basal peat, Siegfried, 1978). Therefore, incision occurred after 11,700 ±110 yr B.P. and deposition of deltaic outwash continued until Sumas outwash channels to the north were abandoned at about 10,000 yr B.P. (Easterbrook, 1962, 1969, 1976a, 1979; Easterbrook and Kovanen, 1998). See Easterbrook (1979, 1992) for a discussion of sea level during the Everson Interstade and Sumas Stade of the Fraser Glaciation.

Exposures of unit $Qgom_s$, important sources of gravel, are present only in the Butler Hill and Butler Flat areas in the southern part of the Bellingham quadrangle. Unit $Qgom_s$ may locally include terrestrial Sumas Stade outwash deposits (unit Qgo_s), since sea level dropped during this time interval. (Description compiled from Easterbrook, 1979, 1992; Dragovich and others, 1998; and Dragovich and Grisamer, 1998.)

Qgt_s **Glacial till, Sumas Stade (Pleistocene)**—Dense, unstratified diamicton consisting of gravel and sand with some silt and clay with rare boulders and cobbles. Clast composition indicates a north derivation from the Coast Plutonic Complex and associated rocks in British Columbia. Color is brown; thickness is less than 13 m. ^{14}C ages between 11,800 and 11,300 yr B.P. were determined from wood in Sumas drift in southern British Columbia (Armstrong and others, 1965; Clague, 1980; Armstrong, 1981; Clague and others, 1997). ^{14}C ages from basal peat in abandoned Sumas outwash channels and kettles give a minimum age limit of about 10,000 yr B.P. (Easterbrook, 1962, 1969, 1976a, 1979; Easterbrook and Kovanen, 1998). Outcrops of unit Qgt_s are limited to the north-central part of the Bellingham quadrangle. (See Easterbrook, 1976a; Clague and others, 1997; and Easterbrook and Kovanen, 1998, for a discussion of the complex nature of the Sumas ice advance.) (Description compiled from Easterbrook, 1976a; Kahle, 1990; Clague and others, 1997; and Dragovich and others, 1997a.)

Fraser Glaciation, Everson Interstade

Qgo_e **Glacial outwash, Everson Interstade (Pleistocene)**—Loose, moderately to well-sorted cobbly gravel, gravelly sand, sandy gravel, sand, and rare silt. Clasts are angular to subrounded. Bedding is planar in fine-grained sediments and commonly trough cross-bedded in coarser deposits. Foreset beds are locally present and are probably the result of scour filling. Subhorizontal bedding is commonly crudely developed and defined by meter-thick, laterally extensive, vertical variations in clast size. Pebble imbrication is common. The unit is terrestrial in origin. Clasts were mostly derived from local and distant sources to the north and east of the Bellingham quadrangle. Granitic and yellow quartzite clasts are the strongest evidence for a British Columbia source. Color is typically some combination of olive-gray, gray, and brown, depending on lithologic content and oxidation state. Thickness ranges from less than a meter to perhaps as much as 100 m.

The age of unit Qgo_e is presumed to be between 13,600 to 11,300 yr B.P. (dates from marine shells, not corrected for marine reservoir effect; Dethier and others, 1995), the duration of the Everson Interstade. However, some deposits may be late Vashon. The unit is interpreted to be generally coeval with Everson glaciomarine drift (unit $Qgdm_e$) and Everson marine deltaic outwash (unit $Qgom_e$). Younger ^{14}C dates from wood in Everson Interstade deposits are 10,370 ±300 yr B.P. (Easterbrook, 1963) near the city of Bellingham and 10,950 ±200 yrs B.P. (Armstrong and others, 1965; Clague, 1980) in southern British Columbia. These dates temporally overlap, within error estimates, ^{14}C wood ages in Sumas Stade deposits in British Columbia (Armstrong, 1981).

Outcrops are common throughout the Bellingham quadrangle from 125 m to more than 200 m elevation, the altitude of the marine limit in the study area during Everson time (Easterbrook, 1963, 1992; Dethier and others, 1995). Most smaller exposures flank the sides of mountains—the result of subglacial meltwater. Large deposits are present in the Lyman 7.5-minute quadrangle as terraces flanking major drainages. This unit may locally include outwash of the Sumas Stade and deltaic outwash of the Everson Interstade. (Description compiled from Dethier and others, 1995, 1996, and Dragovich and others, 1999.)

$Qgom_e$ **Marine outwash, Everson Interstade (Pleistocene)**—Loose, moderately to well-sorted, subangular to subrounded gravelly sand, sandy gravel, and sand with minor interbeds of silt and silty sand. Clasts are subangular to rounded and locally angular. Bedding is well developed on a scale of centimeters to meters and is rarely massive. Unit $Qgom_e$ commonly forms high-amplitude foreset beds and trough cross-bedding, which are indicative of deltaic deposition. These beds are usually tens of meters high, dip 15 to 40 degrees, and are overlain by 1 to 2 m thick subhorizontal topset beds. Distal marine outwash deposits are generally thinly plane-laminated and rarely rhythmically bedded. Clasts were derived from local and distant sources, and clasts and sand are locally phyllite and vein-quartz rich. Color is brown to gray, depending on oxidation state and lithologic content. Thickness is from less than 1 m to 70 m.

The age of unit $Qgom_e$ is between 12,900 and 12,500 yr B.P. in the western San Juan Islands (Dethier and others, 1996) and possibly as young as 11,990 ±110 yr B.P., a ^{14}C date from wood near the top of the unit in the Alger 7.5-minute quadrangle (Dragovich and others, 1998). This unit interfingers with unit $Qgdm_e$ and therefore may locally include it. Outcrops are common within the Bow, Alger, Sedro-Woolley North, and Lyman 7.5-minute quadrangles, especially flanking the Skagit River valley. All exposures occur below the lowering marine limit during Everson time. (See Easterbrook, 1979, 1992, and Dethier and others, 1995, for discussions on changing sea level during Everson time.) (Description compiled from Easterbrook, 1968; Dethier and others, 1995, 1996; Dragovich and Grisamer, 1998; and Dragovich and others, 1998, 1999.)

$Qgom_{ee}$ **Emergence (beach) deposits, Everson Interstade (Pleistocene)**—Loose, moderately to well-sorted gravel and sand and local boulders and fine to medium sand. Clasts are subrounded to rounded. Bedding is massive, laminated, or cross-stratified and locally fills channels cut into underlying deposits. Deposits are typically reworked Everson glaciomarine drift (unit $Qgdm_e$). The unit unconformably overlies older deposits and usually lies beneath or grades upward into eolian deposits rich in organic material. It also occurs as topographic benches interpreted as wave-cut terraces (strandlines). Color is variable and depends on lithologic content and local iron-oxide staining. Thickness is from less than 1 to 7.5 m.

The inferred age of unit $Qgom_{ee}$ in the western San Juan Islands is between 12,800 and 12,300 yr B.P. (Dethier and others, 1996). Siegfried (1978) reports a ^{14}C age of 11,700 ±110 yr B.P. for peat in an uplifted marine terrace (Bay View Ridge), which is a minimum age for these deposits. Outcrops are common below about 200 m elevation and occur near Blaine, Ferndale, and Lake Terrell, on Lummi Island and Bay View Ridge, and in the Butler Hill area (Easterbrook, 1976a). These deposits were formed by wave action as glaciomarine deposits emerged above sea level in Everson time. (See Siegfried, 1978, for a detailed discussion of uplifted marine terraces on Bay View Ridge; also see Palmer, 1977; Easterbrook, 1979, 1992; and Dethier and others, 1996, for discussions of marine terrace and strandline distributions and relationships.) (Description compiled from Easterbrook, 1976a; Siegfried, 1978; Armstrong, 1981; Dethier and others, 1996; Dragovich and Grisamer, 1998; and Dragovich and others, 1998.)

$Qgdm_e$ **Glaciomarine drift, Everson Interstade (Pleistocene)**—Moderately to poorly indurated, moderately to unsorted diamicton with lenses and discontinuous beds of moderately to well-sorted gravel, sand, silt, and clay. Dropstone content is variable, and they are commonly polished, striated, and (or) faceted. A fluvial interbed occurs in the Deming area and within bluffs near Bellingham Bay (Easterbrook, 1963, 1992; Easterbrook, oral commun., 2000; Weber and Kovanen, 2000). (See Easterbrook, 1963, 1976a, for details on the Deming Sand.) Bedding is massive to poorly stratified (planar beds) in marine sediments and locally cross-bedded in sandy interbeds. In the Skagit River valley area, Dragovich and others (1998, 1999, 2000) observed an overall upward-fining sequence in glaciomarine drift. The unit varies from nonfossiliferous to highly fossiliferous and is locally phyllite and vein-quartz rich. Provenance data indicates local sources as well as the Coast Plutonic Complex of British Columbia. Color is gray to blue-gray to olive-gray to brown, depending upon oxidation state. Thickness ranges from a few meters to as much as 90 m.

The age of unit $Qgdm_e$ is roughly 11,300 to 13,500 yr B.P. (Siegfried, 1978; Easterbrook, 1992; Dethier and others, 1995) based on radiocarbon dates of marine shells and woody debris. (Shell ages are not corrected for the marine reservoir effect and uncorrected ages may therefore be ~600 years older than those from wood that grew at the same time; see Dethier and others, 1995, 1996.)

Exposures are pervasive, especially in Whatcom basin and the Skagit River area, and only occur at or below about 200 to 240 m elevation, the marine limit during Everson time (Easterbrook, 1963, 1992; Dethier and others, 1995). Unit $Qgom_e$ locally interfingers with this unit in the lower Skagit River area (Dragovich and others, 1998, 1999). Complex facies relationships exist in this unit, and there is still considerable debate related to the mode of deposition (for example, ice calving at a retreating ice terminus vs. deposition from floating berg or shelf ice). (See Easterbrook, 1963; Domack, 1982; Pessl and others, 1989; Easterbrook, 1992; Dethier and others, 1995, 1996; and Dragovich and others, 1998.) Unit $Qgdm_e$ may locally include units Qgt, $Qgom_{ee}$, and $Qgom_e$. (Description compiled from Easterbrook, 1962, 1963, 1976a, 1992; Domack, 1982; Pessl and others, 1989; Dethier and others, 1995, 1996; Dragovich and Grisamer, 1998; and Dragovich and others, 1998, 1999.)

Fraser Glaciation, Vashon Stade

Qgt **Glacial till, Vashon Stade (Pleistocene)**—Dense, unsorted diamicton consisting of boulders to clay; locally contains interbeds of laminated silt and fine sand and rarely interbedded gravel. Clasts are subangular to rounded, and boulders are commonly faceted, striated, and polished. This unit unconformably overlies unit Qga or older bedrock units and locally overlies other older Quaternary deposits. Clasts were derived from the Coast Plutonic Complex of British Columbia and local sources, commonly the Darrington Phyllite.

Color is some mixture of gray, olive-gray, brown, and yellowish brown, depending on lithologic content and oxidation state. Unit thickness is from less than 1 to 25 m.

Age is older than about 13 ka and younger than 18 ka. Direct dates in the study area are unknown. (See Easterbrook, 1969, 1986, for discussions of the age of this unit.) Outcrops are ubiquitous and form thin veneers over bedrock. This unit may locally include isolated deposits of unit Qgo_e and Qga. (Description compiled from Easterbrook, 1962, 1969; Dethier and others, 1996; and Dragovich and others, 1997a,b, 1998, 1999.)

Qga **Advance outwash, Vashon Stade (Pleistocene)**—Moderately indurated, moderately to well-sorted sandy gravel, pebbly sand, medium to coarse sand, silt, and clay. This unit forms an overall upward-coarsening sequence from silts and clays at the base to coarse sand and gravel near the top (as determined from well logs; Dragovich and Grisamer, 1998). It is generally thickly to thinly bedded with subhorizontal stratification; trough cross-bedding and cut-and-fill structures are common. Silt and clay layers are commonly planar-bedded and locally contain dropstones and soft-sediment deformational features. Local foreset bedding in sand and gravel suggests deposition into standing water (proglacial lakes?) (Dragovich and others, 1998, 1999, and this study). Color is gray to pale yellowish brown, depending on lithologic content and oxidation state. Thickness is variable from a few meters to possibly as much as 80 m.

Unit Qga_v is time-transgressive to the south, and its age is roughly in the range of 14 to 18 ka. (See Thorson, 1980, and Easterbrook, 1992, for discussions of the chronology of the Vashon Stade of the Fraser Glaciation.) Exposures are uncommon in the Bellingham quadrangle, though many outcrops are present in the South Fork Nooksack River and Skagit River valleys. Unit Qga_v may locally include isolated deposits of unit Qgt_v. (Description compiled from Pessl and others, 1989; Easterbrook, 1992; Dethier and others, 1996; Dragovich and Grisamer, 1998; and Dragovich and others, 1998, 1999.)

Fraser Glaciation, Evans Creek Stade

Qat_e **Alpine till, Evans Creek Stade (Pleistocene)**—Dense, unsorted diamicton consisting of boulders to clay. Clasts are generally subangular to subrounded. Dunite, pyroxenite, slate, phyllite, volcanic, and metavolcanic clasts indicate a source upvalley of the South Fork Nooksack River. Color is gray to reddish brown, depending upon oxidation state. Thickness is unknown. This unit is locally overlain by unit Qga. Age is roughly 19 to 23 ka (Armstrong, 1981) or 15 to 25 ka (Armstrong and others, 1965). Outcrops are only recognized in the South Fork Nooksack River valley near or below river level in the Lyman 7.5-minute quadrangle. Tills of similar composition on the south-facing flank of Miner Mountain (unit Qgt) may correlate with unit Qat_e, however poor stratigraphic and age control make this correlation speculative. (Description compiled from Heller, 1978, and Dragovich and others, 1999.)

pre-Fraser Glaciation

Qc_w **Continental sediments, Whidbey Formation (Pleistocene)**—Moderately to well-sorted sand, silt, and clay with local lenses and layers of gravel or peat. Bedding is commonly planar in silt, clay, and peat layers and cross-stratified in sandy layers. Sediments are interpreted to have accumulated in a low-energy flood-plain environment. Color is buff-gray to gray and dark brown to black in organic-rich layers. Thickness is more than 60 m at its type locality near Double Bluff on Whidbey Island. The age of unit Qc_w, as determined from amino acid ratios in peat and thermoluminescense in clay, is between 100 and 150 ka (Easterbrook and others, 1982; Berger and Easterbrook, 1993). Recent work by Dragovich and others (in progress) indicates that outcrops mapped as Whidbey Formation may in fact be Olympia nonglacial sediments. More dating in the Bellingham quadrangle is required to solve this problem. On Guemes Island, unit Qc_w is a confining unit above the Double Bluff aquifer (Kahle and Olsen, 1995). (Description compiled from Easterbrook and others, 1967, 1982; Pessl and others, 1989; and Kahle and Olsen, 1995.)

Tertiary Rocks

Eir **Rhyolite dikes (Eocene?)**—Two small dikes consisting of subhedral to euhedral (locally fragmented) quartz, sanidine, and plagioclase phenocrysts in a hypocrystalline groundmass containing small microlitic quartz and feldspar crystals. Accessory minerals are rare but include epidote and chlorite. Locally, porphyroclasts have trachitic textures in small (1–2 mm wide) shears, possibly related to intrusion into the Padden(?) Member of the Chuckanut Formation. Color is light gray. Dikes strike about N18E and occur as a tabular bodies (~.25 m thick) in a very small area on the northeast side of Lummi Island. Dike faces are slickensided. Poor exposure and a required minus tide make this outcrop difficult to find (this study; M. C. Blake, Western Wash. Univ., oral commun., 2000).

HUNTINGDON FORMATION

$ΦEc_h$ **Huntingdon Formation of Daly (1912) (Oligocene to Eocene)**—Moderately to well-sorted conglomerate, sandstone, siltstone, shale, and clay that is locally unsorted. Bedding is massive to well developed and locally planar to cross-stratified; conglomerate is commonly massive to poorly bedded. Conglomerate contains rounded to angular volcanic, plutonic, gneissic, chert, argillite, serpentinite, and quartz clasts that range in size from 1 to 7 cm, locally as large as 40 cm. Matrix is commonly coarse sand to locally silt and clay (diamict). Sandstone, commonly grading into or interbedded with conglomerate, ranges from coarse to fine grained (locally arkosic) and is commonly planar or cross-bedded. Sandstone is composed predominantly of quartz, feldspar, and lithic grains in variable proportions, with local volcanic-rich interbeds (Moen, 1962; Mustard and Rouse, 1994; Dragovich and others, 1997a). Shale and clay are commonly thinly plane-bedded and locally contain coalified debris on bedding surfaces. Shale is locally highly ferruginous. Scour features are common at the basal contacts of conglomerate beds. Sandstone and conglomerate are poorly cemented by calcite or hematite. Color is yellowish brown for ferruginous cemented rock; sandstones commonly weather buff to light-brown and are greenish-gray on unweathered surfaces; shale and clay vary from blue to yellow. Thickness ranges from very thin (<1 m) to possibly 500 m along western Sumas Mountain. Provenance data suggest local and distant sources of detritus (Moen, 1962; Mustard and Rouse, 1994; Dragovich and others, 1997a). Dragovich and others (1997a) suggest angular discordance between the Huntingdon and Chuckanut Formations on Sumas Mountain, as did Miller and Misch (1963).

The age of the Huntingdon Formation in the Bellingham quadrangle is Late Eocene to possibly Early Oligocene as determined from a single pollen analysis (Mustard and Rouse, 1994). Based on age and stratigraphic control in southern British Columbia, Mustard and Rouse (1994) conclude that this unit (exposures in Washington State) is correlative with strata of the Chuckanut Formation. Outcrops are present on Sumas and Vedder Mountains. Clay from this unit has been mined for refractory purposes (Moen, 1962). (Description compiled from Moen, 1962; Miller and Misch, 1963; Mustard and Rouse, 1994; and Dragovich and others, 1997a.)

CHUCKANUT FORMATION

The Chuckanut Formation was first named by McLellan (1927) and later refined by Glover (1935) and Weaver (1937), who defined representative sections. Johnson (1982) divided the Chuckanut Formation into seven members, six of which are exposed in the Bellingham quadrangle. These six members consist of arkosic sandstone, siltstone, conglomerate, and coal, mostly deposited in the Eocene and possibly the Late Paleocene to Early Oligocene (Johnson, 1982, 1984, 1991; Mustard and Rouse, 1994; Mustoe and Gannaway, 1997). Johnson (1985) interpreted the tectonic environment of deposition as a strike-slip pull-apart basin that received detritus from local uplifts and distant sources. Syndeposition faulting may account for rapid sedimentation (subsidence) and abrupt facies and thickness changes across the Chuckanut Formation outcrop belt (Plate 1) (Johnson, 1985, 1991; Haugerud, 1998). Post-deposition (Eocene–Oligocene?) deformation produced broad to tight, northwest- and east–west-trending folds across the entire outcrop belt.

Members of the Chuckanut Formation exposed in the Bellingham quadrangle are the Bellingham Bay, Governors Point, Padden, Slide, Maple Falls, and Warnick Members. The geologic significance of this member scheme and their stratigraphic relationship is in a state of flux, given new paleoclimate data discussed in Mustoe and Gannaway (1997), field observations by Dragovich and others (1997a), and unpublished mapping by R. A. Haugerud (in progress). Therefore, this report describes the members as lithologic units with little inference of any stratigraphic relationships. (Compare Mustoe and Gannaway, 1997, with Johnson, 1982, 1984, 1985, and 1991.) The principal source of map data (Plate 1) for the Chuckanut Formation, however, was Johnson (1982).

Ec_{cb} **Bellingham Bay Member (Eocene)**—Well-sorted sandstone, conglomerate, and mudstone, with lesser coal. Sandstone is commonly coarse-grained arkose with lesser medium- to fine-grained sandstone composed predominantly of quartz and feldspar (K-feldspar and plagioclase). (See Johnson, 1982 and 1984, for point-count data.) This member is commonly trough cross-bedded and ripple or flat-laminated. Conglomerate, occurring most notably at the base of the section, contains clasts derived from underlying units (phyllite and vein quartz) as well as clasts from more distant sources. Bedding is generally massive to crudely stratified. Mudstone is commonly massive or laminated and contains plant fossils (for example, palm fronds) and local coal layers. Coarse- to fine-grained lithologies are often interbedded and form upward-fining sequences averaging 29 m thick near Bellingham Bay. Color is yellowish gray to gray with a salt and pepper appearance for sandstones; color of conglomerates varies with lithologic content. Mudstone ranges from bluish gray to dark gray, and coal is generally black. Thickness is estimated to be 2,700 m, based on a measured section along Bellingham Bay.

An Eocene to possibly Late Paleocene age is determined from a 49.9 ±1.2 Ma fission-track age of zircon from a dacitic tuff near the top of the Bellingham Bay Member (Appendix, Table 5, map no. 59) and 55 to 58 Ma fission-track ages of the youngest detrital zircons from the base of the section (Johnson, 1982, 1984). These ages are consistent with, though slightly older than, Early to Middle Eocene ages from pollen analyses of nearby strata (Appendix, Table 6, map no. 109) (Reiswig, 1982). The base of the unit unconformably overlies pre-Tertiary bedrock. Honeycomb weathering patterns are common on exposures near sea water (Mustoe, 1982). Exposures are widespread in the map area. (Description compiled from Johnson, 1982, 1984, 1985, 1991; Mustard and Rouse, 1994; Mustoe and Gannaway, 1997; and Dragovich and others, 1997a.)

Ec_{cg} **Governors Point Member (Eocene)**—Moderately to well-sorted sandstone, conglomeratic sandstone, and conglomerate. Sandstone is generally arkosic, medium to coarse grained, and of similar lithology to sandstones in the Bellingham Bay Member. Trough cross-bedding and flat-bedded to flat-laminated and ripple-laminated bedding characteristics are common; beds generally form upward-fining couplets. Conglomerate is massive to crudely stratified and consists mainly of well-rounded metagraywacke, chert, and greenstone clasts. Clasts range up to 20 cm in the longest dimension; matrix material is generally coarse-grained sandstone. Conglomerate layers grade upward into conglomeratic sandstone and sandstone. Erosional surfaces are common at the base of conglomeratic layers. Color ranges from brown to gray. Thickness is estimated to be 375 m near Governors Point. There are no direct estimates of the age; however, this member stratigraphically overlies the Bellingham Bay Member near and just above the 49.9 ±1.2 Ma dacitic tuff (see Unit Ec_{cb}). A Middle Eocene age is inferred. Outcrops are present at Governors Point (type locality) just south of Chuckanut Bay. (Description compiled from Johnson 1982, 1984.)

Ec_{cs} **Slide Member (Eocene)**—Well-sorted, fine- to medium-grained sandstone, siltstone, and mudstone with minor coal; conglomerate is largely absent. Sandstone is generally arkosic and compositionally indistinguishable from sandstones of the Bellingham Bay Member, though finer grained (Johnson, 1982, 1984). Bedding is typically ripple-laminated, trough cross-bedded, or flat-laminated. Sandstone grades upward into siltstone and mudstone; siltstone and mudstone are often massive to laminated and locally contain massive and ripple-laminated beds of sandstone (<50 cm thick) that have sharp upper and lower contacts. Coal and other organic matter is locally abundant; leaf imprints (for example, palm fronds) and animal tracks are locally present on bedding surfaces (Mustoe and Gannaway, 1997). Color is yellowish gray to dark gray with a salt and pepper appearance. Thickness is estimated at about 1,960 m near Slide Mountain (type locality). There is no direct estimate of age; however, Johnson (1982, 1984) infers an Eocene age. Outcrops are present in the eastern outcrop belt of the Chuckanut Formation on Sumas and Slide Mountains. (Description compiled from Johnson, 1982, 1984; Mustoe and Gannaway, 1997; and Dragovich and others, 1997a.)

Ec_{cw} **Warnick Member (Eocene)**—Well-sorted conglomerate, sandstone, siltstone, and mudstone; coarse-grained strata alternate with fine-grained strata. Conglomerates beds (≤11 m thick) are massive to crudely stratified and are composed of well-rounded chert with lesser greenstone and sedimentary clasts up to 25 cm in diameter; matrix material is commonly coarse sandstone. Sandstone ranges from coarse to fine and is commonly trough cross-bedded and compositionally similar to sandstones of the Bellingham Bay Member (Johnson, 1982, 1984). Siltstone and mudstone are dominantly massive to laminated and locally contain thin (<50 cm thick) lenticular beds of conglomeratic sandstone. Color ranges from yellowish brown to gray and dark gray. Thickness is possibly as much as 1000 m (Johnson, 1984). Johnson (1982, 1984) infers a Middle to Late Eocene age based on stratigraphic relationships. Outcrops are present on the southeast flank of Black Mountain (Plate 1). (Description compiled from Moen, 1962, and Johnson, 1982, 1984.)

Ec_{cm} **Maple Falls Member (Eocene)**—Moderately to poorly sorted conglomerate, sandstone, and siltstone with minor coal. Coarse-grained strata alternate with fine-grained strata. Conglomerate ranges from 12-m-thick, poorly sorted, locally diamictic, massive beds containing well-rounded clasts as much as 70 cm in diameter to thinner, well-sorted, poorly stratified, finer-grained beds. Clasts are mainly composed of chert and greenstone. Sandstone associated with conglomerate is commonly massive to trough cross-bedded. Sandstone associated with finer-grained sediments is often massive and fine grained to conglomeratic. Sandstones in general are mainly composed of polycrystalline quartz, chert, and lithic fragments; monocrystalline quartz is conspicuously less abundant than in the Bellingham Bay, Slide, and Warnick Members. Siltstone is commonly laminated and is associated with abundant lenticular beds of fine-grained to conglomeratic sandstone. (See Johnson, 1982, for a depositional model.) Color is light olive-gray, dark yellowish brown, or dark greenish gray. Thickness is possibly as much as 800 m (Johnson, 1984). Johnson (1982, 1984) infers a Middle to Late Eocene age based on stratigraphic relationships. Outcrops are restricted to Sumas Mountain near the town of Maple Falls (type locality). (Description compiled from Johnson, 1982, 1984, and Dragovich and others, 1997a.)

Ec_{cp} **Padden Member (Eocene)**—Moderately to well-sorted sandstone and conglomerate alternating with mudstone and minor coal. Sandstone ranges from fine to coarse grained, with pebbly to conglomeratic sandstone layers common. Planar cross-bedding (≤2 m high), flat-bedding, trough cross-bedding, and ripple-lamination are common bedding features. Sandstone is rich in chert and volcanic lithic clasts. (See Johnson, 1982, for point-count data.) Conglomerate is commonly massive to poorly stratified or cross-bedded and composed primarily of rounded chert, volcanic, and plutonic clasts as much as 16 cm in diameter. The matrix is commonly medium- to coarse-grained sandstone. Mudstone is commonly massive to thinly laminated and usually associated with coal; sandstone and conglomerate layers as much as 50 m thick alternate with mudstone. Color is light olive-gray to pale yellowish brown. Thickness is possibly more than 3000 m (Johnson, 1984). Age is younger than the underlying 49.9 ±1.2 Ma dacitic tuff in the upper Bellingham Bay Member (Johnson, 1982) and as young as Late Eocene (Reiswig, 1982; Appendix, Table 6, map nos. 110–114). Honeycomb weathering patterns are common on exposures near sea water (Mustoe, 1982). Outcrops are widespread on the mainland and occur on Lummi, Matia, Sucia, and Patos Islands. The Padden Member has been the source of substantial amounts of coal in the vicinity of the city of Bellingham. The type locality is exposed near Lake Padden south of Bellingham. (Description compiled from Johnson, 1982, 1984; Reiswig, 1982; Mustoe and Gannaway, 1997; and Dragovich and others, 1997a.)

Pre-Tertiary Rocks

NANAIMO GROUP

The Nanaimo Group (Clapp, 1912) consists of Upper Cretaceous sandstone, conglomerate, shale, and minor coal exposed in Canada as patches along eastern Vancouver Island and in the U.S. as somewhat isolated exposures in the northern San Juan Islands. Clastic units in the Nanaimo Group contain detritus derived from flanking tectonic provinces that include the Northwest Cascades system of Misch (1966) and Brown (1987), the Wrangellia terrane, and the Coast Plutonic Complex. The Late Cretaceous Nanaimo and Comox basins, paleo-depressions in which the Nanaimo Group was deposited, likely formed as fault-bounded grabens or pull-apart basins (Pacht, 1984). Clast types and sedimentation rates were strongly controlled by local uplifts and depressions resulting from basin development (Pacht, 1984). Sediments were interpreted by Muller and Jeletzky (1970) to have been deposited as four complete, and one incomplete, transgressive cycles with a typical succession from fluvial to deltaic and (or) lagoonal to nearshore marine and offshore marine depositional environments. After deposition, the Nanaimo Group experienced northeast–southwest (Eocene?) contraction resulting in northwest-trending folds and associated southwest-vergent thrust faults. (See England and Calon, 1991, for an in-depth discussion of structures in the Nanaimo Group.)

In this report, subdivisions of the Nanaimo Group are based on Ward's (1978) revision of Muller and Jeletzky's (1970) formational scheme. Of the eleven formations of the Nanaimo Group, only five are exposed in the Bellingham quadrangle and they are restricted to the west-central part of the map area.

Km_{nc} **Cedar District Formation (Upper Cretaceous)**—Well-sorted and stratified fossiliferous silty shale; locally massive and poorly bedded; commonly contains thin (2–3 cm thick) siltstone and sandstone bands at intervals of a few centimeters to a meter or more and concretionary layers and lenses of micritic limestone near the top and bottom of the formation. Color is light to dark gray. Thickness at the type section at Dodds Narrows near the city of Nanaimo, B.C., is 330 m. Deposition of this unit likely occurred in an offshore marine environment below the wave base. In the Bellingham quadrangle, unit Km_{nc} is exposed on the southwest side of Sucia Island and on the northern end of Orcas Island, where exposures are lithologically very similar to its type section. On Sucia Island, the base of unit Km_{nc} is characterized by a downward gradation from shale to marine sandstone to conglomerate. The sandstone/conglomerate contact marks the base of unit Km_{nc} and the top of unit Km_{np}. Elsewhere, unit Km_{nc} contains proximal and distal turbidites and massive sandstone layers. The late Campanian age of unit Km_{nc} is determined by abundant fossils present on Sucia Island (Appendix, Table 6). (Description compiled from Breitsprecher, 1962; Muller and Jeletzky, 1970; Janbaz, 1972; Ward, 1973, 1978; and Pacht, 1984.)

Km_{np} **Protection Formation (Upper Cretaceous)**—Well-sorted massive to poorly stratified and cross-stratified conglomerate, medium- to fine-grained sandstone, and local argillaceous and fossiliferous sandstone, siltstone, and coal. Conglomerate layers contain angular to subangular boulder- to pebble-sized clasts consisting of vein quartz, chert, quartzite, and volcanics with lesser amounts of schistose, phyllitic, and plutonic material. The conglomeratic matrix is generally black carbonaceous phyllite, and sandstone layers contain mostly quartz, phyllitic, and schistose material. Color is light to dark gray and gray-green and is rarely iron oxide stained. Thickness ranges from about 200 m near Nanaimo to about 400 m in the southern Canadian Gulf Islands. Outcrops of unit Km_{np} are sparse in the Bellingham quadrangle and occur only at the southeast end of Sucia Island. The late Campanian age of unit Km_{np} was determined by abundant fossils on Sucia Island. (Description compiled from Breitsprecher, 1962; Muller and Jeletzky, 1970; Janbaz, 1972; Ward, 1973, 1978; and Pacht, 1984.)

Kn_{ne} **Extension Formation (Upper Cretaceous)**—Well-sorted, massive to stratified and cross-stratified conglomerate, coarse- to fine-grained sandstone, fossiliferous sandstone, shale, and coal (near Nanaimo, B.C.). Conglomerate layers present at the base of this unit contain subrounded to rounded chert, jasper, argillite, plutonic, gneissic, and volcanic clasts from 6 to 20 cm in diameter. Matrix is generally coarse sand of similar composition though richer in quartz and jasper. Sandstones are generally composed of (in decreasing order of abundance): argillite, chert, volcanic lithic, plutonic, and metamorphic clasts. Lithic arenites and wackes, pebble conglomerates, siltstones, argillites, and shales dominate the upper portion of the section. Sparry calcite is the main cementing agent. Color is generally light gray to gray with a reddish weathering surface for sandstones and variable weathering surface for conglomerates though the weathered matrix material has a reddish or greenish hue. Thickness ranges from about 230 m on Orcas Island to 300 to 400 m in the southern Canadian Gulf Islands. Exposures of unit Kn_{ne} in the Bellingham quadrangle occur only on the north end of Orcas Island where unit Kn_{ne} unconformably overlies the Haslam Formation (unit Km_{nh}) and on Clark and Barnes Islands and nearby islets. A late Campanian age for the unfossiliferous Extension Formation was determined by fossil ages in overlying and underlying formations (Pender and Haslam Formations, respectively). (Description compiled from Muller and Jeletzky, 1970; Ward, 1973, 1978; Carsten, 1982; and Bickford and Kenyon, 1988.)

Km_{nh} **Haslam Formation (Upper Cretaceous)**—Well-sorted, massive to stratified and cross-stratified shale, siltstone, sandy shale, and fine- to coarse-grained sandstone. Thinly bedded fossiliferous shale and siltstone and calcareous concretionary shale beds, usually 5 to 45 cm thick, dominate most of the section. Massive to cross-stratified or graded sandy shale and sandstone beds occur throughout the section but become more common toward the top where massive feldspathic litharenites dominate. Sandstones are generally composed of quartz, feldspar, argillite, chert, metamorphic, and volcanic clasts (in decreasing order of abundance). Rip-up clasts of siltstone and shale, slumps, interference ripple marks, plant fossils, and occasional flow rolls are common in medium- to coarse-grained sandstones. Occasionally, sandstone dikes intrude shale and siltstone layers. Color is generally buff to bluish gray for shale and siltstone layers and light to dark gray for sandstones. Thickness is about 380 m on Orcas Island and generally about 150 to 200 m elsewhere. Exposures of unit Km_{nh} in the Bellingham quadrangle occur only on the north end of Orcas Island, where it is unconformably overlain by basal conglomerates of unit Kn_{ne} and conformably overlies sandstones of unit Kn_{nc}. The late Santonian to early Campanian age of unit Km_{nh} was determined from abundant fossils on Orcas Island (Appendix, Table 6) and elsewhere. (Description compiled from Muller and Jeletzky, 1970; Ward, 1973, 1978; and Carsten, 1982.)

Kn_{nc} **Comox Formation (Upper Cretaceous)**—Well- to poorly sorted, massive to moderately stratified conglomerate and sandstone. Conglomerate layers, common toward the base of the section, contain subangular to rounded, silicified volcanic clasts from 1 to 3 cm in diameter, with lesser plutonic, quartz, and metasediment clasts. The conglomerate matrix is generally lithic graywacke. Sandstone layers, more common toward the top of the exposed section, are generally massive litharenites to lithic subarkoses and composed of approximately 90 percent rock fragments that consist of argillite, diorite, chert, and volcanic grains. Occasional plant fossils are present along bedding planes in sandstone. Color is gray to buff for sandstones and olive-gray to gray for conglomerates. Thickness ranges from about 230 to 530 m, based on boreholes in British Columbia, however, only about 23 m of strata are exposed in the Bellingham quadrangle. Exposures of unit Kn_{nc} in the Bellingham quadrangle occur only at the north end of Orcas Island, where it is overlain by Haslam Formation shales. The Comox Formation is the lowest formation of the Nanaimo Group, though the basal contact with pre-Nanaimo rocks is not exposed in the Bellingham quadrangle. The late Santonian age of unit Kn_{nc} was determined by fossils collected from equivalent strata on Vancouver Island. (Compiled from Muller and Jeletzky, 1970; Ward, 1973, 1978; and Carsten, 1982.)

NORTHWEST CASCADES SYSTEM: ROCKS OF THE NORTHWEST CASCADE RANGE

Heterogeneous metamorphic rocks of the Butler Hill area

The area north of the city of Sedro-Woolley contains low-grade metasedimentary and metavolcanic rocks of unknown affinity. Possible correlatives are the Easton Metamorphic Suite of Tabor and others (1993), the Haystack unit of Cruver (1983), the Deer Peak unit of Reller (1986), or the Helena–Haystack mélange of Tabor (1994). Early studies (for example. Misch, 1966, 1977; Bechtel, Inc., 1979; Miller, 1979) have correlated these rocks with the Chilliwack Group. Brown and others (1981), however, report differences in metamorphic grade and age, thus precluding these early correlations. Dragovich and others (1998, 1999, 2000) correlate these rocks with the Haystack terrane of Whetten and others (1980, 1988) or the Helena–Haystack mélange of Tabor (1994).

Jhmc, Jmv **Heterogeneous metamorphic rocks and metavolcanic rocks (Jurassic)**—Metabasalt, meta-argillite, and metasandstone with lesser metachert, metatuff, and serpentinite. Metabasalt (unit Jmv) is commonly massive to well foliated (locally phyllitic) and brecciated, generally aphanitic, and locally amygdaloidal. Pillow structures (commonly stretched) and pillow breccia are common relict igneous textures. Common metamorphic minerals include albite, chlorite, actinolite, epidote (locally abundant, >15%), pumpellyite, stilpnomelane, and calcite/aragonite. Relict igneous phases include pyroxene and local hornblende. Meta-argillite and metasandstone (unit Jhmc) commonly have a slaty to phyllitic foliation that is locally at an angle to bedding; kink-folds commonly deform the prominent foliation. Relict sedimentary structures include graded bedding and ripple cross-lamination. Metasandstone commonly contains angular to subangular quartz, feldspar, and meta-argillite grains from 0.1 to 0.4 mm in diameter. (See Dragovich and others, 1998, for point-count data.) Common metamorphic minerals in metasandstone include quartz, albite, white mica, chlorite, and graphite, with lesser lawsonite, pumpellyite, and calcite. Metachert and metachert breccia is commonly contorted and fractured with no observable foliation; metamorphic minerals include quartz and stilpnomelane. Chert breccia consists of angular (commonly flattened) chert clasts set in a matrix of meta-argillite or metatuff and is usually associated with pillow basalt. Metatuff is commonly well foliated with abundant albite and quartz veins; relict textures suggest a crystal-vitric to vitric tuff protolith. Metamorphic minerals are generally the same as for metabasalt. Serpentinite is commonly sheared and is usually present in high-strain zones. Serpentine minerals and magnetite are common; tremolite and Mg-chlorite schists are locally associated with serpentinite bodies. Metabasalt is commonly light olive-green to dark green on fresh surfaces and light brownish gray-green on weathered surfaces. Meta-argillite and metasandstone are commonly dark to medium gray, chert varies from reddish orange to green or black, tuff is pale green to orangish yellow, and serpentinite is dark green to black.

Age is tentatively considered to be Jurassic, based on the age of possible correlative rocks and the Mesozoic, and possibly Jurassic, radiolarian extracted from chert on Butler Hill (Dragovich and others, 1998). Outcrops occur on Butler and Sterling Hills and smaller hillocks in the nearby area. (Description compiled from Cruver, 1983, and Dragovich and others, 1998, 1999.)

Easton Metamorphic Suite of Tabor and others (1994)

The Easton Metamorphic Suite of Tabor and others (1993) consists of pelitic and quartzose metasediments of the Darrington Phyllite (unit Jph_d) (Misch, 1966), metagraywacke and metaconglomerate (semischist) of Mount Josephine (unit Jph_j) (Tabor and others, 1994), and green/blueschist and greenstone of the Shuksan Greenschist (units Jsh_s and Jmv_s/$Jigb_s$, respectively) of Misch (1966). Other lithologies, occurring either as rare or scattered outcrops in the Easton Metamorphic Suite, are arc- and mid-oceanic-ridge-related metaplutonic rocks, metatuff, magnesian schists, Fe-Mn quartzose metasediments, talc± tremolite schists, serpentinite, and metachert (Haugerud and others, 1981; Frasse, 1981; Brown, 1986; Gallagher and others, 1988). In the Bellingham quadrangle, the Darrington Phyllite and semischist of Mount Josephine are the dominant exposed units of the Easton Metamorphic Suite. Metaplutonic and metavolcanic rocks in scattered occurrences on Lyman Hill and Bowman, south Chuckanut, Eddys, and Colony mountains are here included with the Easton Suite. These rocks are commonly associated with serpentinite and talc±tremolite schist (Schmidt, 1972; Bechtel, Inc., 1979; Frasse, 1981; Brown, 1986; Gallagher, 1986; Gallagher and others, 1988; Dragovich and others, 1998, 1999, 2000). Misch (1966, 1977), Miller (1979), and Bechtel, Inc., (1979) saw these rocks as part of the Chilliwack Group. Gallagher and others (1988) included these rocks in the Easton Suite, whereas Whetten and others (1980) and Dragovich and others (1998, 1999, 2000) interpreted weakly foliated metavolcanic and metaplutonic rocks north of the Skagit River valley as klippe of the Haystack terrane of Whetten and others (1980) or the Helena–Haystack mélange of Tabor (1994).

Jph_d, Jph_j **Darrington Phyllite and semischist of Mount Josephine (Jurassic)**—Graphitic phyllite and quartzose graphitic phyllite with lesser calcareous phyllite and rare mica schist and metachert (unit Jph_d), and semischistose metasandstone and metaconglomerate (unit Jph_j). Phyllite and semischist are commonly interlayered on a scale of centimeters to hundreds of meters. Phyllite and mica schist usually contain at least two foliations and multiple lineations (stretching and crenulation). Semischistose metasandstone and metaconglomerate generally exhibit a single, well-developed foliation parallel to lithologic layering and an associated stretching lineation. Broad to tight folds of that foliation are also present.

Protolith lithologies are variable, ranging from chert and mudstone to coarse conglomerate with deformed clasts as long as 60 cm. Mudstone and quartzose mudstone were the predominant phyllite protoliths. Semischist protoliths are thin- to medium-bedded lithic-volcanic subquartzose sandstones with clast lithologies including gabbro/diorite, basic to felsic volcanic rock, shale, and detrital mineral species including quartz, feldspar, epidote, chromite, mica, and hornblende. Detrital grains are commonly obliterated in the highly deformed phyllites; rare relict radiolarians occur in chert, and at one locality on Blanchard Mountain, quartz and stilpnomelane veins are abundant (Mustoe, 1998). Metamorphic minerals include quartz, albite, mica, actinolite, graphite, chlorite, epidote, carbonate, and stilpnomelane and minor to rare lawsonite, pumpellyite, margarite, and spessartine garnet. Phyllite is dark to silvery gray; semischist is light to medium gray, gray-green, and light olive-green; and metachert is olive-green.

Units Jph_d and Jph_j locally include units Jsh_s, Jmv_s, and $Jigb_s$ and layers of ultrabasic rock. South of the map area, a quartz-aragonite-talc schist is present as a thin (1–3 cm wide) layer in phyllite (Evans and Misch, 1976). There is no direct determination of the protolith age, however, Frasse (1981) reports that metadiorite and metatrondhjemite consisting of irregular dikes flanked by semischist in the Bowman Mountain area were dated by U/Pb in zircon at 163 ±2 Ma (Gallagher and others, 1988). These dikes were probably a volcanic center that shed diorite and dacite clasts into nearby sediments. If the clasts are related to the intrusions, then the semischist in that area is Middle Jurassic. If the metaplutonic rocks are olistoliths or were faulted in during metamorphism, then 163 ±2 Ma is only a maximum age (Frasse, 1981; Gallagher and others, 1988). Outcrops of phyllite and semischist are common and extensive. (Description compiled from Haugerud, 1980; Frasse, 1981; Brown, 1986; Gallagher, 1986; Brown and others, 1987; Gallagher and others, 1988; Tabor and others, 1994; Dragovich and others, 1997a, 1998, 1999; and this study.)

Jsh_s, Jmv_s, $Jigb_s$ **Shuksan Greenschist (Jurassic)**—Metabasaltic greenschist, local blueschist, and metatuff (unit Jsh_s); metabasaltic greenstone (unit Jmv_s); metagabbro and metadiorite/quartz diorite (unit $Jigb_s$); and intermediate arc-related metavolcanic rocks (unit Jmv_s) that occur locally. Greenschist is moderately to well foliated and generally fine to medium grained and locally phyllitic. Greenstone is nonfoliated to very weakly foliated and generally fine to medium grained. Meta-intrusive rocks are nonfoliated to very weakly foliated and are generally medium to coarse grained. Relict igneous features found locally include pillows (in various stages of flattening), pillow breccia, vesicles, and phenocrysts. Dominant metamorphic mineral assemblages present in most meta-igneous lithologies include actinolite, epidote, albite, pumpellyite, chlorite, white mica, stilpnomelane, calcite/aragonite, quartz, and sphene. Rare meta-igneous lithologies with blue amphibole generally contain crossite, epidote, albite, chlorite, white mica, clinopyroxene, stilpnomelane, magnetite/hematite, and calcite/aragonite. Relict igneous phases include hornblende and clinopyroxene. Color on a fresh surface is always some shade of green and ranges from silvery greenish gray to dark olive-green and rarely blue-green. Weathered surfaces generally have a brown to light gray or creamy color.

The protolith age of three meta-igneous rocks, determined by U/Pb in zircon (Appendix, Tables 1 and 2, map nos. 8–10), is about 163 Ma (Brown, 1986; Gallagher and others, 1988; Dragovich and others, 1998). Peak metamorphic conditions of 7 to 9 kb and 330 to 400°C (Brown, 1986) are dated by K/Ar and Rb/Sr at 120 to 130 Ma (Bechtel, Inc., 1979; Haugerud, 1980; Brown and others, 1982; Armstrong and Misch, 1987) (Appendix, Table 4, map nos. 34–38). Chemical composition indicates mid-oceanic ridge basalt (MORB) and arc protoliths (Street-Martin, 1981; Dungan and others, 1983; Gallagher, 1986; Gallagher and others, 1988; Dragovich and others, 1998, 2000). Outcrops of Shuksan Greenschist occur throughout the quadrangle as isolated lenses or pods and locally as coherent layers in units Jph_d and Jph_j. Most mapped outcrops are in the Acme, Bow, Alger, Sedro-Woolley North, and Lyman 7.5-minute quadrangles. (Description compiled from Haugerud, 1980; Frasse, 1981; Brown, 1986; Gallagher, 1986; Gallagher and others, 1988; Tabor and others, 1994; Dragovich and others, 1998, 1999; and this study.)

Rocks of the Bell Pass mélange

$pThmc_b$ **Bell Pass mélange of Tabor and others (1994) (pre-Tertiary)**—Mélange consisting chiefly of disrupted Elbow Lake Formation (unit $JPhmc_e$) with lesser tectonic clasts of ultramafic material (units pTu_{ts} and pTu), Vedder Complex (unit $pPhm_v$), and Yellow Aster Complex (unit $pDgn_y$). The conglomerate of Bald Mountain (unit $pTms_b$) is included within the Bell Pass mélange on the basis of its similarity to clastic rocks of the Elbow Lake Formation, its tectonic contact with surrounding units within the mélange (see the Sumas Mountain area, Plate 1), and its structural position (within the Welker Peak nappe of Tabor and others, 1994). The age of mélange formation and tectonic disruption is inferred by Tabor and others (1994) to be Late to Middle Jurassic and (or) middle Cretaceous (see also Brown, 1987). Locally mapped as:

pTu **Ultramafic rocks (pre-Tertiary)**—Serpentinite and partially serpentinized dunite and peridotite with minor lenses and thin bands (2–10 cm thick) of chromite. Outcrops are commonly cut by well-developed joints and minor faults and are locally highly sheared. Serpentinite and partially serpentinized dunite generally contain olivine, antigorite, serpophite, chrysotile, and minor subhedral to anhedral enstatite with trace amounts of chromite, magnetite, and diopside. Serpentinized peridotite has the same basic mineralogy as serpentinite and partially serpentinized dunite but has greater amounts of pyroxene (≤20%). Olivine grains are generally 0.15 to 0.20 mm in diameter and more than 50 percent altered to serpentine minerals. Enstatite grains are generally fresh and 3 to 10 mm in diameter; and chromite grains are generally euhedral to subhedral and less than 0.5 mm in diameter. The size and resistance of enstatite relative to serpentine locally gives outcrops a ‘punky’ appearance. Color ranges from brown to yellowish orange on weathered surfaces and dark greenish black to pale green on fresh surfaces. There are no direct age constraints on this unit. However, because these rocks participated in mid-Cretaceous orogeny, a pre-Tertiary age is assigned to the unit. Outcrops are common on the northern end of Sumas Mountain, and the unit is locally referred to as the Sumas Mountain serpentinite (Moen, 1962). (Description compiled from Moen, 1962; Brown and others, 1987; and Dragovich and others, 1997a.)

pTu_{ts} **Twin Sisters Dunite of Ragan (1961) (pre-Tertiary)**—Dunite (80–90%) with lesser serpentinite and harzburgite. Dunite and harzburgite are composed chiefly of forsteritic olivine with lesser (usually <15%) enstatite (orthopyroxene [OPX]) and chromite and trace amounts of chromian diopside (clinopyroxene [CPX]). Olivine grains in dunite and harzburgite are generally 0.1 to 8 mm in diameter, anhedral, commonly fractured, and exhibit evidence for high-temperature tectonic deformation (probable mantle origin). Pyroxene grains are generally subhedral (OPX) or anhedral (CPX). Chromite is euhedral, 0.1 to 3 mm in diameter, and commonly enclosed by olivine or pyroxene. Serpentinite, occurring marginal to and transitional with unaltered dunite, consists of serpentine-group minerals (chiefly antigorite with lesser chrysotile), relict chromite and pyroxene, and other opaque minerals (likely magnetite). Antigorite is generally massive, but well foliated within and near fault zones; chrysotile is generally present as syntaxial vein fillings. Dunite is green to light olive-green on unweathered surfaces and dun to orange-brown on weathered surfaces; serpentinites are usually dark green to black. The Twin Sisters Dunite is a large (6 km wide, 16 km long) alpine-type ultramafic body representing upper-mantle material and is exposed across the boundary between the Bellingham quadrangle and the Mount Baker 1:100,000-scale quadrangle to the east. Gravity and magnetic investigations indicate that this body is a flat pod about 2 km thick (Thompson and Robinson, 1975). The Twin Sisters Dunite is included as a ‘mega-clast’ in the Bell Pass mélange of Tabor and others (1994). Dunite from the Twin Sisters is mined for refractory purposes. (Description compiled from Ragan, 1961; Gaudette, 1963; Christensen, 1971; Thompson and Robinson, 1975; Onyeagocha, 1978; Frasse, 1981; and Tabor and others, 1994.)

$pTms_b$ **Conglomerate of Bald Mountain of Misch (1966) and Tabor and others (1994) (pre-Tertiary)**—Highly indurated and plastically deformed polymictic conglomerate and pebble conglomerate, with lesser highly indurated, poorly sorted, coarse- to medium-grained lithofeldspathic sandstone and argillite. The conglomerate is massive to crudely bedded and commonly clast supported. The sandstone is massive or has thin to medium flat- and cross-beds. Beds in the sandstone are generally highly disrupted. The conglomerate and sandstone contain rounded to well-rounded clasts of chert with lesser argillite, metatonalite, and dacite clasts. Detrital mineral species include quartz, plagioclase, and K-feldspar. Clasts are commonly flattened and boudinaged and are typically 3 cm in diameter and as much as 30 cm in length. Metamorphic minerals include lawsonite (detrital?), white mica, stilpnomelane, pumpellyite, epidote, chlorite, and carbonate. L-S tectonites are present near mapped faults. Color is light gray on weathered surfaces and medium to dark greenish gray on fresh surfaces. Maximum thickness is about 550 m based on map patterns.

The age of unit $pTms_b$ is poorly constrained, however a maximum age was determined from two chert clasts that yielded possible Triassic and Late Triassic radiolarians (Tabor and others, 1994). Johnson (1982, 1984) included parts of this unit near Bald Mountain within the largely Eocene Chuckanut Formation. The plastic deformation and metamorphism recorded in this unit, however, make a pre-Tertiary minimum age likely. Outcrops are present on Black and Sumas Mountains. On Sumas Mountain, this unit forms klippen over the Chilliwack Group and serpentinite of the Bell Pass mélange; on Black Mountain, however, its contact relations are unclear. The type locality is on Bald Mountain just east of Black Mountain in the Mount Baker quadrangle. (Description compiled from Moen, 1962; Misch, 1966; Johnson, 1982; Tabor and others, 1994; Dragovich and others, 1997a; and this study.)

$JPhmc_e$ **Elbow Lake Formation of Blackwell (1983) and Brown and others (1987) (Jurassic to Permian)**—Metamorphosed ribbon chert with lesser high-Ti greenstone, mafic metatuff, metasandstone, and argillite and rare metaconglomerate and limestone. Lithologies are commonly highly disrupted. Chert is recrystallized to a veined and sugary texture and the interbedded pelitic layers are phyllite. Greenstone is aphanitic to porphyritic, typically pillowed, and commonly amygdaloidal. It generally contains the metamorphic assemblage: actinolite, pumpellyite, epidote, albite, chlorite, lawsonite, and calcite/aragonite and rare Na-amphibole. Titaniferous augite and plagioclase phenocrysts are common relict igneous phases. (See Sevigny and Brown, 1989, for details of the geochemistry of meta-igneous rocks.) Metasandstone (possibly equivalent to unit $pTms_b$) is commonly lithic subquartzose, either volcanic- or chert-rich, and both it and associated metaconglomerate contain a well-developed foliation and (or) mylonitic fabric. Relict bedding is 1 to 6 cm in thickness. Argillite is typically scaly and locally grades into phyllite. Metasediments generally contain the metamorphic assemblage: pumpellyite, chlorite, white mica, and lawsonite. Color is dark gray to medium light gray for chert and metasediments and dark olive-green to medium gray-green to sometimes reddish green for meta-igneous rocks.

A Jurassic to Permian age for the unit is based on radiolarians in chert (Brown and others, 1987; Tabor and others, 1994; Dragovich and others, 1997a). The age of the meta-igneous rocks is unknown. Unit $JPhmc_e$ may locally include units pTu, $pDgn_y$, and $pPhm_v$. Outcrops occur on Sumas Mountain and the west side of Twin Sisters Mountain, however many outcrops occur within unit $pThmc_b$. Based on similar ages and lithologies, this unit may be equivalent to the Orcas Chert and Deadman Bay Volcanics in the San Juan Islands (Brown and Vance, 1987). (Description compiled from Blackwell, 1983; Ziegler, 1985; Brown and others, 1987; Tabor and others, 1994; and Dragovich and others, 1997a.)

$pPhm_v$ **Vedder Complex of Armstrong and others (1983) (pre-Permian)**—Amphibolite, greenschist, blueschist, and quartzose pelitic schist. Grain size is generally medium (0.5–2 mm) and foliation is well developed in all lithologies. Mafic schists (metabasalts) generally contain the amphiboles hornblende, barroisite, crossite, or actinolite; quartzose pelitic schists (metachert and siliceous shale) are generally micaceous with some garnet porphyroblasts. Minerals present in all lithologies include albite, quartz, white mica, an epidote mineral, chlorite, sphene, and rutile (sporadic). Color is generally dark green/dark olive green to green for amphibolites and mafic schists and gray to light gray for quartzose pelitic schists. Outcrops of unit $pPhm_v$ are rare in the Bellingham quadrangle but occur on the south-facing flank of Black Mountain and near the edge of the quadrangle on the south side of the Middle Fork Nooksack River valley near Twin Sisters Mountain. Outcrops generally occur as tectonic slivers or pods within the Bell Pass mélange of Tabor (1994). K/Ar and Rb/Sr mineral and whole-rock analyses indicate Permian to earliest Triassic metamorphic ages, demonstrating a pre-Permian protolith age for the Vedder Complex. (See Armstrong and others, 1983, for age data and details.) On the basis of K/Ar dates, petrologic similarities, and structural position in the Northwest Cascades system, Brown and Vance (1987) interpret unit $pPhm_v$ as equivalent to the Garrison Schist in the San Juan Islands. (Description compiled from Bernardi, 1977; Rady, 1980; Armstrong and others, 1983; Brown and others, 1981; Brown and Vance, 1987; and Tabor and others, 1994.)

$pDgn_y$ **Yellow Aster Complex of Misch (1966) (pre-Devonian)**—Quartzose pyroxene gneiss, gabbroic to granitic orthogneiss, rare massive metagabbro, metaquartz diorite, and pyroxenite, and metabasalt and meta-andesite. These rocks are exposed as fault-bound fragments a few meters to 2 to 3 km in breadth. Grain size ranges from fine to coarse for both relict igneous and metamorphic minerals. Gneissic fabrics are commonly mylonitic. Metamorphosed intrusive and volcanic rocks locally intrude quartzose gneiss, however this relationship was not observed in the Bellingham quadrangle. Quartzose gneiss contains alternating felsic and mafic layers (0.1–1 cm thick) consisting of quartz or quartz and plagioclase (felsic) and actinolite, epidote, ±clinopyroxene, ±garnet (mafic) with secondary minerals including chlorite, albite, epidote, pumpellyite, and rare lawsonite. Gneissic and massive intrusive rocks have variable mineralogical compositions based on protolith lithologies, however, in the Bellingham quadrangle, most contain mineralogies associated with two stages of metamorphism: 1) an upper greenschist to amphibolite facies event that was coeval with deformation, and 2) a lower greenschist to subgreenschist facies (static?) overprint. (See Moen, 1962; Blackwell, 1983; Sevigny, 1983; and Sevigny and Brown, 1989, for petrologic, petrographic, and geochemical data.) Color is highly variable from light greenish gray for felsic rocks to dark olive-green for mafic varieties. Meta-intrusive rocks not associated with quartzose gneiss are of uncertain correlation with the Yellow Aster Complex. These rocks may locally correlate with meta-intrusive rocks associated with the Chilliwack Group reported by Tabor and others (1994).

Protolith age estimates are difficult to deduce given discordant U/Pb ages in meta-igneous rocks and questions concerning an igneous vs. detrital origin of zircons in quartzose gneiss. Mattinson (1972) reports a Pb/Pb age for zircon in quartzose gneiss of 1,452 to 2,000 Ma, the former being interpreted as the minimum protolith age. A metamorphic age of 415 Ma is based on U/Pb in metamorphic sphene. A pre-Devonian age is inferred for quartzose gneiss based on this sphene (Mattinson, 1972). (See Mattinson, 1972, and Whetten and others, 1980, for more information and ages of the Yellow Aster Complex.) Based on similar ages, composition, and metamorphic history, many workers consider this unit equivalent to the Turtleback Complex (unit pDi_t) (for example, Brown and Vance, 1987). Outcrops occur on Bowman, Sumas, and Black Mountains and along the west side of Twin Sisters Mountain. The type locality is in Yellow Aster meadows in the Mount Baker quadrangle to the east. (Description compiled from Moen, 1962; Misch, 1966; Mattinson, 1972; Blackwell, 1983; Sevigny, 1983; Brown and others, 1987; Tabor and others, 1994; and Dragovich and others, 1997a.)

Chilliwack Group of Cairnes (1944)

The Chilliwack Group of Cairnes (1944) is composed of Devonian to Permian volcanic and sedimentary rocks deposited in an island-arc environment (Christenson, 1981; Liszak, 1982; Sevigny and Brown, 1989; Dragovich and others, 1997a; Liszak and Ross, 1997). In the NWCS thrust assemblage, the Chilliwack Group structurally overlies the Nooksack Group and underlies the Bell Pass mélange (Brown and others, 1987). Deformation recorded in the Chilliwack Group is characterized by a pervasive, poorly to well-developed slaty to phyllitic cleavage commonly associated with high-pressure/low-temperature metamorphism (Christenson, 1981; Brown and others, 1981; Smith, 1988). Overturned and recumbent folds in bedding are also associated with this deformation (Monger, 1966, 1977; Dragovich and others, 1997a). Though the unit is commonly highly disrupted, a coherent Mississippian to Permian stratigraphic section (~1,200 m thick) exists on Black Mountain (Liszak, 1982). Local high-angle faulting places it in contact with the Bell Pass mélange, the Easton Metamorphic Suite, and the Chuckanut Formation in the Bellingham quadrangle (Frasse, 1981; Brown and others, 1987; Dragovich and others, 1997a). Based on age, fossil, and lithologic similarities, Brown and Vance (1987) and Brandon and others (1988) consider the Chilliwack Group and East Sound Group in the San Juan Islands to be equivalent.

The Chilliwack Group is divided, where feasible, into three lithologic packages: metasedimentary rocks (unit $PDms_c$), metavolcanic rocks (unit $PDmv_c$), and marble (unit $PDmb_c$).

$PDhm_c$ **Chilliwack Group, undivided (Permian to Devonian)**—Includes lithologic packages described below in unknown proportions. Where possible, lithologic distinctions were made. Locally divided into:

$PDmv_c$ **Metavolcanic rocks (Permian to Devonian)**—Metamorphosed basic to felsic flows, tuffs, and volcaniclastic rock. Flows are commonly massive to weakly foliated; tuffs and volcaniclastic rocks are variably foliated and lineated. Volcanic rocks are commonly interbedded with unit $PDms_c$. Grain size in flows ranges from fine (aphanitic) to medium grained and locally porphyritic. Relict igneous features include pillow structure, pillow breccia, and amygdules. Volcaniclastic rock, predominantly volcanic breccia, is generally massive and consists of angular to subrounded volcanic clasts (<1–40 cm in diameter) in a finer-grained matrix of similar material. Tuff is typically fine grained and commonly contains variable amounts of lithic and crystalline material set in a matrix of chlorite and other minerals (in outcrop, tuff appears similar to massive flows). Tuff and volcaniclastic rock are commonly associated with pillow lava and pillow breccia. Composition of volcanic material ranges from basalt to rhyolite, basalt and basaltic andesite being the most common lithologies. Color ranges from light gray-green (felsic) to dark green (mafic) on fresh surfaces and commonly weathers to gray, tannish gray, and brown. Metamorphic minerals include albite, quartz, chlorite, white mica, pumpellyite, epidote, calcite/aragonite, and rare actinolite. Actinolite, however, is not attributed to regional metamorphism. Unit $PDmv_c$ may locally include units $PDmb_c$ and $PDms_c$.

Age ranges from Late Devonian to Permian based on fossils in interbedded limestone, mainly in unit $PDms_c$, and U/Pb ages of detrital zircons (McClelland and Mattinson, 1993). Dragovich and others (1997a) report highly discordant U/Pb zircon ages of basaltic andesite (Appendix, Table 2, map nos. 17–21). Outcrops occur mostly on Red and Black Mountains. (Description compiled from Moen, 1962; Christenson, 1981; Liszak, 1982; Blackwell, 1983; Brown and others, 1987; Tabor and others, 1994; and Dragovich and others, 1997a.)

$PDms_c$ **Metasedimentary rocks (Permian to Devonian)**—Metamorphosed, variably sorted volcanic sandstone, sandstone, siltstone, argillite, and tuff with lesser conglomerate and chert. Bedding in clastic rocks ranges from massive to well-developed rhythmic beds (commonly 1–10 cm and locally thick-bedded). Graded beds, scour structures, planar laminations, and ripple structures are typical. Chert is massive to thinly interbedded with argillite (ribbon chert) and commonly shows varying degrees of contortion. Variably developed foliation is commonly subparallel to bedding. Most clastic rocks are rich in volcanic lithic and feldspar grains with lesser chert, limestone, and argillite clasts (Christenson, 1981; Liszak, 1982; Dragovich and others, 1997a). Primary matrix and pseudomatrix occur in variable, though appreciable, amounts in sandstone and conglomerate. Clasts are angular to rounded. Detrital mineral grains (quartz, feldspar, pyroxene, and hornblende) are commonly subrounded to angular. Argillite is locally siliceous. Tuff commonly varies from crystal lithic to lithic tuff and is difficult to distinguish from volcanic sandstone in the field. The color of volcanic-rich lithologies (tuff and volcanic sandstones) is light to dark green-gray on fresh surfaces and brown to grayish tan on weathered surfaces, argillite is dark greenish gray to black, conglomerates are medium to dark gray, and chert is greenish white to black. Metamorphic minerals include albite, quartz, chlorite, white mica, lawsonite, pumpellyite, epidote, and calcite/aragonite. The unit may locally include units $PDmb_c$ and $PDmv_c$.

The age of unit $PDms_c$ ranges from Late Devonian to Permian based on fossils in interbedded limestone and fine-grained sedimentary rocks (see unit $PDmb_c$) and single-crystal U/Pb ages of detrital zircons (McClelland and Mattinson, 1993). Outcrops occur on Sumas, Red, and Black Mountains and just west of Twin Sisters Mountain. (Description compiled from Smith, 1961; Moen, 1962; Monger, 1966; Christenson, 1981; Liszak, 1982; Blackwell, 1983; Brown and others, 1987; Tabor and others, 1994; and Dragovich and others, 1997a.)

$PDmb_c$ **Limestone and marble (Permian to Devonian)**—Fossiliferous limestone and marble with rare chert. Lithofacies distinctions are complex and are not made here. (See Smith, 1961; Danner, 1966; and Liszak, 1982, for detailed lithologic descriptions.) Bedding is commonly massive but locally poorly developed, averaging 20 to 30 cm thick. Limestone and marble are textural distinctions and do not indicate differing lithologies.

Grain size ranges from microscopic to a few centimeters, and fossils are commonly large with respect to the surrounding matrix limestone. Outcrops occur as small (few meters thick) pods to large, cliff-forming exposures (~100 m thick), though most are discontinuous along strike. The unit is commonly interbedded with clastic and volcanic rock. Dolomitization and silicification of limestone occurs locally, chert occurs locally as small nodules and discontinuous beds, and limestone and marble are locally aragonitic and commonly contain minor graphite. Color ranges from light to dark gray, light to dark bluish gray, and light to dark brownish gray.

The Late Devonian to Permian age of limestones is based on fossil identification and has been the primary means of dating the Chilliwack Group. Danner (1957, 1966), Smith (1961), Liszak (1982), and Liszak and Ross (1997) provide detailed descriptions of the fossil content, paleoecology, and ages of various limestone bodies. Of note, Lower Carboniferous (Visean) limestones on Red and Black Mountains contain Asiatic-type tropical (PaleoTethys) cosmopolitan fauna (Danner, 1957, 1966; Liszak, 1982). Outcrops occur on Sumas, Red, and Black Mountains. (Description compiled from Danner, 1957, 1966; Smith, 1961; Moen, 1962; Monger, 1966; Liszak, 1982; Liszak and Ross, 1997; and Dragovich and others, 1997a.)

NORTHWEST CASCADES SYSTEM: ROCKS OF THE SAN JUAN ISLANDS

KJm_c **Constitution Formation of Vance (1975) (Cretaceous to Jurassic)**—Poorly to moderately sorted volcaniclastic sandstone, cherty sandstone, mudstone, and conglomerate with lesser ribbon chert, green tuff, and pillow lava and rare limestone. Clastic lithologies are commonly massive and locally graded at a scale of a few millimeters to a few centimeters; local cataclastic deformation is especially apparent toward the base of the section where many underlying lithologies are tectonically interleaved within the Constitution Formation. Sandstone is commonly turbiditic and largely contains volcanic detritus with lesser chert, nonvolcanic quartz, and epidote grains; mudstone is commonly massive and consists mainly of clay- and silt-sized grains with minor sand-sized grains and local olistolithic limestone and metavolcanic boulders 1 to 2 m in diameter. Conglomerate contains rounded to angular volcanic, chert, metaplutonic, and schistose clasts in siltstone matrix. Clasts are thought to be derived from underlying units (Orcas Chert, Turtleback Complex, and Garrison Schist; Vance, 1975, 1977). Clasts average 5 cm in diameter. Ribbon chert, rhythmically bedded every 3 to 4 cm, is interbedded with clastic rocks throughout the entire section but is more abundant near the base. Green tuff occurs near the base of the section and is commonly fine grained and indurated; intercalated mudstone and chert in tuff give it a layered appearance. Pillow lava ranges in composition from ocean-floor basalt to possibly arc-derived dacite (Brandon and others, 1988) and is interlayered with clastic rocks. Whether the pillow lava is olistolithic blocks, in place, or both is unclear. Limestone occurs near the base of the unit as isolated pods. Metamorphic minerals in clastic rocks include albite + quartz + chlorite + calcite/aragonite + white mica ± lawsonite ± prehnite. (See Brandon, 1980, and Brandon and others, 1988, for more details.) Clastic rock is generally tan to gray on weathered surfaces and gray to dark gray on fresh surfaces, pillow lavas range from light to dark green and locally red-green, tuff is light green, chert is grayish green to pale black, and limestone is light gray. Unit KJm_c may locally include units pDi_t, $J\overline{T}Rmct_o$, and $pPhm_v$.

The age of unit KJm_c is poorly constrained, but radiolarians from chert give Late Jurassic or Early Cretaceous ages (Brandon and others, 1988). Outcrops occur on Orcas, Shaw, and San Juan Islands. The type locality is Mount Constitution on Orcas Island. (Description compiled from Shelley, 1971; Vance, 1975, 1977; Brandon, 1980; Brandon and others, 1988; and this study.)

Fidalgo ophiolite of Brown and others (1979)

The Jurassic to Lower Cretaceous Fidalgo ophiolite is a dismembered section of oceanic lithosphere located in the eastern San Juan Islands. The tectonic environment in which these rocks formed was likely an island arc, based on chemical analyses of igneous rocks and their association with pelagic oceanic sediments (Brown, 1977; Gusey, 1978; Brandon and others, 1988).

From the base upward, the section consists of serpentinized ultramafics (harzburgite and dunite) (unit Ju_f), layered gabbro (unit Ji_f), keratophyre, plagiogranite, and associated intrusive rocks (unit Ji_f), spilite and lava flows (rare in the map area, included in unit Ji_f), and sedimentary breccia, pelagic argillite, siltstone, and graywacke (unit KJm_f) (Brown, 1977; Brown and others, 1979). Early studies (for example, Whetten and others, 1978; Brandon and others, 1988) grouped the Fidalgo ophiolite with the Lummi Formation as part of the Decatur terrane. Blake and others (2000) reassigned these units and considered the Fidalgo ophiolite and Lummi Formation separate terranes based on differences in metamorphic grade, stratigraphy, and structure. This map adopts Blake and others' reassignment of these rocks.

KJm_f **Marine sedimentary rocks (Lower Cretaceous to Upper Jurassic)**—Well- to poorly sorted sedimentary breccia, argillite, siliceous argillite, tuffaceous chert, siltstone, turbiditic sandstone, pebble to boulder conglomerate, and minor coal and tuff. Bedding is poorly to well developed and locally disrupted by tectonic deformation. Turbiditic rocks commonly display normally graded bedding with rare tabular cross-stratification. Argillite is locally thinly bedded and contains laminae of radiolarite, siltstone, fine sandstone, and thin-bedded turbidites. Sedimentary breccia contains no sedimentary structures and unconformably overlies igneous rocks of the Fidalgo ophiolite. It generally contains subrounded to subangular clasts of serpentinized peridotite, pyroxenite, layered gabbro, plagiogranite, and keratophyre from 1 to 30 cm in diameter, all of which correspond to underlying rock units. Turbiditic sandstones and conglomerates generally contain an appreciable amount of argillaceous matrix material (20–25%) and volcanic, gabbro, pyroxenite, serpentinite, chert, and argillaceous (rip-up) clasts and euhedral to subhedral plagioclase and augite crystals. Fossil twigs and branches occur in sandstones and conglomerates and locally in high enough concentrations to make thin coal seams (for example, Decatur Island; Whetten, 1975). Siliceous argillite is enriched in Ba, Cu, Ni, Co, and Mn (similar to present-day pelagic sediments) and contains abundant radiolarians and lesser tuffaceous debris. It is dark brown to green in color. Turbiditic rocks are commonly gray to tan and are gray to light green on fresh surfaces. The color of other rock types is highly variable. Thickness is poorly constrained due to folding and faulting and spotty outcrops, however, an estimated thickness is more than 500 m. Prehnite-pumpellyite facies metamorphism is characterized by the assemblage prehnite, pumpellyite, calcite, chlorite, epidote, quartz, and albite. Vein fillings, often associated with deformational features (for example, tension gashes), commonly contain prehnite, calcite, and quartz.

The age of the argillite and tuffaceous chert of the Fidalgo ophiolite, based on radiolarians, ranges from Callovian to Tithonian (see table A-10, samples DF15–DF18 in Brandon and others, 1988). A single clam from overlying clastic sediments is of latest Jurassic or earliest Cretaceous age (Mulcahey, 1975) Correlative sandstones on James Island have yielded latest Jurassic fossils (Garver, 1988). Outcrops occur mainly on Lopez, Decatur, and Fidalgo Islands, and the best exposed sections occur on Fidalgo Island in the Port Townsend quadrangle. (Description compiled from Mulcahey, 1975; Whetten, 1975; Brown, 1977; Vance, 1977; Gusey, 1978; Brown and others, 1979; Garver, 1988; Brandon and others, 1988; and Blake and others, in prep.)

Ji_f **Intrusive igneous rocks of the Fidalgo ophiolite (Jurassic)**—Metamorphosed layered gabbro, gabbroic pegmatite, hornblende gabbro, diorite, trondhjemite, albite granite, keratophyre, diabase, and basalt. Grain size is highly variable and often gradational from coarsely crystalline to fine grained. The primary mineralogy of these rocks and their genesis is complex (Brown and others, 1979). Igneous foliation is well developed within some intrusive dikes, namely hornblende gabbro (Brown and others, 1979; Carroll, 1980). Greenschist facies metamorphism, possibly due to dike emplacement, is present in most of the lithologies listed above and is characterized by the presence of actinolite, albite, chlorite, and epidote. A lower grade prehnite-pumpellyite facies assemblage is present in some dike rocks and is likely related to regional metamorphism of the Fidalgo ophiolite as recorded in the sedimentary section (unit KJm_f above). Color varies from dark to light olive-gray, and some lithologies have a ‘salt and pepper’ texture. This unit may locally include lava flows.

Crystallization ages of intrusive rocks, as determined from three U/Pb in zircon dates, range from 170 ±3 Ma to 160 ±4 Ma (Appendix, Tables 1 and 2). Minimum age constraints are radiolarian ages in the overlying sedimentary section, the oldest of which are Callovian. Outcrops in the Bellingham quadrangle are in the eastern San Juan Islands, specifically Fidalgo, Guemes, Lummi, Decatur, and Blakely Islands and nearby smaller islands. (Description compiled from Calkin, 1959; Mulcahey, 1975; Brown, 1977; Gusey, 1978; Brown and others, 1979; Carroll, 1980; Brown and others, 1981; and Brandon and others, 1988.)

Ju_f **Ultramafic rocks of the Fidalgo ophiolite (Jurassic)**—Serpentinite and harzburgite with lesser dunite and olivine chromitite layers. Cross-cutting veins of pyroxenite occur throughout the ultramafic body. Harzburgite contains 80 to 90 percent olivine and serpentine and 10 to 20 percent enstatite with trace diopside and chromite. Dunite is composed of olivine and minor chromite. Olivine in harzburgite and dunite is commonly replaced by serpentine minerals and magnetite. Pyroxenite veins are chiefly enstatite with lesser diopside (chromian diopside?). Olivine grains are commonly anhedral and are reported to reach as much as 8 cm in diameter, however most are much smaller. Olivine also exhibits a high-temperature deformational fabric (Raleigh, 1965). Enstatite grains are commonly anhedral and average 3 to 4 mm in diameter; exsolution lamellae are common. Chromite grains are commonly euhedral as inclusions and anhedral elsewhere and range in size from 0.5 to 1 mm and rarely up to 5 mm in diameter. Color ranges from near black in serpentinized areas to a golden dun color in serpentinized harzburgite; pyroxenite veins are golden brown with emerald green spots (diopside). Gravity studies indicate this unit is a nearly horizontal slab-like body possibly 1 km thick (Carlson, 1972).

Age is unclear but inferred to be Jurassic based on U/Pb zircon ages of meta-intrusive rocks higher in the section (Brown, 1977; Brown and others, 1979). Outcrops occur on Cypress, Blakely, Fidalgo, Hat, and Saddlebag Islands. (Description compiled from Raleigh, 1963, 1965; Carlson, 1972; Gusey, 1978; and Brown and others, 1979.)

Lummi Formation

The Lummi Formation is a package of oceanic rocks exposed in the eastern San Juan Islands. The general stratigraphy of this unit, as described by Blake and others (2000), is MORB-like pillow basalt overlain by and interbedded with radiolarian chert. Basalt and chert are locally intruded by alkalic gabbro and diabase. Chert grades upward into siliceous mudstone which in turn grades into turbiditic sandstone and wacke. Metamorphism is characterized by a variably developed axial-planar cleavage in clastic rocks and high-pressure metamorphic minerals (aragonite and lawsonite) that commonly occur in veins (Carroll, 1980; Blake and others, 2000).

Garver (1988) and Brandon and others (1988) considered the clastic rocks of the Lummi Formation to be deposited on the Fidalgo ophiolite (their Fidalgo Complex), both units constituting the Decatur terrane. Differences in metamorphic grade, structure, and stratigraphy between the two units, however, preclude a depositional link, and therefore they cannot belong to the same terrane (Blake and others, 2000).

$KJmm_l$ **Lummi Formation of Vance (1975) (Cretaceous to Jurassic)**—Metamorphosed, variably sorted pebble conglomerate, sandstone, and mudstone. Bedding ranges from massive to well bedded; bedding structures include graded beds, parallel lamination, climbing ripples, sole marks, and local flame structures.

Metamorphic foliation, defined by aligned minerals and flattened clasts, is variably developed and commonly subparallel to bedding (Carroll, 1980). Lithologies are commonly highly indurated and locally veined. Pebble conglomerate and coarse sandstone are locally polymictic and generally contains abundant rounded to subrounded chert and volcanic lithic clasts in the Obstruction Pass area and subrounded to angular volcanic lithic and lesser mudstone rip-up clasts in the Lummi Island area. Other abundant detrital grains include plagioclase feldspar (albite) and lesser sedimentary lithic clasts; matrix (including pseudomatrix) content varies from 5 percent to about 20 percent. (See Calkin, 1959; Carroll, 1980; and Garver, 1988, for point-count data.) Sandstone and mudstone are commonly interbedded or gradational into each other. Sandstone is commonly thin bedded (<7 cm) or massive and moderately to well sorted. Composition of the sandstone is similar to conglomerates, though possibly richer in quartz. Coalified woody debris on bedding surfaces is common. Color on fresh surfaces ranges from light to dark greenish gray for sandstones to dark gray to black for mudstone, and weathered surfaces are commonly light brown. Metamorphism is characterized by the assemblage lawsonite + pumpellyite + albite + calcite/aragonite + chlorite + white mica. Local actinolite is present on Eliza and Jack Islands (possibly equivalent to unit Jph_d). Prehnite occurs rarely (one sample in Carroll, 1980). Unit $KJmm_l$ includes parts of the Obstruction Formation of Garver (1988) (M. C. Blake, Western Wash. Univ., oral commun., 1999).

An Early Cretaceous to Late Jurassic age is determined from radiolarians in chert near the base of the exposed clastic section (unit $KJmm_l$) (Carroll, 1980). Blake and others (2000) report Toarcian to Tithonian ages for chert overlying and interbedded with metabasalt of unit Jmt_l. Ar/Ar ages of white mica from Jack and Eliza Islands indicate a Mississippian detrital component with a metamorphic event of possible latest Jurassic and (or) Early Cretaceous age (R. Lamb, in press; E. R. Schermer, Western Wash. Univ., written commun., 2000). The unit occurs on Lummi, Eliza, Jack, Cypress, Blakely, Orcas, Obstruction, Peapod, and Fidalgo Islands. (Description compiled from Calkin, 1959; Whetten, 1975; Carroll, 1980; Garver, 1988; Brandon and others, 1988; and Blake and others, 2000.)

Jmt_l **Lummi Formation of Vance (1975) (Jurassic)**—Metabasalt (spilite), metagabbro, and metachert with minor limestone, metadiabase, argillite, and serpentinite. Metabasalt, metadiabase, and metagabbro are nonfoliated and fine to coarse grained. Metabasalt commonly exhibits pillow structures, including pillow breccia, and locally contains pyroxene and (or) relict plagioclase phenocrysts and vesicles. Metachert is commonly well bedded. The thin (~7 cm thick) beds have a ribbon appearance in outcrop and are usually highly contorted. Radiolarian tests are present in the metachert and have been dated (see below and Appendix, Table 6, map nos. 80–83). Recrystallized impure limestone pods occur interbedded with some pillow basalts and range from a few centimeters to about a meter in diameter. Serpentinite and argillite occur as small, localized outcrops associated with meta-igneous rocks. Metamorphic minerals in meta-igneous rocks and associated veins include pumpellyite, albite, chlorite, calcite/aragonite, white mica, epidote, quartz, stilpnomelane, and, less commonly, datolite (veins), lawsonite, and prehnite. Dominant metamorphic minerals in metachert and impure limestone include quartz, carbonate, graphite, chlorite, stilpnomelane, and a higher percentage of prehnite. Color is generally light green to dark olive-green on fresh surfaces for meta-igneous rocks; red, green, and (or) black for metachert; and gray to pinkish gray for limestone.

A protolith age of Early to Late Jurassic was determined from preserved radiolarian tests in metachert overlying and interbedded with meta-igneous and metasedimentary rock (Whetten and others, 1978; Carroll, 1980; Blake and others, 2000). The age of metamorphism is discussed in the description of unit $KJmm_l$. Outcrops are restricted to Lummi, Cypress, Vendovi, Blakely, and Trump Islands. Some outcrops of basalt/gabbro on Cypress Island and Cone Islands are alkalic and thus differ from most other Lummi volcanic rocks, which are generally of MORB character (McLellan, 1927; M. C. Blake, Western Wash. U., oral commun., 2000). (Description compiled from McLellan, 1927; Calkin, 1959; Raleigh, 1963; Whetten, 1975; Carroll, 1980; Brandon and others, 1988; and M. C. Blake, Western Wash. Univ., unpub. data, 2000.)

Other Rocks of the San Juan Islands

$JTRmct_o$ **Orcas Chert of Vance (1975) (Jurassic to Triassic)**—Ribbon chert with lesser pillow basalt, mafic tuff, limestone, and mudstone. Bedding, where preserved, is commonly contorted. Ribbon chert, which is commonly veined and fractured, is well bedded with shaly interbeds every few centimeters. Intraformational chert breccia and coarse chert-lithic sandstone occur locally. Pillow basalt and mafic tuff are interbedded with chert and are virtually identical to rocks of the Deadman Bay Volcanics (unit $TRPv_d$; Brandon and others, 1988), however, they occur much less abundantly. Limestone is recrystallized into aragonite marble (Vance, 1968) and occurs as interbeds in chert and as olistolithic blocks. Interbedded mudstone and mafic tuff are locally abundant. Chert is light blue-gray to black (locally red), basalt and tuffs are green, limestone is gray to light pinkish gray, and mudstone is commonly black.

Triassic to Early Jurassic ages were determined from radiolarians in chert. Recent collections by Blake and others (in prep.) have identified only Late Triassic (Norian) radiolarians. Limestone associated with chert yields Late Triassic conodonts (Brandon and others, 1988). Brown and Vance (1987) consider this unit and the Deadman Bay Volcanics to be equivalent to the Elbow Lake Formation. Unit $JTRmct_o$ may locally include units pDi_t and KJm_c. Outcrops occur mainly on Orcas and Shaw Islands. (Description compiled from McLellan, 1927; Vance, 1968, 1975, 1977; Shelley, 1971; and Brandon and others, 1988.)

$TRPv_d$ **Deadman Bay Volcanics of Brandon and others (1988) (Triassic to Permian)**—Pillow basalt, pillow breccia, and mafic tuff with lesser limestone and chert. Bedding, where preserved, is commonly contorted. Basalt (basaltic andesite) is locally porphyritic and vesicular and is spilitic. Geochemistry of the basalt indicates that it is likely of ocean-island affinity (see Brandon and others, 1988, for details). The pillow breccia contains blocks as much as 30 cm in diameter and locally grades into finer grained mafic tuff-breccias and mafic tuff. Limestone and chert are interbedded with and overlie volcanic rocks and locally fill voids between adjacent basaltic pillows. Mafic tuff is locally interbedded with limestone. Some mixing of rock types occurred during submarine slumping. Limestone is recrystallized to aragonite marble (Vance, 1968), however it locally preserves Tethyan fusulinids. The basalt is commonly red and (or) green, limestone is pink to gray, and chert is commonly red.

The Late Triassic to Early Permian age was determined from fusulinids in limestone and radiolarians in chert. (See Brandon and others, 1988, for age details.) Brown and Vance (1987) consider this unit and the Orcas Chert to be equivalent to the Elbow Lake Formation. (See Brandon and others, 1988, for details on regional correlations.) Outcrops occur near Judd Bay at the north end of East Sound on Orcas Island. The type-locality is Deadman Bay on the west side of San Juan Island (Roche Harbor quadrangle). (Description compiled from Shelley, 1971; Vance, 1975, 1977; and Brandon and others, 1988.)

$PDvs_e$ **East Sound Group of Brandon and others (1988) (Permian to Devonian)**—Volcanic breccia, volcanic sandstone and siltstone, pebble and cobble conglomerate, tuff, and minor basaltic to dacitic flows and hypabyssal rocks with lesser fossiliferous limestone. Bedding in clastic rocks ranges from massive (typically volcanic breccia) to very well bedded. Graded and laminar beds are common. Sorting is highly variable. Massive volcanic breccia (commonly andesitic to dacitic) consists of angular volcanic clasts ($\leq$30 cm in diameter) set in a matrix of finer grained volcanic material of similar composition. Bedded volcanic-rich sandstone and siltstone are associated with, and are likely derived from, this volcanic material. Quartz-rich siltstone occurs locally. Pebble and cobble conglomerate consists of volcanic as well as plutonic clasts that are lithologically similar to plutonic and hypabyssal rocks of the Turtleback Complex. Tuff is commonly fine to medium grained and massive to well bedded. It ranges from crystal- to lithic-rich and is usually interbedded with volcanic breccia and volcanic sandstone and siltstone. Siliceous fine-grained tuff is locally abundant. Lava flows are commonly massive and locally pillowed; hypabyssal rocks are fine grained and intrude clastic volcanic rocks. Hypabyssal rocks and lava flows are lithologically similar to volcanic dikes that intrude the Turtleback Complex. Limestone, locally aragonitic marble, occurs as lenticular bodies interbedded with volcanic and sedimentary rocks and is commonly associated with black shale and argillite (Danner, 1966, 1977). The color of the volcanic rock ranges from various shades of green to less commonly gray, tan, and red; fine-grained siliceous tuff and argillite are commonly dark gray to black; and limestone is commonly some shade of gray. Metamorphic minerals include prehnite and calcite/aragonite.

The Permian to Devonian age is determined from fossils in limestone (Danner, 1966, 1977). Preliminary U/Pb ages of detrital zircons near the base(?) of the unit yielded ages that range from 342 to 426 Ma (W. C. McClelland, Univ. of Idaho, written commun., 2000). Based on similar age, lithology, and fossil content, many workers consider this unit to be equivalent to the Chilliwack Group in the northern Cascade Range (Brown and Vance, 1987; Brandon and others, 1988). Unit $PDvs_e$ may locally include unit pDi_t. Outcrops occur on Orcas Island, and the type locality is on East Sound of said island. (Description compiled from McLellan, 1927; Danner, 1966; Vance, 1975, 1977; and Brandon and others, 1988.)

$pPsc_g$ **Garrison Schist of Danner (1966) and Vance (1975) (pre-Permian)**—Amphibolite and greenschist with minor quartz-mica schist and rare marble. Grain size is generally fine in both schist and amphibolite, and all lithologies except marble are well foliated. Amphibolite and greenschist generally contain albite + epidote + chlorite ± actinolite ± barroisite (in amphibolites only) ± calcite/aragonite. Trace element geochemistry suggests an ocean-floor basalt protolith (Brandon and others, 1988). Quartz-mica schists (metachert and siliceous shale) are graphitic and generally contain quartz and subordinate white mica ± chlorite ± garnet (rare). Amphibolite and greenschist are generally green to rarely black, and quartz-mica schist and marble are light gray to gray.

In the map area, K/Ar metamorphic age determinations (Appendix, Table 4) are 286 ±20 Ma and 167 ±12 Ma for amphibolite and greenschist, respectively. Brandon and others (1988) postulate that the Middle Jurassic age for greenschist is the result of argon loss. A pre-Permian/early Triassic protolith age is supported by another K/Ar age of 242 ±14 Ma for unit $pPsc_g$ outside the map area. In the Bellingham quadrangle, outcrops occur as discontinuous tectonic slices 1 to 4 m thick within unit $J\overline{R}mct_o$ and are exposed only on western Shaw Island and central Orcas Island. On the basis of K/Ar dates, petrologic similarities, and structural position in the Northwest Cascades system (Brown and Vance, 1987), unit $pPsc_g$ is interpreted to be equivalent to the Vedder Complex (unit $pPhm_v$) in the northwest Cascades. (Description compiled from Vance, 1975, 1977; Armstrong and others, 1983; Brown and Vance, 1987; and Brandon and others, 1988.)

pDi_t **Turtleback Complex of McLellan (1927) (pre-Devonian)**—Metagabbro and rare pyroxenite, metaquartz diorite, metatonalite, metatrondhjemite, local orthogneiss, and metamorphosed basaltic to silicic dikes. Grain size ranges from fine to coarse. Metagabbro locally displays cumulate layering and pegmatitic textures. Meta-intrusive rocks are commonly statically recrystallized, however, Vance (1977) reports orthogneiss at one locality on the northwestern slope of Mount Constitution. Metagabbro is commonly the host rock for more silicic plutonic intrusives. All metaplutonic rocks are cut by variably metamorphosed basaltic to silicic dikes and are extensively recrystallized at greenschist to albite-epidote amphibolite facies. They typically contain hornblende or actinolite, albite, epidote, chlorite, and quartz with other, variable accessory minerals. Late veins of prehnite and calcite/aragonite are common. Metamorphosed basaltic to silicic dikes typically contain greenschist facies mineralogy and late veins of prehnite and calcite/aragonite. Brandon and others (1988; p. 13), however, report some dikes lack a greenschist facies overprint. Color is highly variable from light greenish gray for felsic rocks to dark olive-green for mafic varieties.

The protolith ages of the metaplutonic rocks are 554 ±16 Ma (K/Ar in hornblende) for metagabbro (Whetten and others, 1978) and 507 +60/–46 Ma (U/Pb in zircon) for tonalite (Brandon and others, 1988). Mattinson (1972) and Whetten and others (1978) suggest intrusive ages of 460 Ma and 471 Ma, respectively. Pb/Pb in zircon indicates a minimum age of Early Devonian (Whetten and others, 1978; Brandon and others, 1988) (Appendix, Table 1, map nos. 1–4). Based on similar ages, composition (excluding quartzose gneiss), and metamorphic history, many workers consider this unit equivalent to the Yellow Aster Complex (unit pDgn$_y$). Outcrops occur on Orcas Island as slices in fault zones and mountain-scale blocks. The type locality is Turtleback Mountain on the west side of Orcas Island. (Description compiled from McLellan, 1927; Shelley, 1971; Mattinson, 1972; Vance, 1975, 1977; Whetten and others, 1978; Brown and Vance, 1987; and Brandon and others, 1988.)

tz **Tectonic zone**—Zone deformation produced during tectonic activity. Includes fault breccia, cataclasite, and (or) mylonite. Serpentinite locally occurs in these zones (Russell, 1975). Adjacent rock types are typically structurally interleaved within the zone. Exposures occur on Lummi, Blakely, and Guemes Islands.

tz$_o$ **Tectonic zone on Orcas Island**—Tectonic zone where imbricate slices of units JTRmct$_o$ (Orcas Chert), TRPv$_d$ (Deadman Bay Volcanics), and pDi$_t$ (Turtleback Complex) are too small to show at 1:100.000-scale. See mapping in Russell (1975) and authors contained within and Brandon and others (1988).

ACKNOWLEDGMENTS

Reviews by D. J. Easterbrook and E. H. Brown (Western Wash. Univ.), J. D. Dragovich (DGER), and M. C. Blake (USGS, emeritus) greatly improved this report. Reviews of the preliminary text by R. L. Logan, J. E. Schuster, and T. J. Walsh of DGER are also appreciated. Enlightening conversations with R. A. Haugerud (USGS), E. H. Brown, M. C. Blake, J. D. Dragovich, D. J. Easterbrook, D. J. Kovanen (Univ. of British Columbia), R. F. Burmester and George Mustoe (Western Wash. Univ.), H. W. Schasse and P. T. Pringle (DGER), Dan McShane (Stratum Group), and Jon Einarsen (BEK Purnell Engineering Inc.) are greatly valued. Dan McShane also provided some unpublished mapping in the quadrangle. Excellent cartographic support was provided by DGER staff members J. E. Schuster, Anne Heinitz, Keith Ikerd, and Charles Caruthers; Jari Roloff and Karen Meyers provided excellent text editing, figure preparation, and text layout. R. A. Haugerud, E. H. Brown, J. D. Dragovich, R. F. Burmester, and Aimee E. D'Andrea accompanied me on many field excursions. Essential library and reference support was provided by Connie Manson and Lee Walkling; computer support was provided by Renee Christensen; clerical support was provided by Jennifer Southard, Josh Brown, and Jan Allen, all of DGER.

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Appendix

Analytical and age data from U/Pb in zircon, Rb/Sr, K/Ar, fission-track, and fossils. Map numbers refer to locations on Plate 1. Numbered references are given at the end of the appendix.

Table 1. U/Pb in zircon analytical and age data. N/A, not applicable; **, see analytical data in reference(s)

				Concentration (ppm)			Isotopic composition of lead (atom %)				Age (m.y.)				
Map no.	Unit name; unit symbol	Rock type; location; section, township, and range	Mesh size	U	Th	Pb	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	^{208}Pb/^{232}Th	Reference (sample no.)
1	Turtleback Complex; pDi$_t$	tonalite; Orcas Island; SE¼NW¼ sec. 26, T37N R2W	N/A	274	N/A	17.6	0.050	81.67	5.276	13.00	376	384	437 ±10	N/A	1, 2 (68-21)
2	Yellow Aster Complex; pDgn$_y$	quartz diorite; Bowman Mountain; NE¼NE¼ sec. 32, T38N R6E	–150 +400	337.7	133.2	30.99	0.089	80.79	8.578	10.55	523 ±7	733 ±14	1442 ±20	376 ±5	3 (78-59)
3	Yellow Aster Complex; pDgn$_y$	quartz diorite; Bowman Mountain; NE¼NE¼ sec. 32, T38N R6E	-150 +400	398.1	89.9	34.46	0.386	70.97	10.02	18.63	402 ±6	448 ±20	690 ±65	342 ±6	3 (78-250)
4	Yellow Aster Complex; pDgn$_y$	quartz diorite; Bowman Mountain; NE¼NE¼ sec. 32, T38N R6E	-150 +400	182.1	72.7	9.62	0.262	71.57	10.61	17.56	259 ±3	446 ±14	1578 ±50	227 ±4	3 (78-253)
5	Fidalgo ophiolite; Ji$_f$	tonalite; Blakely Island; S½ sec. 35, T36N R1W	-100 +150	729	457	21.29	0.018	79.13	4.192	16.66	170 ±3	171 ±3	177 ±4	168±3	2 (75-227)
6	Fidalgo ophiolite; Ji$_f$	tonalite; Blakely Island; S½ sec. 35, T36N R1W	-200 +270	1010	636	29.54	0.007	78.86	4.150	16.98	170 ±3	176 ±3	256 ±6	176 ±3	2 (75-227)
7	Fidalgo ophiolite; Ji$_f$	trondhjemite; Lummi Island; NE¼NW¼ sec. 15, T37N R1E	-150 +400	322.5	178.2	8.97	0.085	79.28	5.166	15.47	160 ±3	160 ±4	167 ±8	140 ±3	3, 4 (78-254)
8	Easton Metamorphic Suite; Jigb$_s$	metagabbro; Colony Mountain; NW¼NW¼ sec. 23, T36N R3E	3 grains	**	N/A	**	**	**	**	**	163.2 ±0.4	162.5 ±3.5	152.6 ±33.0	N/A	5 (97-51H)
9	Easton Metamorphic Suite; Jsh$_s$	greenschist; Anderson Mountain; SE¼NE¼ sec. 15, T36N R4E	8 grains	**	N/A	**	**	**	**	**	163.8 ±0.2	164.0 ±0.2	166.8 ±2.3	N/A	5 (97-32L)

Table 2. U/Pb in zircon analytical and age data. *, radiogenic Pb; **, see analytical data in reference(s); ***, see reference(s) for methodology of ratio corrections

					Concentration (ppm)		Isotopic Composition***			Apparent age (m.y.)			Th-corrected age (m.y.)		
Map no.	Unit name; unit symbol	Rock type; location; section, township, and range	Fraction size (mm)	Weight (mg)	U	Pb*	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{206}Pb^*$	Reference (sample no.)
10	Easton Metamorphic Suite; Jsh$_s$	metaquartz diorite; Bowman Mountain; NW¼NW¼ sec. 17, T37N R6E	bulk zircon population	.0986	80.51	1.78	1295	**	**	163 ±2	163 ±3	166 ±10	N/A	N/A	7 (BM 87)
11	Huntingdon Formation; ΦEc$_h$	volcanic siltstone; Kendall 7.5-minute quadrangle; NE¼NE¼ sec. 14, T40N R4E	a80-100	0.25	366	9.1	7033 ±15	18.344	10.849	183.2	192.2±0.4	304	183.2 ±0.4	303 ±3	6 (96-77b)
12	Huntingdon Formation; ΦEc$_h$	volcanic siltstone; Kendall 7.5-minute quadrangle; NE¼NE¼ sec. 14, T40N R4E	b100-125	0.4	314	8.9	3066 ±11	15.867	6.270	207.1	236.2 ±0.6	537	207.2 ±0.4	536 ±3	6 (96-77b)
13	Huntingdon Formation; ΦEc$_h$	volcanic siltstone; Kendall 7.5-minute quadrangle; NE¼NE¼ sec. 14, T40N R4E	c125-350	0.3	317	7.1	2619 ±7	17.254	7.339	165.6	174.8 ±0.5	302	165.7 ±0.3	300 ±4	6 (96-77b)
14	Huntingdon Formation; ΦEc$_h$	tuff; Kendall 7.5-minute quadrangle; SE¼NW¼ sec. 7, T40N R5E	a80-100	0.25	952	9.4	1207 ±5	16.715	7.349	73.2	73.5 ±0.2	80	73.3 ±0.2	78 ±6	6 (96-77I)
15	Huntingdon Formation; ΦEc$_h$	tuff; Kendall 7.5-minute quadrangle; SE¼NW¼ sec. 7, T40N R5E	b100-125	0.4	1065	11.6	3521 ±6	18.908	8.759	80.6	82.3 ±0.2	134	80.6 ±0.2	131 ±2	6 (96-77I)
16	Huntingdon Formation; ΦEc$_h$	tuff; Kendall 7.5-minute quadrangle; SE¼NW¼ sec. 7, T40N R5E	c125-350	0.3	803	10.3	1268 ±4	15.121	8.217	95.1	107.7 ±0.3	397	95.2 ±0.2	395 ±4	6 (96-77I)
17	Chilliwack Group; PDhm$_c$	metabasalt/andesite; Deming 7.5-minute quadrangle; NW¼ sec. 23, T39N R4E	a63-100	0.2	60	9.7	28,108 ±165	11.133	9.486	1111.5	1217.7 ±2.5	1411	1111.5 ±2.0	1411 ±1	6 (96-25E1)
18	Chilliwack Group; PDhm$_c$	metabasalt/andesite; Deming 7.5-minute quadrangle; NW¼ sec. 23, T39N R4E	b100-125	0.1	155	4.2	3696 ±8	11.038	8.294	199.9	324.0 ±0.8	1357	199.9 ±0.4	1357 ±2	6 (96-25E1)
19	Chilliwack Group; PDhm$_c$	metabasalt/andesite; Deming 7.5-minute quadrangle; NW¼ sec. 23, T39N R4E	c125-350	0.1	293	7.3	2617 ±4	10.583	8.885	183.0	307.8 ±0.7	1408	183.0 ±0.4	1408 ±2	6 (96-25E1)
20	Chilliwack Group; PDhm$_c$	volcanic breccia; Deming 7.5-minute quadrangle; NW¼ sec. 23, T39N R4E	a45-80	0.01	714	16.8	2575 ±4	10.612	7.861	172.7	291.7 ±1.1	1401	172.7 ±0.2	1401 ±6	6 (96-25E2)
21	Chilliwack Group; PDhm$_c$	volcanic breccia; Deming 7.5-minute quadrangle; NW¼ sec. 23, T39N R4E	b100-125	0.02	428	20.8	4257 ±13	10.894	8.876	352.7	530.7 ±1.1	1394	152.7 ±0.3	1394 ±1	6 (96-25E2)

Table 3. Rb/Sr analytical data. N/A, not applicable

Map no	Unit name; unit symbol	Rock type; location; section, township, and range	Sample type	Sr (ppm)	Rb (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Initial $^{87}Sr/^{86}Sr$	Reference (sample no.)	Remarks
22	Garrison Schist; pPsc$_g$	amphibolite; Orcas Island; NE¼SW¼ sec. 31, T37N R1W	whole rock	361	3.4	0.027	0.7052	0.7051	1 (G2)	Analytical procedures are described in Armstrong and others (1983)
23	Garrison Schist; pPsc$_g$	greenschist; Shaw Island; SW¼NW¼ sec. 32, T36N R2W	whole rock	168	1.4	0.025	0.7043	0.7042	1 (G3)	Analytical procedures are described in Armstrong and others (1983)
24	Darrington Phyllite; Jph$_d$	phyllite; Alger 7.5-minute quadrangle; NW¼NW¼ sec. 18, T36N R4E	whole rock	78.1	57.8	2.14	0.7092	N/A	2 (Alger)	Located in a small outcrop exposed in unit Qgdm$_e$
25	Darrington Phyllite; Jph$_d$	phyllite; Acme 7.5-minute quadrangle; SW¼NE¼ sec. 32, T37N R5E	whole rock	51.6	74.1	4.16	0.7135	N/A	2 (PM 23)	Located in a small outcrop exposed in unit Qgo$_{es}$
26	Darrington Phyllite; Jph$_d$	phyllite; Acme 7.5-minute quadrangle; NE¼SE¼ sec. 7, T37N R5E	whole rock	97.8	119	3.54	0.7127	N/A	2 (Acme P)	
27	Darrington Phyllite; Jph$_d$	phyllite; Acme 7.5-minute quadrangle; NE¼SE¼ sec. 7, T37N R5E	whole rock	413	23.8	0.167	0.7067	N/A	2 (Acme S)	

Table 4. K/Ar age and analytical data. New Ar/Ar ages of white mica from Jack, Eliza, and Samish Islands are available in Lamb (2000)

Map no.	Unit name; unit symbol	Rock type; location; section, township, and range	Sample type (size fraction)	K_2O (weight %)	^{40}Ar (rad) (10^{G10} mol/g)	^{40}Ar(rad)/ ^{40}Ar(total)	Age (±2 sigma)	Reference (sample no.)	Remarks
28	Turtleback Complex pDi_t	gabbro pegmatite; Orcas Island; SE¼NE¼ sec. 24, T37N R1W	hornblende	0.343	3.207	0.78	554 ±16	1, 2 (SJ-13A)	
29	Turtleback Complex pDi_t	gabbro; Orcas Island NW¼NW¼ sec. 36, T37N R1W	hornblende	0.378 n=3	2.3382 n=2	0.850 n=2	332 ±16	2 (0-511)	"n=" indicates an average of n replicate measurements
30	Turtleback Complex pDi_t	diorite orthogneiss; Orcas Island NW¼NW¼ sec. 29, T37N R2W	whole rock	N/A	N/A	N/A	259 ±16	1, 2, 3 (D-18)	No analytical information available for this sample
31	Garrison Schist $pPsc_g$	amphibolite; Orcas Island NE¼SW¼ sec. 31, T37N R1W	hornblende (–100 +200)	0.499	2.678	0.897	286 ±20	2, 4 (0-507)	Analytical procedure in Armstrong and others, 1983
32	Garrison Schist $pPsc_g$	greenschist; Shaw Island SW¼NW¼ sec. 32, T36N R2W	amphibole (–80 +140)	0.132	0.4002	0.626	167 ±12	2, 4 (7981J-1C)	Analytical procedure in Armstrong and others, 1983
33	Lummi Formation Jmt_l	metabasalt; Lummi Island SW¼SE¼ sec. 29, T38N R1E	whole rock	0.0276	N/A	N/A	160 ±22	5 (19)	No detailed analytical data available
34	Darrington Phyllite Jph_d	phyllite; Lyman 7.5-minute quadrangle; SE¼SW¼ sec. 12, T35N R5E	whole rock	4.010	N/A	N/A	126 ±5	5 (37)	No detailed analytical data available
35	Darrington Phyllite Jph_d	phyllite; Lyman 7.5-minute quadrangle; SE¼SW¼ sec. 12, T35N R5E	whole rock	0.938	N/A	N/A	123 ±6	5 (38)	No detailed analytical data available
36	Darrington Phyllite Jph_d	phyllite; Lyman 7.5-minute quadrangle; SE¼SW¼ sec. 12, T35N R5E	whole rock	3.502	N/A	N/A	126 ±5	5 (39)	No detailed analytical data available
37	Darrington Phyllite Jph_d	phyllite; Canyon Lake 7.5-minute quadrangle; SE¼NE¼ sec. 30, T38N R6E	whole rock	N/A	N/A	N/A	108 ±4	6 (PM 17)	No detailed analytical data available
38	Darrington phyllite Jph_d	phyllite; Acme 7.5-minute quadrangle; NW¼SE¼ sec. 7, T37N R5E	whole rock	N/A	N/A	N/A	105 ±3	6 (PM 18)	No detailed analytical data available

Table 5. Fission-track age data

Map no.	Unit name; unit symbol	Rock type; location; section, township, and range	Mineral dated (grains counted)	Age (ma)	Reference (sample no.)	Remarks
39	Turtleback Complex; pDi$_t$	tonalite; Orcas Island; SE¼NW¼ sec. 26, T37N R2W	zircon	246 ±45	1 (68-21)	
40	Turtleback Complex; pDi$_t$	tonalite; Orcas Island; SE¼SE¼ sec. 5, T36N R2W	zircon (6) apatite (60,34)	275 ±31 84.1 ±19.5	3 (78-206)	See reference for analytical data
41	Turtleback Complex; pDi$_t$	dacite dike; Orcas Island; SW¼SW¼ sec. 4, T36N R2W	zircon	246 ±41	2 (T10 JV-270)	See reference for analytical data; age determined by J. A. Vance
42	Fidalgo ophiolite; Ji$_f$	tonalite; Blakely Island; sec. 35, T36N R1W	zircon (6)	145 ±20	1, 3 (75-227)	See reference for analytical data
43	Fidalgo ophiolite; Ji$_f$	gabbro; Blakely Island; N½, Sect, 10, T35N R1W	zircon (8)	127 ±13	3 (78-204)	See reference for analytical data
44	Fidalgo ophiolite; Ji$_f$	diabase dike; Blakely Island; SW¼ sec. 4, T35N R1W	zircon (6)	136 ±16	3 (78-203)	See reference for analytical data
45	Fidalgo ophiolite; Ji$_f$	gabbro dike; Frost Island; SE¼ sec. 7, T35N R1W	zircon (6) apatite (8)	152 ±20 107 ±15	3 (78-202)	See reference for analytical data
46	Lummi Formation; KJmm$_l$	graywacke; Orcas Island; SW½ sec. 15, T 36N R1W	zircon (7) apatite (10)	107 ±13 73.9 ±9.5	3 (81-N7)	See reference for analytical data
47	Fidalgo ophiolite; KJm$_f$	graywacke; Lopez Island; NE¼ sec. 1, T35N R2W	zircon (6) apatite (4)	142 ±14 52.7 ±12.3	3 (78-201)	See reference for analytical data
48	Lummi Formation; KJmm$_l$	graywacke; Lopez Island; NW¼ sec. 22, T35N R2W	zircon (6) apatite (11)	105 ±10 87.9 ±14.6	3 (78-200)	See reference for analytical data
49	Fidalgo ophiolite; KJm$_f$	quartz diorite clasts; Decatur Island; NE¼NE¼ sec. 22, T35N R1W	zircon (6)	78.7 ±12.4	3 (75-10)	See reference for analytical data
50	Fidalgo ophiolite; KJm$_f$	quartz diorite clasts; Decatur Island; NE¼NE¼ sec. 22, T35N R1W	zircon (7)	61.0 ±8.2	3 (75-14)	See reference for analytical data
51	Turtleback Complex; pDi$_t$	quartz diorite; Orcas Island; NW¼NW¼ sec. 32, T37N R1W	zircon (9)	191 ±26	3 (81-N5)	See reference for analytical data
52	Turtleback Complex; pDi$_t$	quartz diorite; Orcas Island; NW¼NE¼ sec. 18, T37N R1W	zircon (8)	216 ±31	3 (81-N9)	See reference for analytical data
53	Nanaimo Group; Kn$_{ne}$	quartz diorite clast; Orcas Island; NW¼SW¼ sec. 10, T37N R2W	zircon (6) apatite (52, 60)	133 ±17 60.0 ±13.1	3 (78-216)	See reference for analytical data
54	Nanaimo Group; Km$_{nh}$	sandstone; Orcas Island; S½NW¼ sec. 7, T37N R1W	zircon (14) apatite (10)	75.8 ±5.6 69.3 ±9.5	3 (81-N8)	See reference for analytical data
55	Nanaimo Group; Kn$_{ne}$	sandstone; Barnes Island; sec. 14, T37 R1W	sphene (6) zircon (6) apatite (10)	131 ±14 105 ±10 89.6 ±12.0	3 (79-11)	See reference for analytical data
56	Chuckanut Formation; Ec$_{cp}$	sandstone; Matia Island	zircon (6) apatite (9)	88.9 ±8.5 49.7 ±9.2	3 (78-217)	See reference for analytical data
57	Chuckanut Formation; Ec$_{cp}$	sandstone; Sucia Island; sec. 25, T38N R2W	zircon (8)	58.0 ±6.0	3, 4 (79-100)	See reference for analytical data
58	Chuckanut Formation; Ec$_{cp}$	sandstone; Lummi Island; NW¼ sec. 32, T38N R1E	zircon (6) apatite (15)	65.3 ±5.3 53.4 ±7.1	3 (78-255)	See reference for analytical data
59	Chuckanut Formation; Ec$_{cb}$	lithic tuff; Lookout Mountain; SE¼ sec. 11, T37N R3E	zircon (6)	49.9 ±1.2	4	See reference for analytical data and error
60	Chuckanut Formation; Ec$_{cb}$	sandstone/conglomerate; Chuckanut Mountain; NW¼SW¼ sec. 9, T36N R3E	zircon (6)	52.9–70.9	4	See reference for analytical data
61	Chuckanut Formation; Ec$_{cb}$	sandstone/conglomerate; Samish Lake; SW¼NW¼ sec. 25, T37N R3E	zircon (6)	55.1–67.4	4	See reference for analytical data
62	Chuckanut Formation; Ec$_{cb}$	sandstone/conglomerate; south Lake Whatcom; SE¼NE¼ sec. 20, T37N R4E	zircon (6)	50.5–101.1	4	See reference for analytical data

Table 6. Fossil age data. References are listed at the end of the appendix

Map no.	Unit name; unit symbol	Rock type; location; section, township, and range	Age-diagnostic fossil(s) or fossil zones	Age	References (sample no.)
63	East Sound Group; PDvs$_e$	limestone interbedded with volcanic rocks; Orcas Island; NE¼SW¼ sec. 30, T37N R2W	brachiopods, stromatoporoids, and gastropods	Middle or Late Devonian (late Givetian to early Frasnian)	2, p. 494; 1, p. 177–179; 3 (D13); 4 (E3)
64	East Sound Group; PDvs$_e$	limestone interbedded with volcanic rocks; Orcas Island; SW¼ sec. 20, T37N R2W	corals, brachiopods, algae, foraminiferans, and stromatoporoids.	late Middle Devonian	1, p. 142–144; 3 (D8); 4 (E4)
65	East Sound Group; PDvs$_e$	limestone interbedded with volcanic rocks; Orcas Island; NE¼SW¼ sec. 30, T37N R2W	stromatoporoids	Probably Devonian	1, p. 183–184; 4 (E6)
66	East Sound Group; PDvs$_e$	isolated limestone body; Orcas Island; S½, sec. 16, T37N R1W	fusulinids	Middle or Early Pennsylvanian	1, p. 198–199; 2, p. 494–495; 3 (D15); 4 (E7)
67	East Sound Group; PDvs$_e$	limestone interbedded in siliceous argillite; Orcas Island; NW¼NW¼ sec. 19, T37N R1W	fusulinids	Early Pennsylvanian	1, p. 203; 3 (D16); 4 (E8)
68	East Sound Group; PDvs$_e$	isolated limestone body; Orcas Island; NW¼SE¼ sec. 15, T37N R2W	foraminiferans	Early Pennsylvanian	1, p. 154–155; 3 (D10); 4 (E9)
69	East Sound Group; PDvs$_e$	isolated limestone body; Orcas Island; SE¼NE¼ sec. 20, T37N R3W	foraminiferans	Early Pennsylvanian or possibly Late Mississippian	1, p. 161–162; 3 (D11), 4 (E10)
70	East Sound Group; PDvs$_e$	poorly exposed limestone near volcanic rocks; Orcas Island; NW¼SE¼ sec. 15, T37N R2W	fusulinids and bryozoa	Early Permian (Wolfcampian)	1, p. 151–153; 3 (D9); 4 (E12)
71	East Sound Group; PDvs$_e$	limestone interbedded in volcanic sequence; Orcas Island; NE¼SW¼ sec. 30, T37N R2W	fusulinids and algae	Permian	1, p. 188; 3 (D14); 4 (E13)
72	Deadman Bay Volcanics; JPv$_d$	isolated limestone surrounded by argillite, chert and volcanic rock; Orcas Island; SE¼ sec. 15, T37N R2W	fusulinids (Tethyan)	Middle Permian	1, p. 155–156; 2, p. 496–497; 4 (D1)
73	Deadman Bay Volcanics; JPv$_d$	limestone lenses interbedded in pillow basalt and chert; Orcas Island; NE¼NE¼ sec. 22, T37N R2W	fusulinids (Tethyan); radiolarians (2 samples)	Late Permian (early Guadalupian) to Late Triassic	1, p. 167–168; 2, p. 497; 3 (D12); 4 (D5 [79J–141, 79812J–2])
74	Deadman Bay Volcanics; JPv$_d$	isolated limestone body surrounded by chert and volcanic rocks; Orcas Island; NE¼NE¼ sec. 22, T37N R2W	fusulinids (Tethyan)	Late Permian (early Guadalupian)	1, p. 165; 2, p. 497; 3; 4 (D6)
75	Deadman Bay Volcanics; JPv$_d$	limestone interbedded in pillow basalt and chert; Orcas Island; NE¼NE¼ sec. 22, T37N R2W	fusulinids (Tethyan)	Late Permian (early Guadalupian)	1, p. 169–171; 2, p. 497; 3; 4 (D7)
76	Orcas Chert; JTRmct$_o$	ribbon chert; Shaw Island; NW¼ sec. 30, T36N R2W	radiolarians	probably Early Jurassic	4 (O26)
77	Orcas Chert; JTRmct$_o$	interbedded limestone, chert, and argillite; Orcas Island; NW¼ sec. 17, T36N R2W	conodonts	Late Triassic (late Carnian to late Norian)	1, p. 182; 4 (O30); 5
78	Orcas Chert; JTRmct$_o$	ribbon chert; Orcas Island; SW¼NE¼ sec. 9, T36N R2W	radiolarians	Late Triassic to Early Jurassic	3 (77-59); 4 (O31)
79	Lummi Formation(?); tz	chert interbedded with pillow basalt; Lummi Island; SE¼NE¼ sec. 15, T37N R1E	radiolarians	Middle Jurassic	4 (DF9); 7, p. 10
80	Lummi Formation; Jmt$_l$	chert interbedded with pillow basalt; Lummi Island; NE¼ sec. 25, T37N R1E	radiolarians	Middle to Late Jurassic (late Bajocian to Kimmeridgian)	3 (PRC-23); 4 (DF10); 7, p. 10
81	Fidalgo ophiolite; Ji$_f$	black siliceous mudstone interbedded with pillow basalt; Lummi Island; NW¼ sec. 9, T37N R1E	radiolarians	Middle to Late Jurassic (late Bajocian to Kimmeridgian)	3 (PRC-64); 4 (DF11); 7, p. 10

Map no.	Unit name; unit symbol	Rock type; location; section, township, and range	Age-diagnostic fossil(s) or fossil zones	Age	References (sample no.)
82	Lummi Formation; Jmt_l	chert interbedded with pillow basalt; Lummi Island; NE¼ sec. 25, T37N R1E	radiolarians	Middle Jurassic or younger	3 (PRC-0); 7, p. 10; 4 (DF12)
83	Lummi Formation; Jmt_l	chert interbedded with pillow basalt; Lummi Island; SW¼SE¼ sec. 29, T38N R1E	radiolarians	Mesozoic	7, p. 10; 4 (DF13)
84	Lummi Formation; $KJmm_l$	chert at base of Lummi turbidites; Lummi Island; SW¼NW¼ sec. 36, T37N R1E	radiolarians	Late Jurassic to Early Cretaceous	7, p. 10; 4 (DF21)
85	Lummi Formation; $KJmm_l$	siliceous argillite interbedded with siltstone and tuff; Trump Island; sec. 20, T35N R1W	radiolarians	Late Jurassic (early Tithonian)	3 (75-62); 4 (DF19)
86	Tectonic zone; tz	minor chert interbedded with clastic rocks; Orcas Island; S½NW¼ sec. 19, T36N R1W	radiolarians	Late Jurassic	3 (77-61); 4 (DF22)
87	Tectonic zone; tz	minor chert interbedded with clastic rocks; Orcas Island; S½NW¼ sec. 19, T36N R1W	radiolarians	Late Jurassic to Early Cretaceous	3 (77-60); 4 (DF23)
88	Tectonic zone; tz	minor chert interbedded with clastic rocks; Orcas Island; S½NW¼ sec. 19, T36N R1W	radiolarians	Jurassic to Cretaceous	3 (77-64); 4 (DF24)
89	Nanaimo Group; Km_{nh}	siltstone and shale; Orcas Island; SE¼NW¼ sec. 10, T37N R2W	Elongatum Zone of Muller and Jeletzky (1970)	Late Cretaceous (Santonian)	9 (McM 159, UWB 1482)
90	Nanaimo Group; Km_{nh}	siltstone and shale; Orcas Island; S½NW¼ sec. 7, T37N R1W	Elongatum Zone of Muller and Jeletzky (1970)	Late Cretaceous (Santonian)	9 (McM 160, UWB 1487)
91	Nanaimo Group; Km_{nc}	shale, sandstone, and lesser conglomerate; Sucia Island; sec. 25, T38N R2W	Vancouverense Zone of Muller and Jeletzky (1970); refined by Ward (1978)	Late Cretaceous (Upper Campanian)	9 (McM 161)
92	Nanaimo Group; Km_{nc}	sandstone; Sucia Island; sec. 25, T38N R2W	Vancouverense Zone of Muller and Jeletzky (1970); refined by Ward (1978)	Late Cretaceous (Upper Campanian)	9 (UWB 1241)
93	Nanaimo Group; Km_{nc}	shale; Sucia Island; sec. 25, T38N R2W	Vancouverense Zone of Muller and Jeletzky (1970); refined by Ward (1978)	Late Cretaceous (Upper Campanian)	9 (UWB 1246)
94	Nanaimo Group; Km_{nh}	shale; Orcas Island; SE¼NW¼ sec. 10, T37N R2W	Elongatum Zone of Muller and Jeletzky (1970)	Late Cretaceous (Santonian)	12 (UWB 1488)
95	Nanaimo Group; Km_{nh}	shale; Orcas Island; SE¼NE¼ sec. 12, T37N R2W	Elongatum Zone of Muller and Jeletzky (1970)	Late Cretaceous (Santonian)	12 (UWB 1486)
96	Nanaimo Group; Km_{nc}	shale and calcareous shale; Little Sucia Island	Vancouverense or Pacificum Zones of Ward (1978)	Late Cretaceous (Upper Campanian)	12 (UWB 1248)
97	Nanaimo Group; Km_{nc}	sandstone and shale; Barnes Island; sec. 14, T37N R1W	foraminiferans	Late Cretaceous	10 (B 31)
98	Nanaimo Group; Km_{nc}	conglomerate and sandstone; Clark Island; sec. 14, T37N R1W	foraminiferans	Late Cretaceous	10 © 16)
99	Huntingdon Formation; ΦEc_h	chert clast from conglomerate; Sumas Mountain; SE¼NE¼ sec. 12, T39N R4E	radiolarians	~Middle to Late Permian	11 (96CB-0371; USGS DR 2200), locality 97-57A
100	Huntingdon Formation; ΦEc_h	chert clast from conglomerate; Sumas Mountain; SE¼NW¼ sec. 10, T37N R2W	radiolarians	Triassic and Early Jurassic	11 (96CB-0375; USGS DR 2204), locality 96-57A

Map no.	Unit name; unit symbol	Rock type; location; section, township, and range	Age-diagnostic fossil(s) or fossil zones	Age	References (sample no.)
101	Huntingdon Formation; ϕEc_{h}	chert clast from conglomerate; Sumas Mountain; SE¼NW¼ sec. 10, T37N R2W	radiolarians	Early Cretaceous	11 (96CB-0376; USGS DR 2205), locality 96-57A
102	Chuckanut or Huntingdon Formation; ϕEc_{h} or Ec_{c}	chert clast from conglomerate; Sumas Mountain; SE¼NW¼ sec. 10, T37N R2W	radiolarians	Early Jurassic (Hettangian and Sinemurian)	11 (96CB-0381; USGS DR 2208), locality 96-57B1
103	Elbow Lake Formation; $JPhmc_{e}$	bedded chert, Sumas Mountain; NW¼ sec. 28, T40N R5E	radiolarians	Middle Jurassic (Bajocian)	11 (96CB-40A; USGS DR 2210), locality 96-57D
104	Chuckanut Formation; Ec_{cb}	sandstone; Chuckanut Mountain; NW¼SW¼ sec. 9, T36N R3E	pollen	Middle Paleocene	13 (Pb3781)
105	Chuckanut Formation; Ec_{cp}	sandstone; Chuckanut Mountain; S½NE¼ sec. 25, T37N R2E	pollen	Late Paleocene to Early(?) Eocene	13 (Pb3791)
106	Chuckanut Formation; Ec_{cb}	sandstone; Lake Samish; SW¼NW¼ sec. 25, T37N R3E	pollen	Late Paleocene	13 (PP0033)
107	Chuckanut Formation; Ec_{cb}	sandstone; Lake Whatcom; SE¼NE¼ sec. 20, T37N R4E	pollen	Paleocene	13 (PP0034)
108	Chuckanut Formation; Ec_{cb}	sandstone; Lake Whatcom; NE¼SE¼ sec. 17, T37N R4E	pollen	Early to Middle Eocene	13 (PP0035)
109	Chuckanut Formation; Ec_{cb}	sandstone; Lookout Mountain; SE¼ sec. 11, T37N R3E	pollen	Early to Middle Eocene	13 (PP0017)
110	Chuckanut Formation; Ec_{cp}	sandstone; Lake Whatcom; NW¼ sec. 25, T38N R3E	pollen	Late Eocene	13 (PP0025)
111	Chuckanut Formation; Ec_{cp}	sandstone; WWU campus; NE¼NE¼ sec. 1, T37N R2E	pollen	Late Eocene	13 (PP0041)
112	Chuckanut Formation; Ec_{cp}	sandstone; Squalicum Mountain; NW¼NW¼ sec. 18, T38N R4E	pollen	Late Eocene	13 (PP0012)
113	Chuckanut Formation; Ec_{cp}	sandstone; Toad Lake; SW¼SW¼ sec. 11, T38N R3E	pollen	Late Eocene	13 (PP0028)
114	Chuckanut Formation; Ec_{cp}	sandstone; Whatcom quarry; SW¼SE¼ sec. 11, T39N R3E	pollen	Late Eocene	13 (PP0011)

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