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CASCADIA TECTONICS ISSUE

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Cover Photo: North-overturned tight fold (left of geologist) of Red Mountain limestone north-northeast of Kendall. Overturned folds and other structures suggest generally north–south mid-Cretaceous contraction and thrusting of the nappes in this area. Photo by Tim Walsh. See article, p. 15.

The Washington State Geologic Map Program

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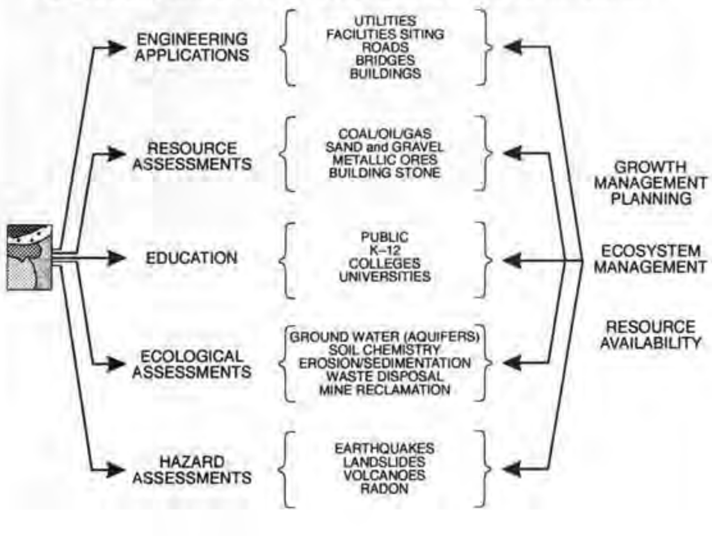
Geologic maps show the types and ages of unconsolidated earth materials and rocks that occur at or near the Earth's surface and the locations of faults and folds. Geologic maps are the most fundamental and important database for the earth sciences. They are used for a broad range of practical applications as depicted in the figure below.

Since 1983, the Division has conducted a State Geologic Map program to produce three types of statewide geologic map coverage: black-and-white maps at 1:100,000 scale (1 in. ≅ 1.6 mi), full-color maps at 1:250,000 scale (1 in. ≅ 4 mi), and digital geology, where 1:100,000-scale quadrangles are converted to digital form in a geographic information system.

Reductions in state funding have slowed the release of our geologic map products. We had expected that statewide geologic map coverage would be completed by mid-1996. To date, of the 51 1:100,000-scale quadrangles covering Washington, 34 full and 3 three partial quadrangles have been released by the Division as open-file reports. We now expect the remainder of the quadrangles, all of which are in the northwest part of the state, to be completed by the end of calendar 1998. With support from the federal STATEMAP program, by June 30 of this year, 17 1:100,000 quadrangles will have been converted to digital format. A similar contract will allow us to digitally prepare about a dozen more quadrangles by July 1998. (See the article, p. 20-21, in *Washington Geology*, v. 24. no. 4, Dec. 1996, for more details about program status.) However, at the present time, the method(s) of releasing or distributing these files has not been determined.

During June, the southeast 1:250,000-scale quadrant of the state geologic map was published (see p. 14 for ordering information). However, faced with additional budget reductions in the 1997–1999 biennium, the Division will probably have to delay the completion of the 1:250,000-scale geologic map of the northwest part of the state to at least the year 2000. ■

GEOLOGIC MAPS + APPLICATIONS = SOUND MANAGEMENT



Something Old, Something New, Something Borrowed, Something Blue—A New Perspective on Seismic Hazards in Washington Using Aeromagnetic Data

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INTRODUCTION

The geology of the state of Washington shows the imprint of tectonic processes related to oblique subduction, first of the Farallon plate, then of the Juan de Fuca plate, beneath North America. "Old" (pre-Neogene) structures, the boundaries of terranes "borrowed" from elsewhere, and fault-bounded topographic depressions ("blue") have been reactivated, some of them repeatedly, so that they control the location of volcanoes and seismicity. In addition, "new" crustal zones that localize deformation may connect or cross these old trends. Seismicity lineaments that follow these more recent crustal features may present an important seismic hazard.

Both the more recent and older crustal boundaries in Washington are reflected in aeromagnetic maps. The clarity and continuity of these crustal zones in the aeromagnetic maps makes them useful tools for understanding the regional geologic framework and tectonic evolution of Washington. The goal of this paper is to present a new compilation of aeromagnetic data for the state of Washington that shows the location of important tectonic trends and to discuss the relation of some of these trends to seismicity.

DESCRIPTION OF AEROMAGNETIC ANOMALIES

A new aeromagnetic map of Washington (Finn and others, 1996) was compiled from 40 separate aeromagnetic surveys of varied quality. When merged together on a common observation surface, these separate surveys provide the first relatively high-resolution, synoptic view of anomalies associated with regional tectonic features. In this paper, we use the new aeromagnetic map to delineate crustal blocks and fault and dike trends, as well as to connect tectonic features and associate some of them with seismicity.

A shaded-relief version of the new aeromagnetic compilation (Fig. 1) shows positive magnetic anomalies (light grays) produced by normally magnetized rocks and negative anomalies (dark grays) related to rocks less magnetic than adjacent rocks or to reversely magnetized volcanic rocks. Unavoidable problems with the compilation are evident as (1) largely north–south or east–west linear features representing boundaries between surveys of varying resolution, (2) striping in the northeast corner of the map due to problems between flight line levels, and (3) areas of poor data quality (for example, in the southeast corner of the map). Nevertheless, linear trends and aeromagnetic patterns that outline a variety of geologic provinces can still be distinguished.

RELATION OF AEROMAGNETIC TRENDS TO GEOLOGY

Something Old: pre-Tertiary Rocks

The north-central and northeast parts of Washington are composed of Precambrian to Mesozoic ophiolites and crystalline terranes (for example, Hamilton, 1978) that were accreted to the Precambrian margin by the end of the Mesozoic (for example, Monger, 1977; Hamilton, 1978). The ophiolites produce very high amplitude positive aeromagnetic anomalies (for example, the Ingalls and Fidalgo ophiolites (O, Fig. 1)). Some of the Mesozoic plutons produce small aeromagnetic highs (east of about 118°W and north of about 47°30′N, Fig. 1). Magnetically quiet areas characterize most of the crystalline terranes, (for example, near 48°N and 121°W (Fig. 1)).

This basement was cut by Late Cretaceous–early Tertiary dextral strike-slip faults, many of which appear as linear anomalies on the aeromagnetic map between 118° and 121°W and 47°30′ and 49°N (for example, Darrington–Devils Mountain fault, DDF, Fig. 1). Some of the faults separate Eocene volcanic rocks from adjacent intrusions and metamorphic rocks. The sources of the north-northwesterly-trending positive anomalies between 120° and 120°30′W just north of 48°30′ (Fig. 1) may be buried Eocene volcanic rocks aligned along faults.

Something Borrowed: Accreted Terranes

Basement in the Coast Range of western Washington consists of Eocene marine basaltic and mafic intrusive rocks formed in a near-margin rift setting that were accreted to the continent in the Eocene (Wells and others, 1984; Babcock and others, 1992). Positive aeromagnetic anomalies in the Coast Range (Fig. 1) reflect exposed and buried normally magnetized Eocene basalts. Negative anomalies in the Coast Range result from several sources: (1) deep magnetic basement under sedimentary basins (see next section), (2) reversely magnetized Eocene basalts (for example, the magnetic low near 45°45′N and 123°45′W), and possibly (3) overturned normally magnetized basalts (near R and E in RANGE, Fig. 1).

The most intense magnetic high on the aeromagnetic map (near the T in COAST RANGE, Fig. 1) straddles the Columbia River and may be due to a mafic or ultramafic intrusive body that formed in a northeast-trending zone of extension; strong gradients bound the anomaly, suggesting faulted edges.

Gravity and magnetic data (Finn and others, 1984; Finn, 1990) indicate that the Coast Range rocks form discrete, commonly fault-bounded blocks. Wells and Coe (1985) suggested that the mafic blocks are bounded by northwest- and west-striking thrust faults that formed in response to the north-directed component of oblique subduction of both the Farallon and Juan de Fuca plates. The aeromagnetic data show some of these thrust faults as linear trends. One of these trends is associated with the Doty fault (DF, Fig. 1). Another bounds the southwestern edge of the Chehalis basin (low south of DF, Fig. 1). The westerly trending Seattle fault (south of S, Fig. 1) is visible as a linear sharp gradient truncating a magnetic high on the south.

West of Seattle (S, Fig. 1), positive anomalies correspond to the core of Coast Range mafic crust that forms a rim around the Olympic Mountains. This rim encompasses thick, imbricated nonmagnetic sedimentary rocks of Tertiary and Quaternary age (magnetically quiet area near OM, Fig. 1).

Something Blue: Pull-apart Basins

Late Cretaceous to early Tertiary dextral strike-slip faults formed rapidly subsiding grabens that produce magnetically quiet areas between linear positive anomalies in north-central Washington. Forearc basins in western Washington may also have formed as a result of these dextral strike-slip faults (Johnson and others, 1994, 1996). Steep gravity gradients define the edges of these basins, indicating that they are fault-bounded (Finn, 1990). The basins are not as clearly imaged in the magnetic data, but some do appear as magnetically quiet areas. These include the Seattle (between S and SWIF, Fig. 1), Everett (between SWIF and DDF, Fig. 1), Grays Harbor (low near 47°N and east of 124°W, Fig. 1), and Chehalis (near DF, Fig. 1) basins.

Another important tectonic element in the region is roughly bounded by Mount St. Helens, Mount Adams, and Mount Rainier (H, A, and R, respectively, Fig. 1). This buried element, called the southern Washington Cascades conductor (SWCC), produces an electrical conductivity anomaly that is interpreted to be associated with thick Upper Cretaceous to middle Eocene marine sedimentary rocks, possibly related to

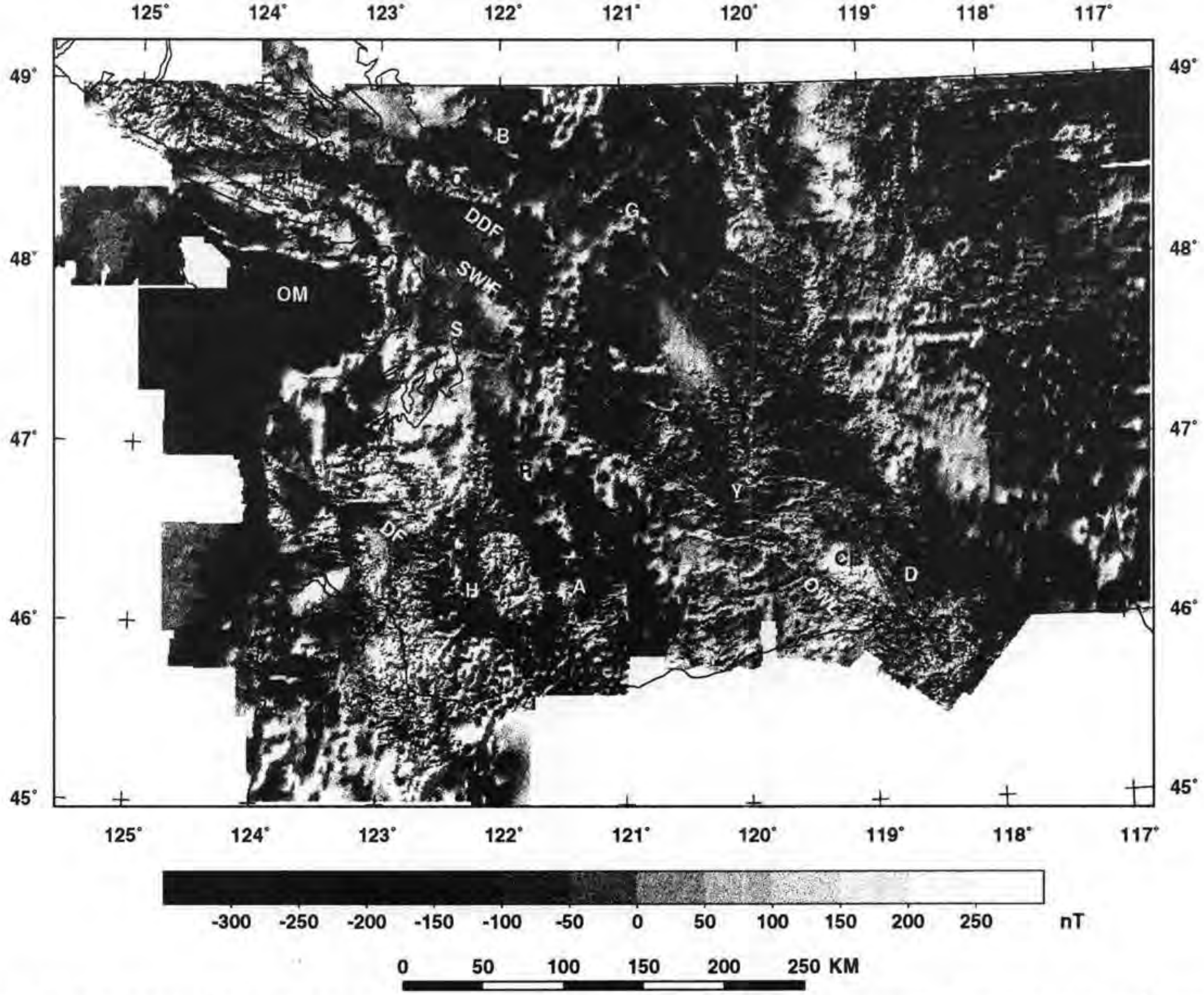

Figure 1. Gray-shaded relief map of the merged aeromagnetic data for Washington. Letters refer to anomalies discussed in the text. A, Mount Adams; B, Mount Baker; CB, Columbia Basin; D, dikes; DDF, Darrington–Devils Mountain fault; DF, Doty fault; G, Glacier Peak; H, Mount St. Helens; I, intrusions; LRF, Leach River fault; OM, Olympic Mountains; O, ophiolite; OWL, Olympic–Wallowa lineament; P, Portland; R, Mount Rainier; S, Seattle; SWIF, South Whidbey Island fault; and Y, Yakima fold belt.

a combination of an accretionary prism/forearc basin complex overlain by sediments deposited in a pull-apart basin (Stanley and others, 1987). A circular magnetic low (ringing H, A and R, Fig. 1) reflects these upwardly arched sedimentary rocks in the SWCC (Stanley and others, 1987).

Something New: Post-accretionary Magmatism

Magmatic products from the Cascade arc have intruded and covered the older basement east of the Coast Range since the late Eocene. Positive magnetic anomalies are associated with exposed and inferred buried plutons (along 121°30′W north of 47°N, Fig. 1) and volcanic rocks (H, R, A, and the intervening area; B and G, Fig. 1) in the Cascade Range.

The geology of southeastern Washington is dominated by the Columbia Basin (CB, Fig. 1), which is covered by basalts erupted between 17 and 6 Ma and filled with Tertiary continental sediments. (See Reidel and others, 1989.) The Columbia Basin is presumably underlain by pre-Tertiary basement terranes. High resolution aeromagnetic data show a set of positive and negative anomalies with a trend of about N25°W (near D, Fig. 1) that correspond to a sequence of reversed and normally magnetized dikes associated with fissures from which basalts erupted (Swanson and others, 1979). The anomalies caused by the dikes align with the north-northwest-trending anomalies at the top of Fig. 1, between 120°15′ and 121°W, that are associated with graben-related faulting. This alignment suggests that the dikes could have formed along pre-existing faults in the pre-Tertiary basement.

Subsequent to dike formation, folds and thrusts developed under north–south compression in the Yakima fold belt (Reidel and others, 1989). The folds cause a fanning set of curving positive and negative anomalies that trend from N60°W to east–west (near Y, Fig. 1) (Swanson and others, 1979). The fold belt is cut by the Olympic–Wallowa geomorphic lineament (OWL) (Raisz, 1945), which is associated with a diffuse zone of anticlines in the central part of the basin. The OWL is similar to other lineaments mapped in the western part of the Basin and Range Province that have been interpreted as right-lateral megashears that accommodate extension and other North America plate interior effects of oblique subduction between the Pacific and North American plates (Reidel and others, 1989). The aeromagnetic data show that part of the OWL (Fig. 1) cuts the dikes in the southeast and transects the central part of the curving set of Yakima folds (Y, Fig. 1). In the aeromagnetic data, the OWL (Fig. 1) continues from the Columbia Basin (through the area marked Y, Fig. 1) until it intersects the eastern end of the Seattle fault (south of S, Fig. 1). There is no expression of the OWL in the aeromagnetic data northwest of this intersection.

RELATION OF AEROMAGNETIC TRENDS TO SEISMICITY

To highlight trends, we calculated the magnitude of the horizontal gradient of the pseudogravity of the aeromagnetic data. The local maxima of the horizontal gradient help locate the edges of tabular bodies or the near-vertical boundaries between rocks of differing magnetizations (Cordell and Grauch, 1979; Blakely, 1995). Figure 2 shows lineaments derived from the location of the maxima of the horizontal gradient of the pseudogravity, and from trends observed in the original magnetic and the gravity data (Finn and others, 1984).

One of the goals of this paper is to examine relations between seismicity and linear trends observed in the magnetic data that may represent individual faults or regional trends in faults. Therefore, recorded earthquakes in Washington from the Pacific Northwest Seismic Network for depths from the surface to 10 km (from Stanley and others, 1997) are plotted with the lineaments (Fig. 2).

Something Old: Reactivated Boundaries

Two prominent northwest-trending bands of seismicity can be observed in south-central Washington. One corresponds to the Mount St. Helens seismic zone (SHZ) (Weaver and Smith, 1983), and the other to the western Rainier seismic zone (WRZ) (Stanley and other, 1996). These bands (Fig. 2) correspond to portions of the ring-shaped magnetic low associated with the SWCC (between H, A, and R, Fig. 1) (Stanley and others, 1987). The SHZ seismicity occurs at the contact of Coast Range basaltic crust on the west with the thick sedimentary rocks in the SWCC on the east. The WRZ occurs in a more continuous magnetic low over sedimentary rocks that have been thrust upward to the near surface. Seismicity in the SHZ terminates at the southeastern edge of a large block of the Coast Range Province represented by a large magnetic high (north of DF, Fig. 1). The seismicity from the SHZ steps eastward across the southeastern margin of this block until it merges with the WRZ and trends north along the terrane boundary between the Coast Range and pre-Tertiary rocks to the east (CRE, Fig. 2).

Small lineaments observed clearly in larger scale color aeromagnetic maps and only faintly in Figure 1 trend northwest from Portland (P, Figs. 1 and 2) across the Columbia River (toward W, Fig. 2) and follow thrust faults between blocks of Coast Range crust. These thrusts developed during major episodes of compression and rotation of the Coast Range during Eocene to Miocene time (Wells and Coe, 1985).

In the Columbia Basin, a cluster of seismicity occurs at an arcuate zone where northwest-trending dikes (D, Figs. 1 and 2) are truncated by the easterly trending folds of the Yakima fold belt (Y, Figs. 1 and 2). Another knot of seismicity occurs farther north where several northwest-trending faults and lineaments (southeast of NC and MH, Fig. 2) intersect the margin of the Columbia Basin.

A linear band of seismicity follows the reactivated Darrington–Devils Mountain fault (Zollweg and Johnson, 1989), as well as the South Whidbey Island fault (Johnson and others, 1996) (DDF, SWIF, respectively, Figs. 1 and 2).

Something New: Cross-cutting Boundaries

Young structures may be represented by a zone of aeromagnetic lineaments trending northeast in the area between Portland and the SHZ that corresponds to a diffuse zone of northeast-trending seismicity (Fig. 2). Northeast trends in the aeromagnetic data and seismicity (Fig. 2) can also be observed in the region between the SHZ and WRZ. These northeast-trending zones of seismicity have been interpreted as stepovers of dextral slip toward the SHZ and WRZ (Stanley and others, 1996; 1997).

A detailed study of the relation between seismicity and faults in the Portland area could not conclusively link specific earthquakes with specific faults, but general correlations could be seen (Blakely and others, 1995). Yelin and Patton (1991) studied seismicity in the Portland area, including a November 6, 1962, M5.2 earthquake. Their preferred focal mechanism indicated normal faulting on northeast- or north-northeast-trending fault planes. Stanley and others (1997) interpret that this mechanism is compatible with northeast-directed com-

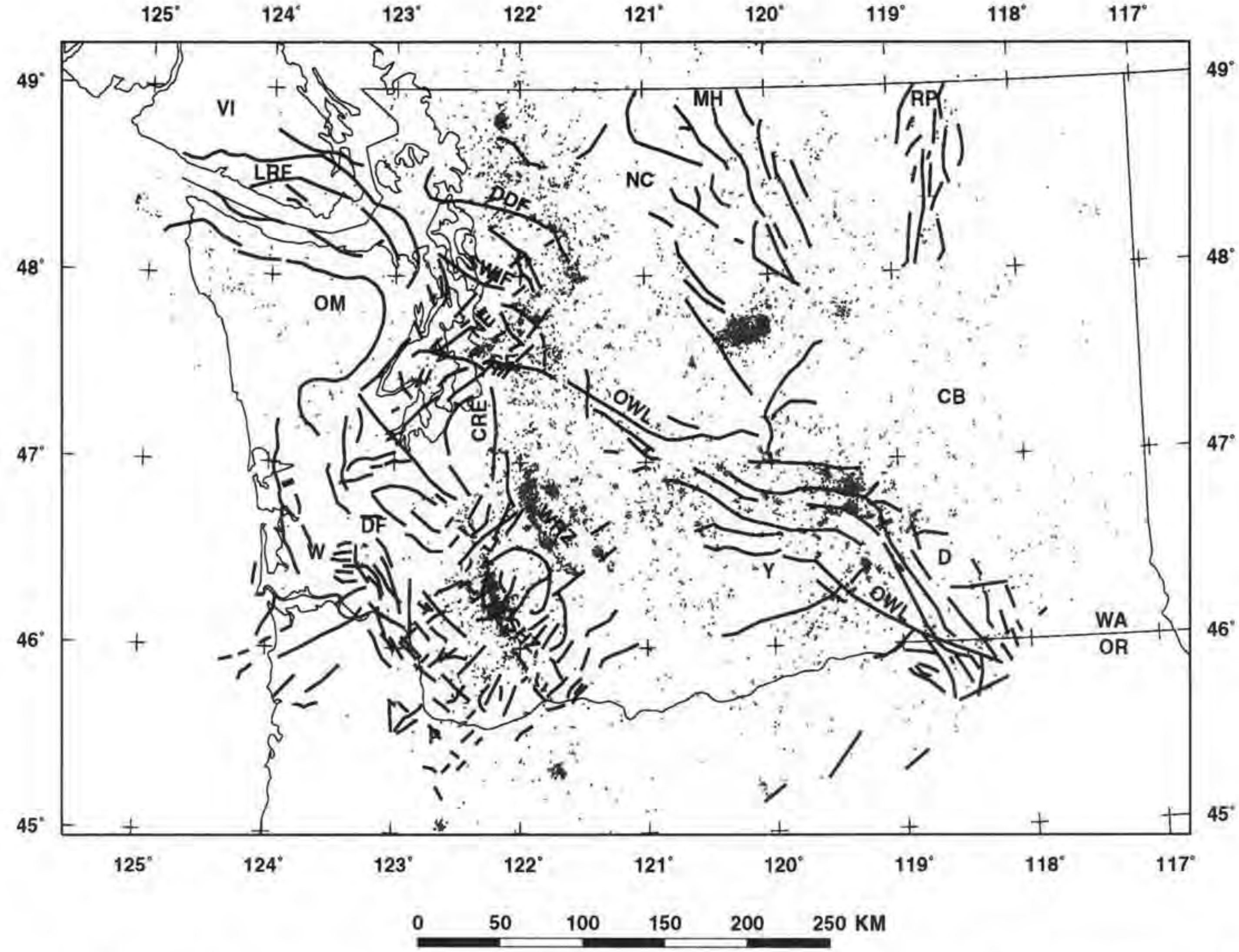

Figure 2. Black lines represent linear features observed in the aeromagnetic data (Fig. 1), the magnitude of the horizontal gradient of the pseudogravity of the aeromagnetic data, and the gravity data (Finn and others, 1984). Gray dots represent epicenters shallower than 10 km depth (Stanley and others, 1997). Abbreviations same as in Figure 1, plus: CRE, eastern boundary of Coast Range rocks; DF, Doty fault; LR, Leach River fault; MH, Methow trough; NC, North Cascades; NE, northeast magnetic trends; RP, Republic graben; SF, Seattle fault; SHZ, St. Helens seismic zone; VI, Vancouver Island; W, Willapa Hills; and WRZ, western Rainier seismic zone.

pression from subduction stress reflected in the seismicity trends (and magnetic lineaments, Fig. 2) in the region between Portland and the SHZ.

An uplifted block of the Coast Range south and southwest of the Seattle fault (southwest of S, Fig. 1; SF, Fig. 2) is imaged as a magnetic high cut by a northeast-trending magnetic low. Subtle northeast-trending lineaments can be observed in the aeromagnetic data north of the Seattle fault in the Puget Sound region (Figs. 1 and 2). The magnetic basement is deeper here than to the south, accounting for the more subtle magnetic signature. There is a northeast grain to several clusters of seismicity in the Puget Sound region. According to Stanley and others (1997), this northeast seismicity trend from the Seattle fault to the Darrington–Devils Mountain is related to strong coupling of the plate and crust in Puget Sound and reflects the direction of maximum compression from the subducting plate. These northeast-trending seismicity features may represent a serious seismic hazard because they may result neotectonic coupling of subduction stress across a matrix of older boundaries (Stanley and others, 1997). New high-resolution magnetic data planned in the Puget Sound region (Blakely, U.S. Geological Survey, written commun., 1997) should provide additional information on locally important features such as the northeast trend of aeromagnetic and seismicity lineaments that crosses the Seattle fault.

CONCLUSIONS

Aeromagnetic data for Washington State provide a complex but coherent image of geologic features that contributes to understanding of the geology and tectonic history. For example, the clarity with which large dikes and folds are revealed in the Columbia Basin provide a resource for new tectonic interpretations. The OWL tectonic feature is well imaged in the magnetic data that, when combined with geologic and other geophysical data, should improve understanding of this feature. The correspondence of northeast aeromagnetic and seismicity trends may have significant implications for understanding seismic hazards in western Washington. The ability to map such fundamental faults in detail in the aeromagnetic data allows correlation of seismicity and neotectonics, which can assist in tectonic studies and hazards assessment.

Acknowledgments

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NPA Elects New Officers

At its May meeting, the Northwest Paleontological Association elected Mike Sternberg as president, Bruce Crowley as vice president, Jan Hartford as secretary, and Jan Freeland as treasurer. Bill Smith, past president, will take on an even more active role as field-trip chairman. The next meeting will be held in July, but because the Burke Museum is closed for renovations, please watch for meeting site announcements. For more information about the association, contact Mike Sternberg at 2208 31st St., Anacortes, WA 98221; *phone:* (360) 293-2405; *e-mail:* mstern@cnw.com.

Wright State Offers Environmental Geophysics Course

Wright State University will present a course on the application of geophysical methods starting September 29, 1997, and January 12, 1998. Offered through its Interactive Remote Instructional System, the course will cover topics such as resistivity, electromagnetics, and gravity and magnetics for the investigation of sites of geological, hydrological, and (or) environmental interest. The course is designed for geologists, engineers, environmental managers, and geophysicists. For more information, contact: Wright State University; Center for Ground Water Management; 3640 Colonel Glenn Hwy, 056 Library; Dayton, OH 45435-0001. *Phone:* (937) 775-3648; *fax:* (937) 775-3649; *e-mail:* IRIS@wright.edu; *Internet:* http://geology.wright.edu/iris.html.

Paleomagnetism of Miocene Volcanic Rocks near Mount Rainier and the Paleomagnetic Record of Cenozoic Tectonism in the Washington Cascades

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INTRODUCTION

Simpson and Cox (1977) were the first to apply detailed paleomagnetic studies to the detection of local vertical-axis rotations in the coast mountains of Oregon and Washington. Since that time, there have been many similar studies of coastal exposures of Tertiary rocks from southern California to British Columbia (summarized in Beck, 1989). In general, pre-Miocene rocks south of about latitude 47°N have anomalous paleomagnetic declinations that indicate that they have rotated clockwise about a nearby vertical axis, perhaps as a result of dextral shear (for example, Beck, 1976). North of 47°N, Paleogene rocks are rotated clockwise (Fox and Beck, 1985), counterclockwise (Symons, 1973a), or not at all (Warnock and others, 1993). Neogene rocks are rotated sharply clockwise in California (for example, Luyendyk and others, 1985) but elsewhere tend to be more nearly concordant (unrotated).

Nearly all Cenozoic rocks of coastal Washington, Oregon, California, and British Columbia have paleomagnetic inclinations that match reference inclinations for stable North America fairly closely. This indicates that, whether rotated or not, they originated close to their present location. This is in striking contrast to Cretaceous rocks from the same area, all of which have anomalously shallow inclinations suggesting large-scale northward displacement (for example, Beck, 1980, 1989; Irving and others, 1996). A slight bias toward shallow paleomagnetic inclinations is found in Paleogene rocks of the Washington–Oregon Coast Range and has been interpreted to suggest northward displacement of a few hundred kilometers (Beck, 1996). In general, north–south relative displacements of less than about 500 km cannot be detected with any confidence by a single paleomagnetic study.

In this article, we review the Cenozoic paleomagnetism of the Washington Cascade Range. We also describe new data from a crucial part of the range. In a final section, we speculate briefly on the tectonic significance of the paleomagnetic data.

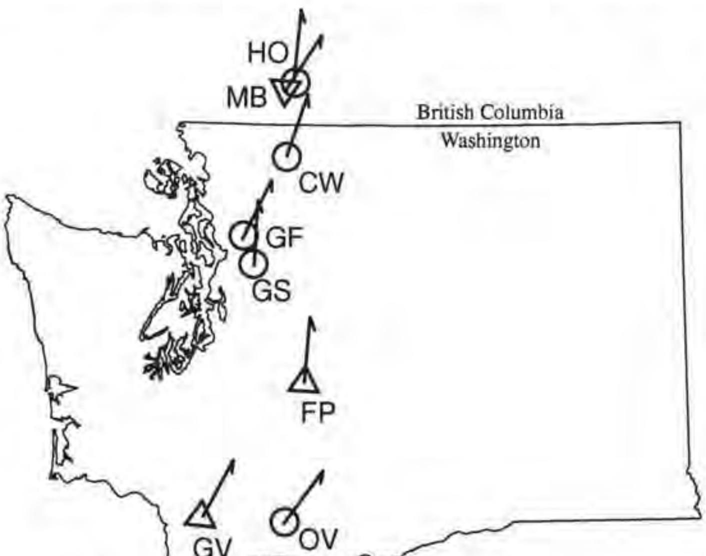

Figure 1. The Tertiary paleomagnetic database for the Washington Cascades. Symbols are identified in Table 1. Rotations are shown by direction of arrows. Circles indicates studies for which no north–south movement is indicated (that is, for which $F_{abs} < \Delta F$). Triangles indicate studies for which $F_{abs} > \Delta F$. If the triangle is upright the paleomagnetic direction suggests northward transport; if inverted, southward transport. By F_{abs} is meant the absolute value of the flattening statistic, F.

CENOZOIC PALEOMAGNETISM OF THE WASHINGTON CASCADES

General Discussion

Figure 1 shows the sampling localities of paleomagnetic studies on Cenozoic rocks from the Washington Cascades; results of these investigations are summarized in Table 1. Included in this compilation are data from eastern exposures of the Goble Volcanics (Wilkinson and others, 1946), which may not be the product of volcanism in the immediate Cascade Range. However, because these rocks are adjacent to the western edge of the Cascades, their tectonic history is relevant to this study. Paleomagnetic results for the western part of the Goble field (Wells and Coe, 1985), which is spatially related more to the Coast Range than the Cascades, are not included in this report.

All entries in Table 1 were recalculated for this publication. Differences (if any) between the directions given in Table 1 and those in the original publication represent the use of more stringent selection criteria or the inclusion of new data. The statistics R and F are rotation and flattening, respectively. As originally defined (Beck, 1980), $R = D_o - D_x$, and $F = I_x - I_o$, where D and I are declination and inclination and the subscripts o and x denote observed values and "expected" values, respectively. Thus D_o and I_o are the values listed in Table 1. D_x and I_x are calculated from the 20–40 Ma reference pole of Diehl and others (1988) or the 20 Ma pole of Harrison and Lindh (1982) and assume a geocentric axial dipole magnetic field.

The statistics R and F are designed to measure relative displacement of potentially allochthonous crustal blocks (Beck, 1980). Values D_x and I_x are calculated for each individual sampling locality as described above. If a particular sampling locality has remained firmly attached to North America (has not been displaced north–south or rotated about a vertical axis), then the observed direction of remanent magnetization ought to be close to the expected direction. If R or F are large,

Table 1. Paleomagnetic studies of Cenozoic rocks from the Washington Cascades. Symbols keyed to Figure 1. **Dec./Inc.**, declination and inclination of remanent magnetization after magnetic cleaning. **N**, number of sites used to compute average directions (number in parentheses is number of specimens in single site); α_{95}, radius of circle of 95% confidence; **R±ΔR**, clockwise rotation and 95% confidence limit; **F±ΔF**, inclination flattening and 95% confidence limit. For **R**, **F**, and their confidence limits, see text. All directions and displacement statistics recalculated by the authors. For most entries the reference pole is taken to be the 20–40 Ma pole of Diehl and others (1988), 81.5N, 147.3E, α_{95} (confidence circle on pole) = 2.4°. For younger rocks (marked with an *), the reference pole used is the 20 Ma pole of Harrison and Lindh (1982), 85.9N, 151.1E, α_{95} = 3.6°

Symbol	Unit	Dec./Inc.		N	α_{95}	R±ΔR	F±ΔF	Reference
GV	Goble Volcanics	17.5°	58.4°	38	4.3°	29.6±7.4	5.3±3.9	Beck and Burr (1979)
OV	Ohanapecosh Formation	28.8°	63.9°	28	4.3°	40.9±8.3	-0.2±3.8	Bates and others (1981)
FP*	Fifes Peak Formation	351.0°	54.1°	31	8.0°	-5.6±14.0	12.4±7.8	This paper
GS*	Snoqualmie and Grotto batholiths	356.5°	68.3°	7	3.2°	2.6±8.2	-2.7±3.4	Beske and others (1973)
GF	Granite Falls stock	181.6°	-67.9°	1(5)	6.3°	14.2±13.8	-2.7±5.3	Beske and others (1973)
CW	Chilliwack batholith	2.8°	65.0°	1(34)	1.5°	15.5±4.0	0.6±2.2	Beck and others (1982)
MB*	Mount Barr pluton	22.0°	75.0°	5	9.8°	28.3±33.2	-8.3±8.2	Symons (1973b)
HO	Hope pluton	358.2°	68.2°	5	4.4°	11.1±10.0	-2.1±3.8	Symons (1973b)

and especially if they exceed their confidence limits, then some displacement (measured with respect to stable North America) may have taken place. Positive R suggests that the sampling locality has rotated clockwise about a nearby vertical axis. Positive F suggests that the sampling locality has been transported relatively northward. Purely longitudinal displacements cannot be detected paleomagnetically.

Factors other than tectonic disturbance can affect R and F; these include undetected tilt, failure to average the geomagnetic secular variation, and failure to properly "clean" the rocks magnetically. An incorrect reference pole also will affect values of R and F. For a discussion of these and other factors affecting the use of paleomagnetic measurements to determine relative block displacements, see Beck (1991).

Discussion of Individual Studies

In this section, we discuss each entry in Table 1. Because it is unpublished, entry FP (Fifes Peak Formation) will be described at greater length in the next section.

GV *Goble Volcanics* (Burr, 1978; Beck and Burr, 1979). Age cited in Beck and Burr (1979) is late Eocene to early Oligocene, based on fossils and K/Ar whole-rock dates. Wells and Coe (1985) date the Goble rocks in their field area at about 39 Ma. Mean directions from the western (Wells and Coe, 1985) and eastern (Beck and Burr, 1979) segments of Goble outcrops agree well. Both polarities are found in the eastern area; N and R mean directions agree at 99 percent probability. A fold test proved inconclusive; scatter decreased upon unfolding, but not enough to be significant statistically. Scatter characteristics are compatible with a proper averaging of nonaxial elements of the dipole field. The eastern Goble field area appears to be rotated nearly 30° with respect to stable North America. This agrees well with the results of Magill and Cox (1980) for roughly contemporary volcanic rocks from the central Oregon Cascades. The Goble Volcanics also show significant (at 95% probability) inclination flattening.

OV *Ohanapecosh Formation* (Bates, 1980; Bates and others, 1981). Calc-alkaline flows and volcaniclastic rocks were sampled. Age probably middle Oligocene (31–37 Ma). Both polarities are present; mean directions are antiparallel at 95 percent confidence. A positive fold test was obtained (Bates and others, 1981), indicating that the rocks were magnetized before folding. The mean declination for these rocks is rotated sharply clockwise with respect to the expected declination. The observed and expected inclinations are essentially identical.

FP *Fifes Peak Formation* (Furlong, 1982; this paper). This will be discussed in the next section.

GS *Grotto and Snoqualmie batholiths* (Beske, 1972; Beske and others, 1973). These two plutons differ slightly in age (Snoqualmie, 15–18 Ma; Grotto, 25–26 Ma), but the difference is small enough so that averaging the two together is acceptable. Of many sites sampled, only seven proved to be magnetically stable, but these include both magnetic polarities and are well grouped. Compared to

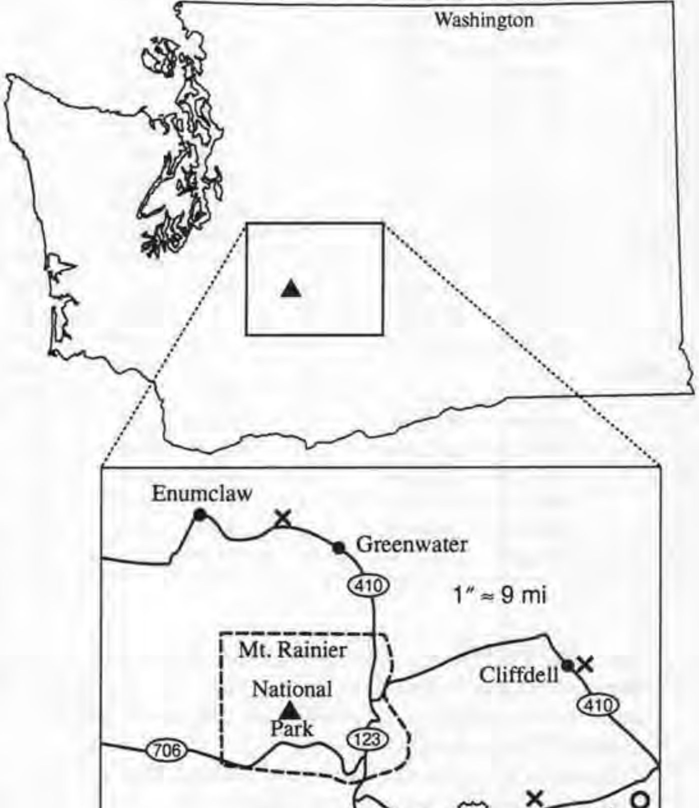

Figure 2. Location of sampling areas for FP. X indicates Fifes Peak Formation sites; Circle indicates Columbia Plateau basalts. For more exact locations, see Table 2.

Table 2. Mean directions of remanent magnetization for sites in the Fifes Peak Formation near Mount Rainier, Washington. **Site no.**, site number; **Lat./Long.**, latitude and longitude of site location; **N**, number of independently oriented samples used to calculate mean direction at each site; **Dec./Inc.**, declination and inclination give site-mean direction after tectonic correction; α_{95}, radius of circle of 95% confidence; *, indicates sites not used to calculate overall mean direction. Sites 34 through 40 are from Columbia Basin basalts

Site no.	Lat./Long.		N	Dec./Inc.		α_{95}
81FP-1*	46°41'N	121°04'W	8	165.6°	-19.3°	3.0°
2*	46°41'N	121°04'W	8	164.9°	-12.9°	3.6°
1,2c			16	165.2°	-16.1°	2.6°
3*	46°41'N	121°04'W	6	145.8°	-38.6°	3.1°
4*	46°41'N	121°04'W	7	147.8°	-41.2°	5.6°
3,4c			13	146.0°	-40.0°	11.9°
5	46°41'N	121°04'W	8	157.1°	-10.3°	5.0°
6	46°42'N	121°02'W	9	313.0°	72.7°	3.1°
7	46°43'N	121°02'W	8	313.0°	38.1°	6.7°
8	46°41'N	121°04'W	7	147.7°	-19.6°	2.2°
9	46°40'N	121°04'W	6	147.9°	-32.1°	2.6°
81FP-10*	46°41'N	121°03'W	7	48.4°	-89.1°	21.4°
11	46°41'N	121°03'W	7	171.9°	-60.9°	4.4°
12*	46°41'N	120°57'W	7	122.9°	-12.9°	7.4°
13*	46°41'N	121°03'W	7	359.7°	-59.2°	21.0°
14	46°41'N	121°03'W	7	302.2°	77.4°	13.3°
15	46°41'N	121°03'W	5	84.1°	-65.8°	8.0°
16	46°41'N	121°03'W	7	336.8°	55.1°	6.0°
17	46°41'N	120°57'W	6	130.2°	-31.2°	5.3°
18	46°41'N	121°00'W	6	195.8°	-30.2°	3.4°
19	47°11'N	121°46'W	7	344.3°	54.0°	5.9°
81FP-20*	47°11'N	121°46'W	6	201.5°	-14.7°	15.6°
21	47°10'N	121°44'W	5	182.9°	-42.7°	8.2°
22	47°10'N	121°44'W	5	196.0°	-65.5°	3.1°
23	47°10'N	121°40'W	7	213.2°	-51.2°	8.9°
24*	47°10'N	121°40'W	6	117.9°	66.2°	37.6°
25	46°55'N	121°03'W	7	7.0°	61.1°	2.5°
26*	46°55'N	121°03'W	7	59.8°	50.9°	1.3°
27*	46°55'N	121°03'W	6	52.8°	48.9°	3.8°
26,27c			14	56.5°	50.0°	11.7°
28	46°55'N	121°03'W	7	350.3°	40.0°	2.3°
29	46°55'N	121°03'W	5	352.7°	50.6°	10.0°
81FP-30	47°00'N	121°12'W	7	20.4°	56.8°	2.6°
31	46°55'N	121°03'W	7	16.5°	55.7°	2.8°
32	46°55'N	121°03'W	7	349.7°	75.1°	13.0°
33*	46°55'N	121°03'W	7	2.2°	57.9°	3.7°
34*	46°55'N	122°03'W	7	2.4°	57.4°	2.6°
33, 34c			14	2.3°	57.6°	2.0°
35	46 43'N	120 51'W	6	330.2°	60.1°	5.9°
36	46 43'N	120 53'W	7	355.0°	37.5°	10.6°
37	46°42'N	120°54'W	6	175.4°	-71.9°	5.5°
38	46°42'N	120°55'W	7	192.5°	-64.5°	2.1°
39	46°42'N	120°55'W	5	185.3°	-56.8°	8.2°
40	46°42'N	120°55'W	6	164.2°	-47.9°	14.7°
41*	46°41'N	121°03'W	7	316.8°	23.1°	70.0°

the 20 Ma reference pole of Harrison and Lindh (1982) these rocks are concordant; that is, there is no paleomagnetic evidence that they have been displaced relative to cratonal North America.

Because GS sites are located in plutons, it is not possible to correct for post-magnetization tilt. (There are no indicators of paleohorizontal, such as bedding.) Because the mean direction is concordant, it probably follows that any post-early-Miocene tilt in this area was of very small magnitude.

GF *Granite Falls stock* (Beske and others, 1973). Age cited as upper Eocene by Beske and others (1973). This study consists of a single site (5 specimens collected over a small outcrop area). It has a single polarity (reverse) and very little scatter (k = 141.2). There is therefore little reason to believe that this study has averaged the geomagnetic secular variation. Postmagnetization tilting also could have occurred and be undetected. R and F values for this body should be regarded with suspicion.

CW *Chilliwack batholith* (Beck and others, 1982). Like the previous entry, this also consists of results from only one site, although, in this instance, 34 samples were collected over a distance of about 2 km. Nevertheless, very low scatter (k = 284) suggests that secular variation may not have been averaged. All samples have reversed polarity. The rocks are Oligocene in age (Misch, 1979). As with GF, R and F values for this study may be unreliable.

MB *Mount Barr plutonic complex* (Symons, 1973b). Radiometric ages cited in Symons (1973b) are middle Miocene. Both polarities are present; that, plus reasonably high scatter, suggest that the geomagnetic secular variation has been averaged properly. Because this unit is a pluton with no paleohorizontal indicators, uncorrected postmagnetization tilting may affect the mean direction. Symons (1973b) regarded results from this pluton as unreliable because they gave a discordant mean direction, but in view of the dozens of discordant directions obtained in the western Cordillera subsequently, we prefer to retain this study, although it is difficult to interpret.

HO *Hope pluton* (Symons, 1973b). Symons (1973b) gives the age of this body as late Eocene to early Oligocene. Both polarities are present. Between-site scatter for the five Hope sites is low (k = 299.2). We take this to mean that slow cooling has averaged the secular variation within each site. It probably does not indicate that the result is unreliable because of failure to average nonaxial-dipole elements of the field. Again, this is a pluton, so no correction could be made for postmagnetization tilt, if any.

PALEOMAGNETISM OF THE FIFES PEAK FORMATION

Samples were collected at 41 sites in volcanic rocks east and north of Mount Rainier (Fig. 2). Included in this study are seven sites from nearby exposures of basalts belonging to the Columbia River Basalt Group (sites 81FP34–40; Table 2). Five or more samples per site were drilled in the field with a portable diamond drill and oriented using sun and magnetic compasses. Most sites were single lava flows exposed in roadcuts. All samples were batch-cleaned in alternating fields ranging from 20 to 60 mT; the demagnetization level for each site was selected after progressive alternating field demagnetization of several representative specimens. Strike and dip were estimated at each site to permit correction for tilt. Site-mean directions, corrected for tilt, are given in Table 2.

It should be pointed out that this study originated as an M.S. thesis performed more than 15 years ago. Accordingly, the laboratory techniques used do not conform to the standards in use today (1997). However, nearly all samples we included in this study had simple, univectorial directions of remanent magnetization, with at most a small present-field overprint. For such rocks, the laboratory methods used are entirely adequate.

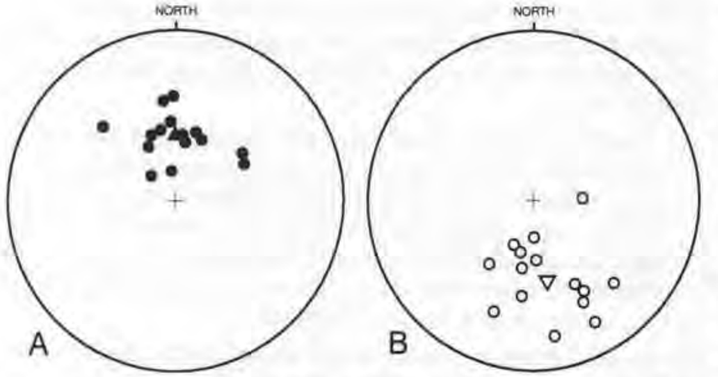

Figure 3. Distribution of site-mean directions for the Fifes Peak Formation (seven sites in Columbia Basin basalts are included). **A**, normal polarity sites; **B**, reverse polarity sites. Equal-area projection; open symbols indicate upper hemisphere. Sites combined in Table 2 are plotted separately.

We employed several arbitrary data-processing procedures to enhance the tectonic significance of the final mean direction. First, in five cases (sites 1,2; 3,4; 12,13; 26,27; 31,32) contiguous flows yielded nearly identical directions. These were combined (for example, 1, 2c, Table 1). Next, all sites with poorly defined site-mean directions (α_{95}>15°) were eliminated. Finally, site 12 diverged from the group mean by more than two standard deviations (50.2°) and was also rejected. Ten sites were eliminated using these criteria. The remaining sites consist of nearly equal numbers of reverse and normal directions; these two subsets (Fig. 3) are antiparallel at 95 percent confidence. Combining these two subsets yields the overall mean direction given in Table 1. A modified fold test (comparing between-site scatter before and after making the tilt correction) gives an inconclusive result; scatter decreases when the tilt correction is made, but not by an amount that is significant at 95 percent confidence. However, there is little doubt that the rocks retain a stable, prefolding magnetization. This is argued by the amount and pattern of between-site scatter (commensurate with proper sampling of the geomagnetic field), and the fact that the normal and reverse subgroups are antiparallel. The paleomagnetic pole corresponding to the mean direction of these rocks is located at 82.0°N, 160.7°E (δp_{95}, 7.7°; δm_{95}, 11.1°).

Rotation and flattening statistics for the Fifes Peak Formation are interesting. From Table 1, rotation is small and counterclockwise. All other Cascade Tertiary results show clockwise rotations, although for entry GS (Grotto and Snoqualmie plutons), the rotation is small and not significant at 95 percent confidence. Even more surprising is the shallow mean inclination recorded by Fifes Peak samples; as shown in Table 1, the statistic F is positive and highly "significant" at 95 percent probability. One way to interpret this result would be to propose that the sampling area has been displaced 1,200 km or so northward, measured with respect to stable North America. This is hardly feasible, however, in view of results from other nearby units. Other explanations need to be considered.

One possible, although unlikely, explanation for the anomalously low inclinations found in the Fifes Peak Formation involves magnetic anisotropy. It is well known that strongly magnetized, sheetlike rock bodies may acquire a direction of thermoremanent magnetization that is slightly different from the direction of the ambient magnetic field. In such cases, the direction is deflected toward the sheet—for example, in the case of a flat-lying lava flow, toward the horizontal. However,

Table 3. Comparison of Tieton and non-Tieton sites. Tieton sites were sampled along U.S. Highway 12, in the southern part of the field area. See Table 1 for explanation of column heads

Group	N	α_{95}	Dec./Inc.		R±ΔR	F±ΔF
Non-Tieton	15	7.2	7.1°	57.8°	13.2±14.1	7.9±7
Tieton	16	12.5	333.8°	46.4°	−19.3±17.2	19.3±11.0

experiment and theory both indicate that the amount of deflection would exceed 1 or 2 degrees only in the case of very strongly magnetized rock bodies. Mineral foliation (planar alignment of inequant magnetic mineral grains) can also produce inclination-shallowing due to anisotropy. However, since the magnetization of the Fifes Peak Formation is not particularly strong, and the rocks themselves are almost entirely unfoliated, we conclude that this explanation is unlikely.

A more likely cause for this anomalously shallow inclination is original dip. Approximately half the sites included in this study (16; referred to hereafter as Tieton sites) were along U.S. Highway 12, where dips tend to be steep and directed toward the north. According to Swanson (1966), U.S. 12 traverses the northern flank of a volcano (his "older volcano") where original dips might be expected to be generally northward. In calculating the mean direction for our sampling sites, we first corrected the mean directions of all sites to the horizontal. This process will yield an incorrect result if *systematic* original dip is present. In particular, it would produce an erroneously shallow mean inclination if original dips were to the north. In studying the paleomagnetism of a volcanic field, the usual practice is to spread the sampling localities over as large an area as possible, in the hope that by so doing, original dip will average to zero. This must not always be the case, however.

We attempted to make allowance for northerly original dip, with little success. The amount of original dip (if any) present in the Tieton section is problematical, and original dips elsewhere in the field area are unknown. If we assume an average northerly original dip of 10 degrees for the Tieton sites, the overall mean becomes D, 349.9; I, 58.5. Displacement statistics for this direction, using the Harrison and Lindh (1982) pole, are: R = -4.0±12.2; F = 7.2±6.3. With these new numbers, rotation is still small and counterclockwise, but F remains fairly large and statistically significant, although it is less than for the earlier calculation.

Another way to attack the problem of original dip is to compare the Tieton sites with all other sites in the study. This is done in Table 3. The two directions are quite different (the difference is significant at 95 percent confidence). The mean direction for non-Tieton sites shows a clockwise rotation that is not quite significant at 95 percent confidence. In this respect, it resembles directions for other Tertiary rocks in the Cascades. However, it still retains the anomalous positive inclination-flattening (F). If the non-Tieton sites represent the true mean Fifes Peak direction, then the average initial dip for the Tieton sites averages nearly 30 degrees to the west. This appears unlikely and suggests that the non-Tieton sites also have significant original dip.

From this discussion, it is clear that we do not know why the Fifes Peak Formation yields such an anomalously shallow mean inclination. Probably a combination of original dip, uneven sampling, anisotropy, and a small amount of northward displacement is responsible. Details of this study can be found in Furlong (1982).

TECTONIC INTERPRETATION OF PALEOMAGNETIC RESULTS

Tectonic interpretation of an individual paleomagnetic study in an orogenic belt can be fraught with danger and uncertainty (as exemplified by the probably spurious inclination-flattening found in our Fifes Peak result). The danger and uncertainty arise because most of the problems that may beset a paleomagnetic study—remagnetization, undetected tilting, anisotropy, etc.—are at their most virulent in orogenic zones. However, *patterns* of anomalous paleomagnetic directions found in *groups* of studies are far safer to interpret. In the case of the Washington Cascades, there are several patterns:

(1) All studies except those for Miocene rocks in the Mount Rainier–Snoqualmie Pass area have large, positive values of R, and all but one are significant at the 95 percent probability level.

(2) There is no clear pattern of inclination-flattening. Five of the eight studies have negative values of F and three have positive values. Of the three values of F that are "significant" at 95 percent probability, two are positive and one is negative.

Note that five of the eight studies are of plutons for which no correction for post-magnetization tilt (if any) could be made, and two of these are single sites that may not have averaged the nondipole elements of the geomagnetic field. With these patterns and caveats in mind, we suggest the following interpretations:

(1) The Washington Cascades have experienced pervasive clockwise block rotations throughout much of Tertiary time. Rotation seems to have been greater in the south than in the north. Rotation was probably driven by north-oblique subduction (Engebretson and others, 1985). Rotation apparently varied from place to place; the entire range did not rotate as a single rigid block.

(2) By Miocene time, rotation had ceased in the Snoqualmie Pass area, and perhaps near Mount Rainier as well, although it remained active to the north (MB) as well as in Oregon.

(3) The region has not moved significantly northward (or southward) relative to stable North America since the Eocene. "Significantly" in this case means more than a few hundred kilometers. Northward displacement was probably impeded by the buttressing effect of the change in trend of the continental margin from north–south to northwest–southeast (Fig. 4). Because of this change, north-oblique subduction was unable to produce northward displacement (Beck and others, 1993)

(4) Tertiary plutons in the northern Cascades have apparently experienced little if any differential tilt. This is argued by the close agreement between paleomagnetic poles for three Eocene–Oligocene plutons (CW, GF, HO). Even though results for two of these are suspect (see above), the three poles agree to within 5 degrees, and the angular standard deviation of the group is only 2.3 degrees. This strongly indicates that there has been no differential tilting of the northern Cascades since middle Tertiary time. An alternative interpretation—that the three plutons have been tilted differentially, then remagnetized parallel to the present dipole field direction—is far less tenable.

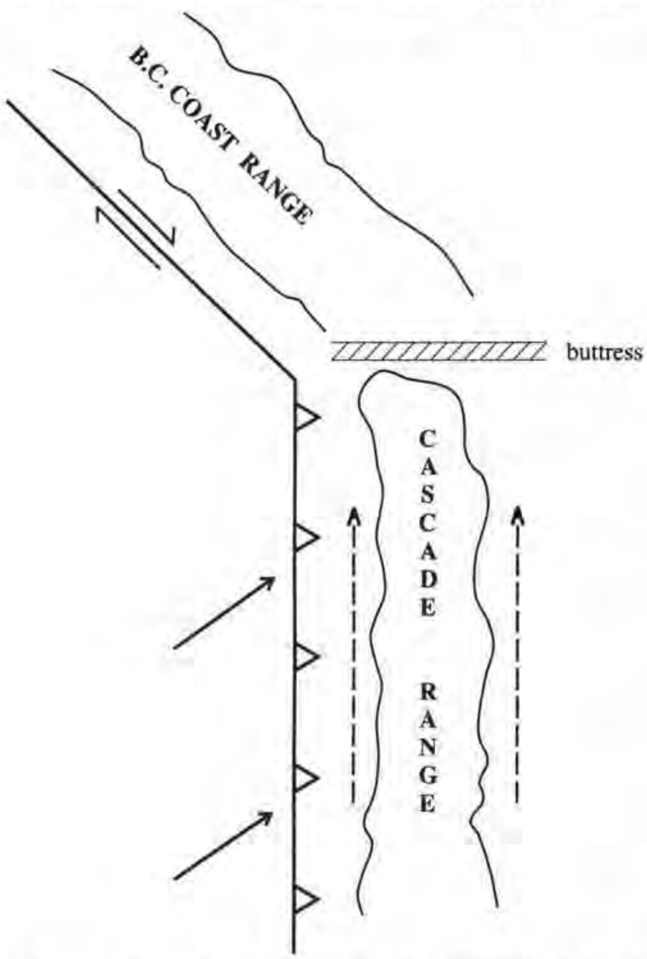

Figure 4. A geometrical buttress prevents northward relative displacement. Oblique subduction provides traction tending to push an outboard sliver of the western edge of the continent relatively northward. However, the leading edge of the sliver impinges on the British Columbia Coast Range which, being opposite a transform, does not move. Northward relative displacement is impeded but *in situ* clockwise rotations can still occur.

The Mount Barr Dilemma

As stated earlier, the direction obtained by Symons (1973b) for the Miocene Mount Barr pluton is hard to interpret. Mount Barr rocks are located only about 30 km southwest of Symons' sampling sites from the older (Oligocene–late Eocene) Hope plutonic complex. Both Mount Barr (MB) and Hope (HO) rocks appear to be rotated clockwise, but the MB rotation is more than twice that obtained for the older Hope plutonic complex (28° vs. 11°). Moreover, although both units have negative values of the statistic F (inclination flattening), the value for HO is essentially negligible, whereas that for MB is large and statistically significant (at 95 percent confidence). It would be difficult to concoct a tectonic history that would permit the Miocene Mount Barr pluton to rotate nearly 30 degrees—and move 800–900 km southward!—while leaving the older Hope rocks comparatively unaffected. However, one possible explanation involves tilt (rotation around a quasi-horizontal axis). Both MB and HO are plutons, so the amount of post-magnetization tilt they may have experienced is unknown. As argued earlier, agreement between the paleomagnetic poles for HO, CW and GF suggests that little differential tilting of these widely separated localities has taken place. If, nevertheless, the Mount Barr pluton has been tilted about 10 degrees to the northwest, its direction of remanent magnetization would be similar to that of the Hope pluton. If this explanation is correct, there must be a major structure separating the MB and HO sampling areas.

CONCLUDING REMARKS

Enough paleomagnetic work has been done on Tertiary rocks in the Washington Cascades to demonstrate that the method is useful, but not enough has been done to make a true first-order contribution to tectonic studies. Paleomagnetic studies are able to detect vertical-axis block rotations that conventional geological studies have completely overlooked. Block rotations are common in the Washington Cascades, but the size of the rotating blocks and the timing of rotation are not known. Paleomagnetic studies in the Cascades show that there have been no large-scale (>500 km) northward displacements since the Eocene, although such large-scale displacements were common in the late Mesozoic. The time at which northward displacements ceased is also not known precisely. Uncertainty remains as to the relationship between the Coast Range, which has probably been displaced northward a few hundred kilometers, and the Cascade Range, which probably has not. The eastward extension of Tertiary rotation also is unknown. These are important questions to be answered. The Western Cordillera is favorably configured to provide a natural laboratory for examining tectonic processes active in zones of oblique subduction. After 25 years of study, the outline of such processes is apparent. Now it is time to concentrate on the details.

ACKNOWLEDGMENTS

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Review of the New Disaster Movie "VOLCANO"

Volcano is a typical disaster movie where the good guy OEM (Office of Emergency Management) director (Tommy Lee Jones) and the lovely geologist (Anne Heche) save Los Angeles from a lava flow. A few minor bad guys get melted (??) by the lava, and there are cutsie side stories of the hero's daughter getting lost, the cool-dude assistant OEM guy really running the show, and race relations in LA getting cooled by fighting hot lava together and all being covered in the same color ash. Actually, some of the lines make the movie almost watchable.

Now for the geotechnical dirt. What's a volcano doing in central LA? OK, suspend disbelief for this. How can the whole thing from start to finish take place in less than a day? OK, so everything goes ultrafast in film. There were still so many other minor to major technical mix-ups, exaggerations, and outright goofs that it is not worth mentioning more than a few that stand out. There are so many explosion-type things (many with back-sucking of fire, steam, and smoke) emanating from ponds, fountains, manhole covers, basements, subway tunnels, and cracks that one should consult an exorcist rather than a geologist. The cause of the volcano here is explained by the lovely geologist as "haven't you heard of plate tectonics" and "there are oceans of molten lava down there and sometimes a crack just opens".

The ridiculous political message is that the building of subway tunnels in LA is the bad and dangerous thing to do because they can cause earthquakes and/or volcanoes, or at least can channel the lava underground from different parts of the city to pop up just where you don't want it. There are gobs of runny red stuff, which never seems to cool, and plenty of volcanic bombs, which pop up individually now and then, whistle as they sail for blocks, explode like an artillery shell, but then sit there glowing red. While some of the scenes of flowing lava look almost real (probably filmed in Hawaii), it usually doesn't act like lava—doesn't cool after traveling for blocks, but then is conveniently tamed by a row of portable concrete freeway barriers and some squirts of water from a fire truck.

Bur enough of this complaining. The OEM dudes are great. Jones does all sorts of hero things, has some good lines, and even gets a ride at the end from the geologist. But the real hero is Emmett (Don Cheadle), the cool-talking assistant OEM director who runs the show from the EOC (Emergency Operations Center). He is the envy of any emergency manager; able to mobilize huge armies of emergency equipment through gridlocked streets to build barricades, dig canals, and topple buildings in only 20 minutes...and tell a few jokes now and then while doing it. The promos bill the lovely geologist as a seismologist. While she doesn't display much seismologic or geologic knowledge, she can run all sorts of fancy and cool, beeping and flashing lava-o-meters, or what ever, and the movie gives her credit for helping to save the city.

Ratings? Overall: "C". While the story and lines are more entertaining than Dante's Peak, the geological bizarreness, often silly special effects, and ridiculous rescues should downgrade it for the geoaudience. In comparison, I rated Dante's Peak a "B".

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The Southeast Quadrant of the Geologic Map of Washington Is Finished!

The map of the southeast quadrant of Washington, the third in our series of 1:250,000-scale full-color geologic maps of the state is hot off the press. GM-45 consists of a map sheet (61 in. x 38 in.), a sheet of explanatory information that includes a 1:625,000 bedrock geologic and tectonic map and a list of named units, and a pamphlet that provides maps showing sources of compilation data and cited references. The envelope features an aerial oblique photo of Palouse Falls. A topographic map at the same scale (our TM-3) is available as well.

The authors, Eric Schuster, Chuck Gulick (of the Department's Northeast Region office), Steve Reidel and Karl Fecht (with Pacific Northwest National Laboratory and Bechtel Hanford Co., respectively) and Stephanie Zurenko (of the Southwest Region office), also prepared the 1:100,000-scale open-file reports on which this map is based. As with the previous quadrant maps, the geologic units are age-lithologic units. Formations are shown only for the Miocene volcanic rocks of the Columbia River Basalt Group, which cover extensive areas in southeastern Washington. The maps and accompanying graphics were prepared by Carl Harris and Keith Ikerd, with assistance early in the process by Nancy Eberle.

The folded map set costs $7.36 + .64 (tax for Washington residents only) = $8, and the flat set (mailed in a tube) costs $9.20 + .80 tax = $10. The topographic map costs $1.85 + .15 = $2 folded, $3.24 + .26 = $3.50 flat. Please remember to add $1 to each order for postage and handling.

The companion quadrants we have released are GM-34 (southwest) and GM-39 (northeast). Folded versions are available for $6 and $8 respectively, flat versions for $8 and $10, respectively. Topographic maps TM-1 (southwest) and TM-2 (northeast), are the same prices as TM-3.

When the northwest quadrant geologic map is prepared it will likely be done by digital methods, largely because the industry is phasing out materials for producing maps by manual methods. We will publish status reports for the northwest quadrant from time to time in this journal.

The Macaulay Creek Thrust, the 1990 5.2-magnitude Deming Earthquake, and Quaternary Geologic Anomalies in the Deming Area, Western Whatcom County, Washington—Cause and Effects?

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INTRODUCTION

The Deming earthquake of April 14, 1990, was the largest earthquake in the Puget Lowland between 1965 and 1996 and was unusually shallow (3–4 km). This 5.2-magnitude earthquake (maximum intensity of VI on the modified Mercalli scale) is the largest shallow crustal quake to occur north of Seattle since 1920. The main Deming shock probably occurred at the base of the Chuckanut Formation (Chuckanut herein) at a depth of about 3 km; aftershocks occurred along conjugate faults at depths less than 3.2 km, many less than 2.5 km (Qamar and Zollweg, 1990; Zollweg and others, unpub. data). Because of their shallow depth, aftershocks smaller than M2.0 were felt in Deming and Van Zandt. Prior to this study, no surface fault mapped near the epicentral region could be correlated with the observed hypocentral pattern (Zollweg and others, unpub. data).

Recent geologic mapping of the Deming 7.5-minute quadrangle (Dragovich and others, 1997a) has revealed that a gently dipping fault directly northwest of the epicenters separates the Chuckanut from the underlying semischist of Mount Josephine on southern Sumas Mountain. Although no surface rupture was observed, we hypothesize that the Macaulay Creek thrust (**MCT**) is the causative structure of the earthquake sequence. We base our conjecture on the apparent correspondence of the surface expression of the MCT, and associated thrust culmination (highest point on the crown of a nappe), with the seismically defined subsurface shallow structure that reveals a south-southwest dipping thrust (ramp) plane. We suggest that the MCT was active during the Quaternary (and possibly before), which may explain the anomalously high incidence of deep-seated landsliding, locally high altitudes of the Everson Interstade glaciomarine drift on geomorphically unusual (structurally uplifted) bedrock terraces, and the occurrences of fluvial sands in the glaciomarine drift.

DEMING QUADRANGLE GEOLOGY, MACAULAY CREEK THRUST, AND SEISMIC DATA

Geologic mapping of the Deming quadrangle, partially shown in Figure 1A, provides new insights into the structure and stratigraphy of the epicentral area of the Deming quake. The MCT separates hanging wall Chuckanut from footwall semischist of Mount Josephine. Miller and Misch (1963) speculated that a west-dipping thrust fault separates Chuckanut from underlying pre-Tertiary bedrock. Johnson (1982) proposed high-angle faults to juxtapose sparse outcroppings of the "Darrington Phyllite" with the Chuckanut on southern Sumas Mountain. A thrust fault contact is suggested by (1) the jointed, weathered, and cataclastic to locally mylonitic aspect of rocks along the contact, (2) the orientation of subsidiary slickenlines (striations) and slickensided planes as well as fractures, (3) the anomalous folding and refolding of the Chuckanut Formation and possibly pre-Tertiary basement adjacent to the thrust (discussed below), and (4) the horizontal to slightly south dip of the contact determined from outcrop pattern. Chuckanut outcrops east and south of the MCT (Loc. I, Figs. 1A, 5A) constrain thrust geometry. (Note the distribution of the semischist of Mount Josephine and Chuckanut and the inferred geometry of the concealed thrust in Fig. 1A, locs. H, J.) Geometrical constraints and Deming aftershock hypocenters suggest a south- to southwest-dipping thrust ramp perpendicular to an eroded east-plunging thrust ramp culmination producing a window into the underlying Shuksan rocks. (See Fig. 5A, loc. K.) Windows may form by simple differential erosion into undisturbed planar faults, but usually they form by erosion through a culmination (for example, ramps or ramp anticline topographic highs; Boyer and Elliot, 1982). The Nooksack River west of Deming has apparently eroded this window.

Maple Falls and Padden Members of the Chuckanut consists of Eocene fluvial to locally alluvial fan deposits (Johnson, 1982, 1984; Dragovich and others, 1997a). The Jurassic semischist of Mount Josephine consists of phyllite with locally abundant serpentinite and is probably a sandy facies of the Darrington Phyllite and is thus part of the Shuksan thrust plate. (See Tabor and others, 1994; Brown and others, 1987.) Displacement between the Chuckanut and semischist of Mount Josephine was probably accommodated by the distinct rock strength discontinuity afforded by the unconformable nature of the contact between the units, as well as by interleaved weak serpentinite in the semischist of Mount Josephine directly below the thrust. (See McKenzie, 1969; Logan, 1979; Logan and Rauenzahn, 1987 for a discussion of rock strength and faulting.)

About 1,800 aftershocks of various magnitudes were associated with the Deming quake. The day after a magnitude 4.8 foreshock on April 2, 1990, three temporary seismic stations were installed and operated for four days. Following the April 14 main shock, a temporary 10-station seismic network was installed within 15 km of the epicenter (for example, Fig. 1A, triangles). This network provided well-constrained hypocenter locations and the most comprehensive thrust-earthquake aftershock data set obtained to date in the Pacific Northwest. Amadi (1992) and Qamar and Zollweg (1990) indicate that the main shock and associated foreshocks and aftershocks probably occurred near the base of the Chuckanut as well as in the underlying Shuksan Metamorphic Suite. Low-angle conjugate

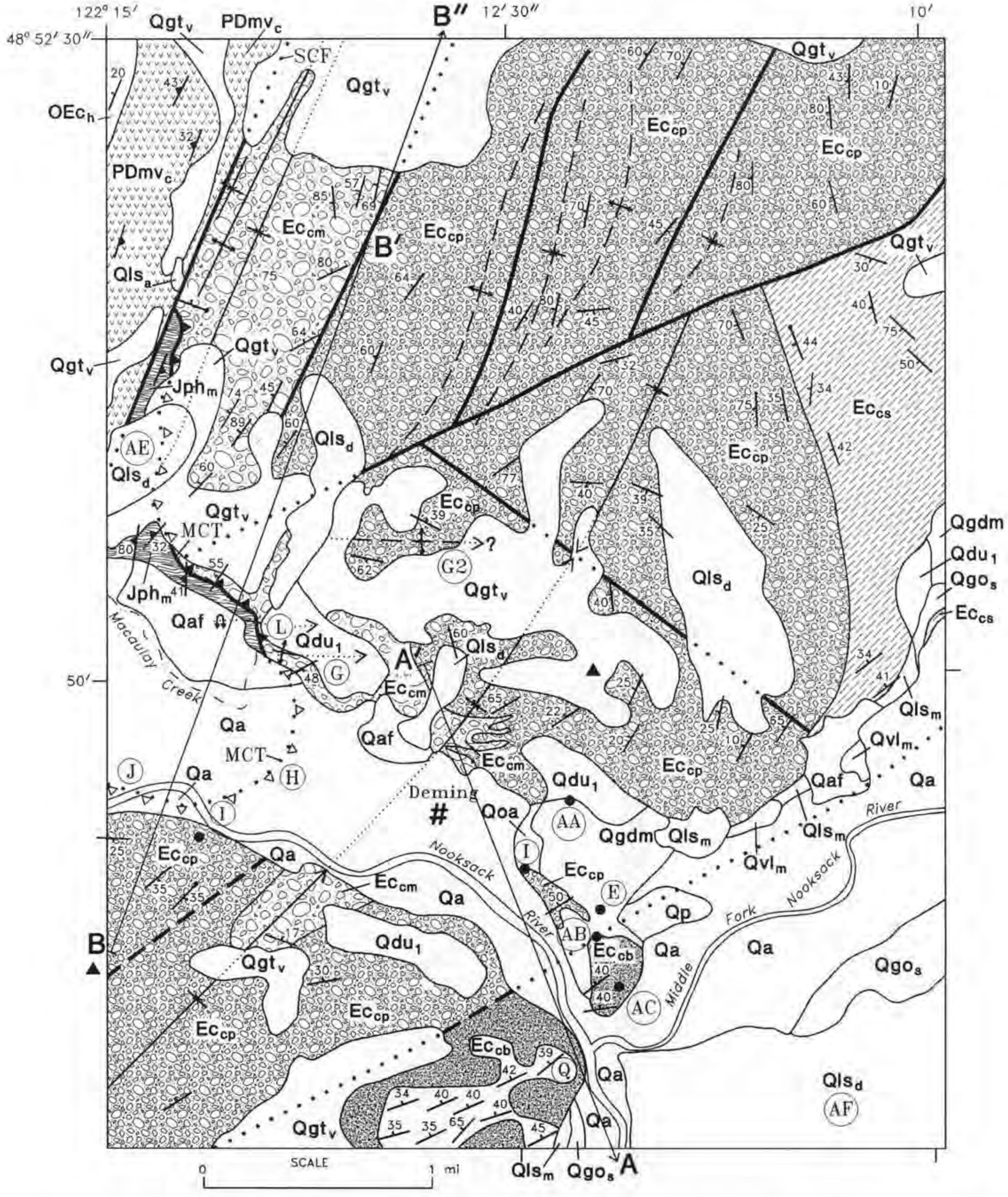


Figure 1A. Simplified geologic map of a portion of the Deming 7.5-minute quadrangle (Dragovich and others, 1997a). Explanation and Figure 1B on facing page. Local map sources for Dragovich and others (1997a) include Miller and Misch (1963), Johnson (1982), Kovenan (1996), Moen (1962), and Easterbrook (1976, directly west of the quadrangle). Point E is the computed location of the main shock on April 14, 1990. SCF, Smith Creek fault. MCT, Macaulay Creek thrust. Circled letters are locations cited in the text. Complete location of cross sections B′–B″ and A–A′ shown on Figure 4;. A–A′ on Figure 2; B–B′ and B′–B″ on Figure 5A and 5B, respectively.

EXPLANATION

Rocks and Deposits

- **Qa** Alluvium (Quaternary)
- **Qoa** Older alluvium and undivided glacial drift (Quaternary)
- **Qp** Peat (Quaternary)
- **Qvl_m** Middle Fork Nooksack River lahar (Quaternary)
- **Qls_a** Debris avalanche (Quaternary)
- **Qls_d** Deep-seated landslide (Quaternary)
- **Qls_m** Mass-wastage deposits (may include local glacial drift), undivided (Quaternary)
- **Qaf** Alluvial fan deposit (Quaternary)
- **Qgo_s** Sumas Stade (Fraser glaciation) outwash (Pleistocene)
- **Qgt_v** Vashon Stade (Fraser glaciation) till (Pleistocene)
- **Qgdm** Everson Interstade (Fraser glaciation) glaciomarine drift, undivided (Pleistocene)
- **Qdu_1** Units Qgt_v and/or Qgdm, undivided (Pleistocene)
- **OEc_h** Huntingdon Formation (Oligocene–Eocene)

Chuckanut Formation (Eocene)

- **Ec_{cm}** Maple Falls Member
- **Ec_{cp}** Padden Member
- **Ec_{cs}** Slide Member
- **Ec_{cb}** Bellingham Bay Member
- **Jph_m** Semischist of Mount Josephine
- **$PDmv_c$** Chilliwack Group metavolcanic rocks (Permian–Devonian)

Geologic Symbols

- Contact
- High-angle fault—Dashed where inferred; dotted where concealed
- Thrust fault—Dotted where concealed; sawteeth on upper plate
- Anticline / Syncline — Upright fold axis in the Chuckanut Formation—Dashed where inferred; dotted where concealed; arrow shows direction of plunge
- Overturned fold axes in the semischist of Mount Josephine—Dotted where concealed; arrow shows direction of plunge
- 75 — Bedding, inclined (no top indicated)
- 42 — Bedding, inclined (sedimentary structures indicate bedding upright)
- 73 — Tectonic foliation
- ▲ Temporary seismometer location

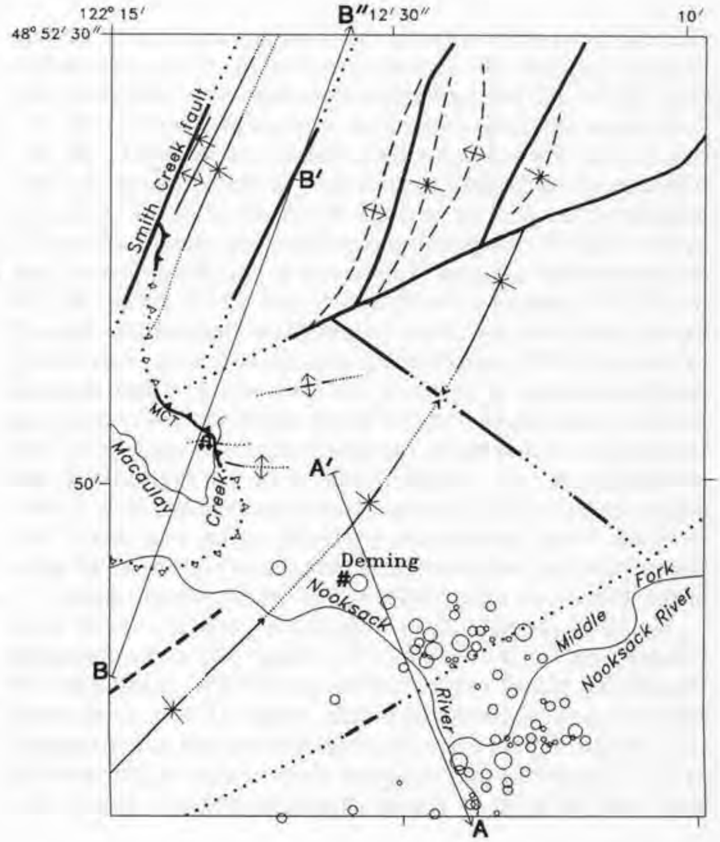


Figure 1B. Deduced from A, showing the location of the faults, major fold axes, and distribution of the best-located aftershock epicenters within the map area. April 14 through 18, most of the quakes occurred to the northwest; after April 18, the majority of events nucleated in the south-southeastern portion of the aftershock zone (Zollweg and others, unpub. data). Furthermore, the foreshocks and main shock occurred in the northwest two-thirds of the epicentral region, as did the regionally recorded aftershocks during the first 9 hr after the main shock (Zollweg and others, unpub. data).

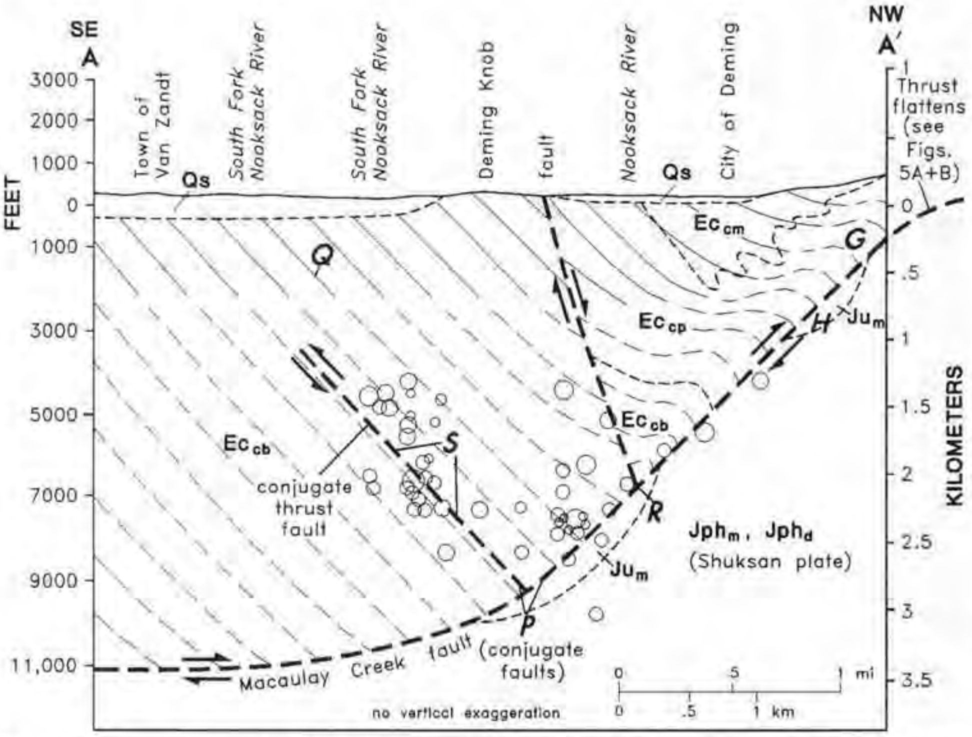


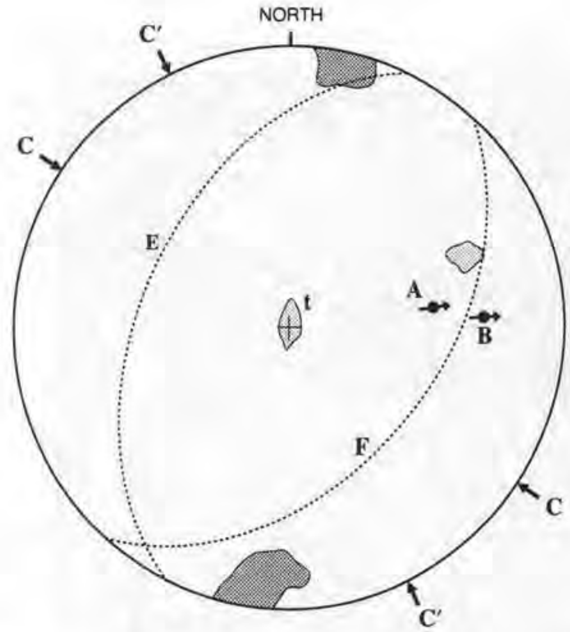
Figure 2. Cross section A–A′ (see Figs. 1 and 4A). Thrust *R* between 1.5 and 3.5 km depth, the hypocenters (circles; size proportional to magnitude), and backthrust (*S*) from Amadi (1992). Hypocenters shown are the best located aftershocks. Bedding (*Q*) inferred at depth. Qs, undivided Quaternary sediments; Jph$_d$, Darrington Phyllite; Ju$_m$, diagrammatically shown locally abundant serpentinite bodies in the semischist of Mount Josephine (inferred to reduce frictional resistance along the MCT); other geologic unit symbols defined in Figure 1. The number of events located on features (*R* and *S*) is biased in favor of the plane dipping to the northwest because the temporary network installation was not completed until April 19, 1990, five days after the main shock (J. Zollweg *in* Amadi, 1990, p. 75). The northwest-dipping plane (*S*) is regarded as the auxiliary plane because most events occurred on this fault after April 18. The intersection of the conjugate planes at location *P* trends N70°E (Amadi, 1992). Amadi reports a 150-m hypocentral error for the best located events.

fault features were interpreted (Zollweg and others, unpub. data) to explain the spatial distribution of the aftershocks (Fig. 2, loc. P). Inferred stress directions were obtained from fault-plane solutions using first-motions of P-waves. The orientations of the conjugate thrust faults are defined by the distribution of earthquake hypocenters in three dimensions. Hypocenter cross-section analysis by Amadi (1992)(Fig. 2) suggests a N20°W compression direction, consistent with the focal mechanism solution. This result is slightly different from the N55°W compression direction and N25°E strike, 46°SW dip for the principal thrust failure-plane orientation obtained by Amadi (1992) and Zollweg and others (unpub. data) using focal mechanism analyses of the main shock. These data are generally consistent with the north–south shallowly plunging slickenlines and roughly perpendicular *small* (amplitude and wavelength of tens of meters) fold axes near Macaulay Creek that record older MCT compressional movements (Fig. 3). Aftershock focal mechanisms generally agree with that of the main shock and indicate nearly pure thrust faulting in all areas of the aftershock zone (Zollweg and others, unpub. data).

Zollweg (unpub. data) obtained a vertical axis of least compressive stress (trend N33°E, plunge 82°) and a conjugate "backthrust plane" (strike N40°E, dip 45°NW) using April 14 main event focal mechanism data. Amadi (1992), using models of Mandl (1988) and following Zollweg and others (unpub. data), illustrated how conjugate thrust faults might develop from back thrusting in a main thrust ramp or as a thrust rides over a basement structure. We note that bedding in the Chuckanut (Loc. Q, Figs. 1A, 2, 4A) parallels the backthrust reverse fault. A reverse fault appears to be consistent with the calculated hypocenters and the character of the recorded seismograms. (We note, however, that this interpretation is not entirely consistent with the ad hoc velocity model derived to locate the events.) We therefore place the back thrusting in the Bellingham Bay Member of the Chuckanut, which overlies the thrust fault (Fig. 2), is generally very thinly bedded, and provides abundant discontinuities for accumulated relief of stress in the overlying plate. Back thrusting could be related to an increase in shear stress off the fault plane caused by the main shock rupture (Das and Scholz, 1981; Hafner, 1951). The majority of early seismic events occurred on the nearly planar, southeast-dipping main thrust (Fig. 2, loc. R), whereas seismicity on a conjugate northwest-dipping backthrust did not develop until about the fourth day after the main shock (Zollweg and others, unpub. data; Qamar and Zollweg, 1990). (The hypocenter cross-section data are biased, however, toward the conjugate backthrust plane due to the earlier development of main thrust hypocenters, later development of backthrust hypocenters, and the delay in temporary seismometer set-up.)

North–south contraction along the MCT is suggested by striations on generally flat slickensided and gouged surfaces near the thrust, the orientation of anomalous folds in the adjacent units (Fig. 3, structural elements A and B), and the general outcrop pattern (Figs. 1A, 2). Striations in the adjacent Chuckanut and semischist of Mount Josephine record the last movements on these planes. (See Rutter and others, 1986, Jaeger, 1959, and Engelder, 1974, for the significance of slickenside striae to seismicity.) Contemporary north-over-south displacement of the MCT is suggested by seismic thrust-plane solutions. General north–south thrust transport is also consistent with contemporary crustal stress directions in the region (for example, Crosson, 1972).

The MCT and associated structures postdate deposition of the late Eocene Maple Falls and Padden Members of the Chuckanut Formation (Johnson, 1984; G. Mustoe, Western Wash. Univ., oral commun., 1996). Fold wavelength in the Chuckanut is typically about a kilometer (Fig. 4A, loc. F). These large, generally tight folds are post-Chuckanut deposition but still Eocene to perhaps Oligocene; the latest Eocene to early Oligocene Huntingdon Formation unconformably overlies the Chuckanut and is only gently folded (Miller and Misch, 1963; Dragovich and others, 1997a and unpub. data). We contend that the large folds are carried in the Chuckanut upper plate and have been heterogeneously slightly refolded and tightened by more recent north-vergent MCT deformation. MCT contractional structures include an anomalous localized Chuckanut anticlinal fold with an amplitude and wavelength



A Average of tight to isoclinal fold axes overturned to the north in the semischist of Mount Josephine directly below the Macaulay Creek thrust (n=8 average)

B Open fold axis of the Chuckanut Formation directly above the Macaulay Creek thrust (determined from n=11 bedding plane measurements)

C Compression direction of the 5.2-magnitude main shock (Amadi, 1992; Zollweg and others, unpub. data) derived from focal mechanism data

C′ Inferred principal compression direction derived from focal mechanism data (Qamar and Zollweg, 1990); approximate compression direction inferred from clustering of hypocentral data (Amadi, 1992)

E Orientation of the 5.2-magnitude (main shock) primary southeast-dipping thrust plane derived from focal mechanism data (Amadi, 1992; Zollweg and others, unpub. data)

F Orientation of conjugate thrust plane developed after the main shock (Amadi, 1992; Zollweg and others, unpub. data)

t Tensional axis (Amadi, 1991)

Maximum data density of fault striations on slickensided fracture planes (5–12% data per 1% area) (n=20)

Maximum data density of poles to slickensided fracture planes and subsidiary fractures (5–6% data per 1% area) (n=25)

Figure 3. Lower hemisphere Schmidt stereonet showing selected structural features in the Deming and Kendall quadrangles. Striation lineations and poles to slickensided fracture planes near the thrust are scattered but show distinct maximum (patterned areas) that are correlated with MCT deformation.

of tens of meters that occurs directly above the MCT (Loc. G, Figs. 2, 5A). To our knowledge, folds of this amplitude and wavelength are nonexistent elsewhere in the Chuckanut. The fold axis has a trend of N85°E and plunges shallowly east, roughly perpendicular to the northward MCT vergence direction as suggested by striations (Fig. 3). Furthermore, the overall orientation of the small fold mimics the orientation of (1) the structural culmination (Loc. H, Figs. 1, 2, 5A) in the Nooksack Valley directly south of the exposed MCT and (2) another probable small fold north of Macaulay Creek (Fig. 1A, loc. G2). Erosion of the culmination, producing the window into the semischist of Mount Josephine at Macaulay Creek probably renders the exposed MCT inactive. This suggests older MCT deformation (quakes?) on the western portion of this structure and younger deformation to the east, as exemplified by the Deming quake.

Rocks adjacent to the MCT are well exposed in Macaulay Creek where the semischist of Mount Josephine displays tight to isoclinal, few-meter-wavelength north-overturned folds (Loc. L, Figs. 1A, 5A). These folds in the semischist plunge moderately to shallowly east and fold a strong mylonitic cleavage (Figs. 3; 5A, loc. L). Hinges are angular to kinked, and some of the fold axial planes appear to be truncated by small faults. Ideally, these folds are related to the youthful north-directed compression along the MCT. However, kinematic analyses of rocks of the Northwest Cascade System in the Kendall and Deming quadrangles is consistent with the overturned style of the folds at Macaulay Creek (Dragovich and others, 1997a; unpub. data). For example, the overturned fold on the cover photo is similar to those at Macaulay Creek, yet occurs in Chilliwack Group rocks well north of the inferred thrust area. Kinematic analyses indicate north to northwest–south to southeast mid-Cretaceous thrust transport consistent with findings of Monger (1966) and Brown (1987) (Fig. 5B, loc. M). We tentatively assign these folds to MCT shear deformation but note that they are probably rejuvenated mid-Cretaceous thrust-related macrostructures that record mostly older strain.

Johnson (1982) estimated the Chuckanut to be about 2 km thick in the epicentral area, consistent with our projected geometry of the MCT to the east (Fig. 2). Also, regional wavelength-filtered gravity data of Finn and others (1991)(Fig. 4C) are consistent with (1) thrust ramping directly south of Sumas Mountain and the MCT culmination and (2) thrust flattening north of the culmination on southern Sumas Mountain (Figs. 2, 5A,B). Additionally, Deming earthquake mislocation bias between the regional network and temporary stations indicates significant lateral velocity variations in the uppermost crust near Deming. Velocities are either higher than assumed to the northeast of the hypocentral region or slower than assumed to the southwest, or both. Pre-Tertiary bedrock under the MCT has significantly higher velocities than does the Chuckanut. We interpret these data as further evidence for MCT ramping under the hypocentral area (Figs. 1A,B, 2). Thinning of the low-velocity Chuckanut due to MCT ramping brings high-velocity pre-Tertiary metamorphic rocks closer to the surface on southern Sumas Mountain, resulting in higher than previously expected velocities.

DISCUSSION

Seismic Hazards and Regional Tectonic Implications

Just a few decades ago, shallow quakes in the Puget Sound region were not believed to clearly correlate with active faults of significant length. As a result, Crosson (1972) suggested that shallow earthquakes in this region resulted from volumetric strain processes that did not favor development of master fault systems. However, this and other studies (for example, Johnson and others, 1996, 1994; Gower and others, 1985; Zollweg and Johnson, 1989; Rogers and others, 1991, 1996) show that shallow crustal earthquakes can be correlated with significant surface structures. Regional geologic evidence

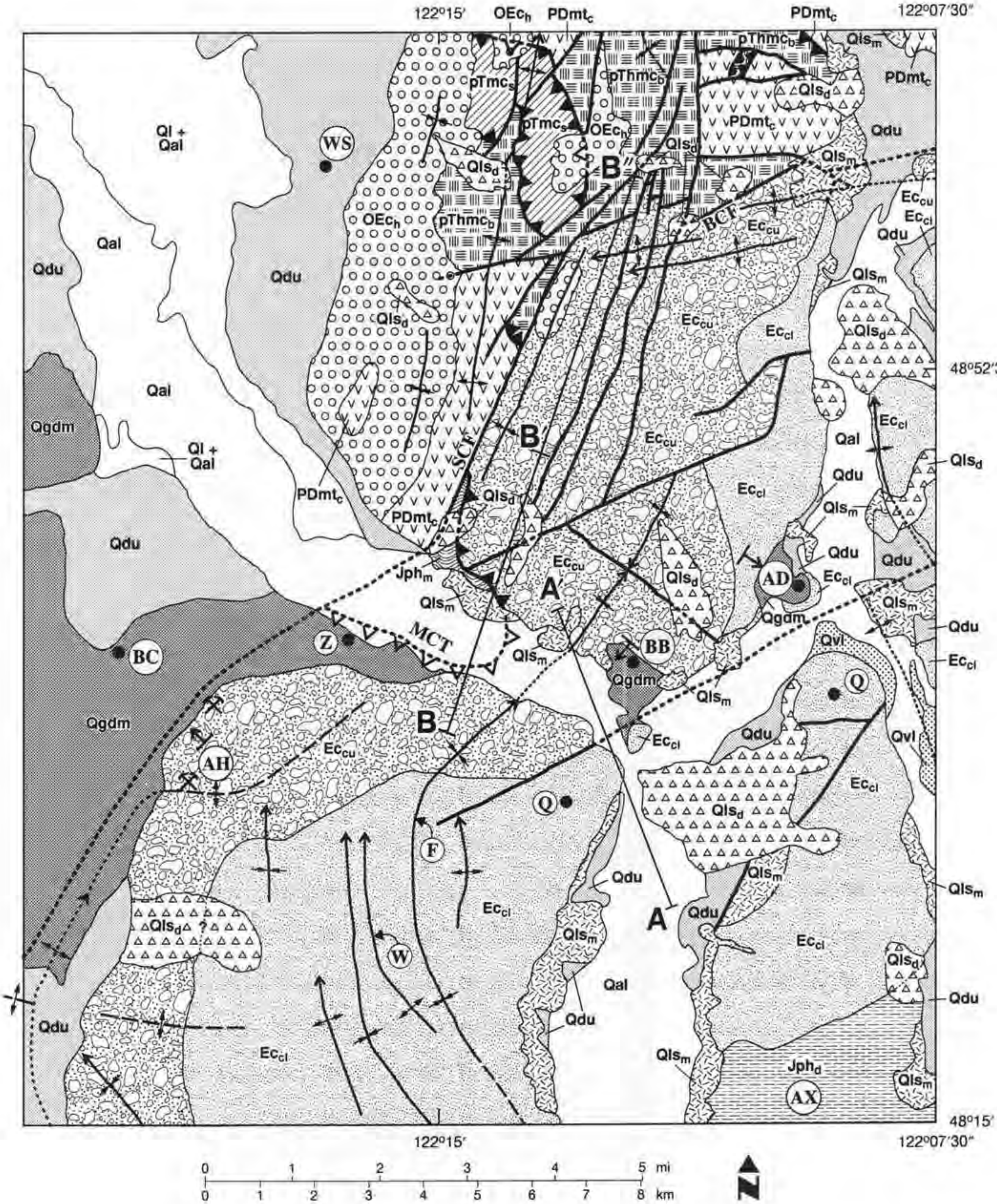


Figure 4A. Simplified geologic map of the Deming and south one-third of the Kendall 7.5-minute quadrangles and area to the west of the quadrangles; compiled from Dragovich and others, 1997a; Jenkins (1923); Easterbrook (1976); Johnson (1982); Miller and Misch (1963); K. Schmidt, Univ. of Wash., unpub. data; Cameron (1989). BCF, Boulder Creek fault; MCT, Macaulay Creek thrust; SCF, Smith Creek fault. Circled letters are locations cited in the text. Cross section locations: A–A′ (Fig. 2), B–B′ (Fig. 5A), and B′–B″ (Fig. 5B). An unconformable contact between the Darrington Phyllite and Chuckanut Formation is shown in the southeast corner of the figure. Also note the thrust faults between the Chilliwack Group and the Bell Pass mélange. Shuksan plate rocks such as the Darrington Phyllite tectonically overlie the Bell Pass mélange, indicating substantial Eocene dip-slip displacement on the Smith Creek fault and Boulder Creek fault. (See Fig. 5B.) Refolded fold axes (for example, southwest corner) may be related to post-Eocene north–south compression along the MCT.

EXPLANATION

Rocks and Deposits

- **Qal, Ql** — Alluvium and lacustrine deposits (Quaternary) (S. Kahle, USGS, written commun., 1997)
- **Qal** — Alluvium (Quaternary)
- **Qdu** — Vashon and Sumas Stade glacial drift, undivided (Quaternary)
- **Qls_m** — Alluvial fans and mass-wastage deposits, undivided (see Fig. 1) (Quaternary)
- **Qls_d** — Deep-seated landslide (Quaternary)
- **Qgdm** — Glaciomarine drift, undivided (locally contains Deming Sand) (Quaternary)
- **Qvl** — Middle Fork Nooksack River lahar (Quaternary)
- **Ec_{cu}** — Upper Chuckanut Formation (Eocene)
- **Ec_{cl}** — Lower Chuckanut Formation (Eocene)
- **OEc_h** — Huntingdon Formation (Eocene–Oligocene)
- **$pTmc_s$** — Metaconglomerate of Sumas Mountain of Dragovich and others (1997a) (pre-Tertiary)
- **$pThmc_b$** — Bell Pass mélange, undivided (pre-Tertiary)
- **Jph_d** — Darrington Phyllite (Jurassic)
- **Jph_m** — Semischist of Mount Josephine (Jurassic)
- **$PDmt_c$** — Chilliwack Group metavolcanic rocks (Permian–Devonian)

Geologic Symbols

- Contact—Dotted where concealed
- High-angle fault—Dotted where concealed
- Thrust fault—Dotted where concealed; sawteeth on upper plate
- Anticline—Dashed where inferred, dotted where concealed; arrow shows direction of plunge
- Syncline—Dashed where inferred, dotted where concealed; arrow shows direction of plunge
- Location of mines used by Jenkins (1923) to constrain fold AH geometry
- ~180 m altitude glaciomarine drift

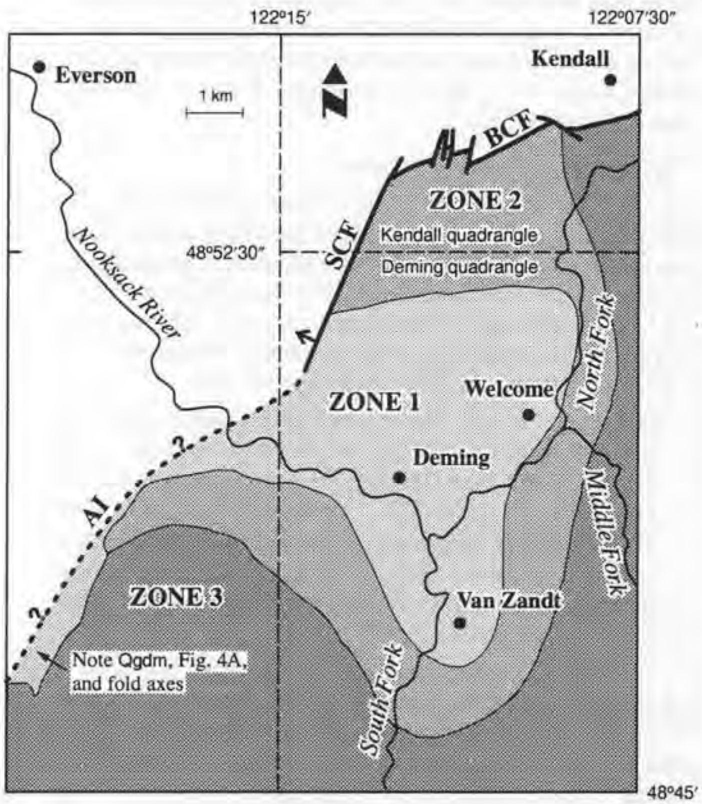


Figure 4B. Same area as in Figure 4A, here showing geographic features and qualitative assessment of evidence of the direct, indirect, or inferred displacement on the MCT. Inferred boundaries of the MCT are all or part of the Boulder Creek fault and Smith Creek fault. Direct and indirect evidence for the extent of the upper plate of the MCT cited in text. AI, inferred extension of the Smith Creek fault based on the westerly dip of the fault along its southern end (Miller and Misch, 1963) and distribution of anomalous fold axes. Zone 1, Direct or indirect seismic and other geologic evidence for active and Quaternary displacement on the MCT and associated structure; Zone 2, indirect or inferred geologic evidence for post-Eocene to Quaternary displacement on the MCT; Zone 3, Possible geologic evidence for post-Eocene to Quaternary displacement on the MCT.

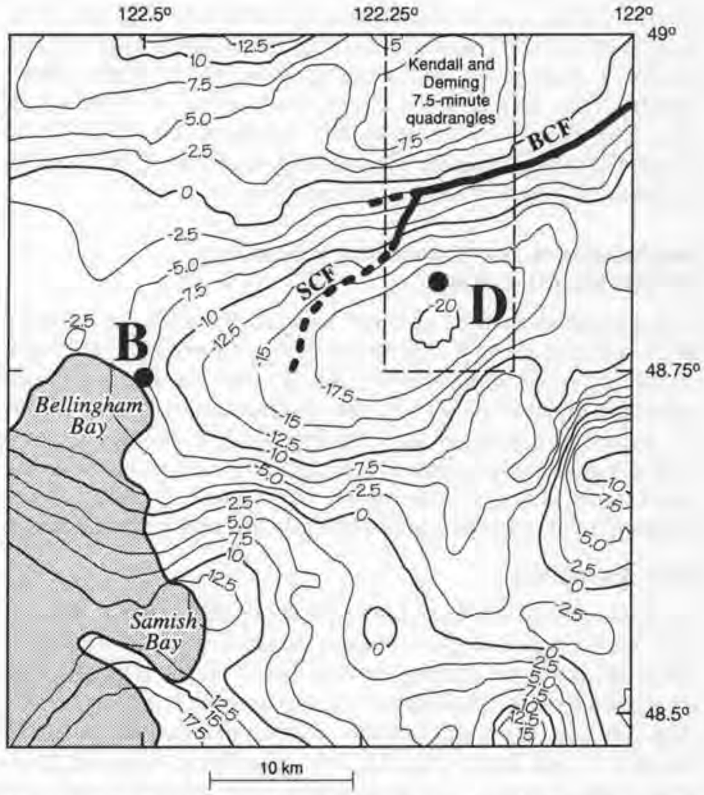


Figure 4C. Residual wavelength gravity anomaly ("upper crustal gravity") of the region. B, Bellingham; D, Deming; BCF, Boulder Creek fault; SCF, Smith Creek fault and southern extension. Tapered gravity anomaly south of the Boulder Creek fault is consistent with the shallowing of relatively dense pre-Tertiary bedrock south of the Boulder Creek fault. Gravity contours in milligals.

(Tabor, 1994), crustal-level focal mechanisms, some geodetic data, *in-situ* borehole measurements (Werner and others, 1991), and seismic data (Ludwin and others, 1991; Thomas and others, 1996; Ma and others, 1996) indicate the Puget Lowland is in a domain of north–south compression. These data suggest that Pacific–North American plate interaction is the dominant driving mechanism, not Juan De Fuca–North American plate interaction (Crosson, 1972; Yelin and Crosson, 1982; Zollweg and Johnson, 1989).

Correlation of the Deming quake with the MCT structure at depth (Fig. 2) suggests that (1) the foreshocks and main shock generally occurred on or near the projection of the MCT where a thrust ramp separates the Chuckanut and Shuksan plates, and (2) the later aftershock sequence occurred *in* the Chuckanut, probably along bedding-parallel fault(s). We differ here most significantly from Amadi (1992), who speculated that the Shuksan thrust (Fig. 5B, loc. T), which underlies the Shuksan plate, may be involved in the quake. However, we support his secondary contention that the Chuckanut–Shuksan unconformity was the locus of primary displacement.

The Eocene Smith Creek and Boulder Creek faults are basin-boundary normal faults that controlled deposition of the upper Chuckanut, including the Maple Falls Member (unit Ec_{cm}). The Maple Falls Member contains clasts derived from the adjacent Chilliwack Group and ultramafic rocks of the Bell Pass mélange (Johnson, 1982, 1984; Moen, 1962; Miller and Misch, 1963; G. Mustoe, oral commun., 1996; Dragovich and others, 1997a). The Smith Creek fault and faults of similar trend displace and thus are at least partly younger than the west-trending Boulder Creek fault (Dragovich and others, 1997a). On the basis of indirect geologic evidence (below), we suggest that the MCT has a wider areal extent than indicated by surface exposures and correlated seismicity (Fig. 4B). Projection of the MCT to the west (Fig. 1) and north suggests that the MCT intercepted and utilized the older and higher angle Smith Creek and Boulder Creek faults (Loc. V, Figs. 4A,B, 5B). This inference kinematically connects the MCT, Smith Creek fault, and Boulder Creek fault, implying that these interconnected structures may not be extinct.

Implications for Quaternary Geology of the Deming Area

Correlating structures defined seismically with the exposed MCT and postulating that this zone may have been intermittently active during (before?) the Quaternary sheds light on some geologic anomalies in the Deming area. These include (1) anomalous folds in the Chuckanut, (2) numerous Quaternary mass-wasting features, (3) high altitudes of the Everson Interstade glaciomarine drift, (4) certain aspects of the Deming Sand, and (5) geomorphically unusual bedrock knobs.

Fold Anomalies

Anomalous fold orientations and refold patterns in the Chuckanut may be due to post-Eocene displacement on the MCT. These folds are not consistent with either (1) the typical northwest trend of the formation (for example, Johnson, 1982) (Fig. 4A, loc. W) or (2) Eocene *extension* along the Smith and Boulder Creek faults (Fig. 5B, loc. X). (These folds are compressional features, not monoclines that are commonly observed adjacent to listric normal faults.) At least two large tight folds parallel the Boulder Creek fault (Fig. 5B, loc. Y). These folds indicate compression *after* Eocene extensional faulting and deposition of the upper Chuckanut. These anomalous fold orientations may be the result of (1) deflection of strain by more competent pre-Tertiary bedrock opposite these faults and/or (2) Tertiary displacement along the MCT or similar decollement structure. Chuckanut folding, which is generally tight, is probably post-Eocene because the latest Eocene(?) to early Oligocene Huntingdon Formation unconformably overlies the Chuckanut, probably onlaps the Boulder Creek fault, which is at least partly synchronous with the upper Chuckanut, and displays only open folds (Miller and Misch, 1963; Dragovich and others, 1997a). Permissible north to northwestward MCT displacement and compression and transfer of strain to the Boulder Creek fault (and Smith Creek fault?) may have tightened these structures. In support of this contention, we note the subparallelism of open east–west folds (Fig. 1A, loc. G; Fig. 3) directly above the MCT with the larger tight folds next to the Boulder Creek fault (Loc. Y, Figs. 4A, 5B). Also, we note the parallelism of the Boulder Creek fault, MCT, and active structures such as the east–west Seattle fault, where reverse fault ramp anticlines (with local overturned bedding) in adjacent rocks imply young, large strains associated with north-vergent Quaternary deformation. Furthermore, we speculate that the large northwest-trending fold axes, which appear refolded as they enter the inferred MCT upper plate area (for example, Fig. 4A, loc. F), may have been rotated during post-Eocene movement on the MCT. That is, these fold axes may be locally rotated to a position almost perpendicular to the inferred MCT maximum compression direction as a result of north to northwest displacement of the upper plate Chuckanut. (See, for example, Fig. 4A, loc. AH, fold axis of Jenkins, 1923).

Glaciomarine Drift Anomalies

The Everson Interstade of the Fraser glaciation began with marine incursion during retreat of the Puget glacial lobe. The maximum altitude of the resultant blanket of generally gravelly clay to clay glaciomarine drift in the northern Puget Lowland (Easterbrook, 1963; Armstrong and others, 1965) increases to the north as a result of greater postglacial isostatic rebound. Dethier and others (1995) state that

> "inflections in the northward rise of marine limit and resubmergence at about 12.3 ka at several sites, best exemplified by the Deming locality (Mathews and others, 1970; Clague, 1981; Easterbrook, 1962, 1963, 1992), suggest complexities in the generally smooth record of emergence. Inflections in the marine limit may reflect postglacial tectonism, stillstands during ice-retreat, or incomplete data."

The Deming Sand type locality provides the best stratigraphic evidence for anomalous emergence (Easterbrook, 1976) (Fig. 4A, loc. Z). Exposures and ^{14}C ages suggest that a zone of unknown areal extent emerged and submerged following the initial marine incursion at about 13.5 ka and prior to final emergence during the Sumas glacial readvance at about 11.0 ka (Easterbrook, 1963; Kovenan and Easterbrook, 1996a,b). At the type section, the *marine* Bellingham glaciomarine drift overlies the *fluvial* (subaerial) Deming Sand, which overlies the *marine* Kulshan glaciomarine drift (Easterbrook, 1976). Easterbrook and Kovenan (1996b) indicate that (1) glaciomarine drift reaches elevations of 180 to perhaps 200 m (~600–690 ft) (Fig. 1, locs. AA, AB; Fig. 4A, locs. Z, AD, BB) above present sea level, about 30–70 m anomalously high using Dethier and other's (1995) contour plot of the

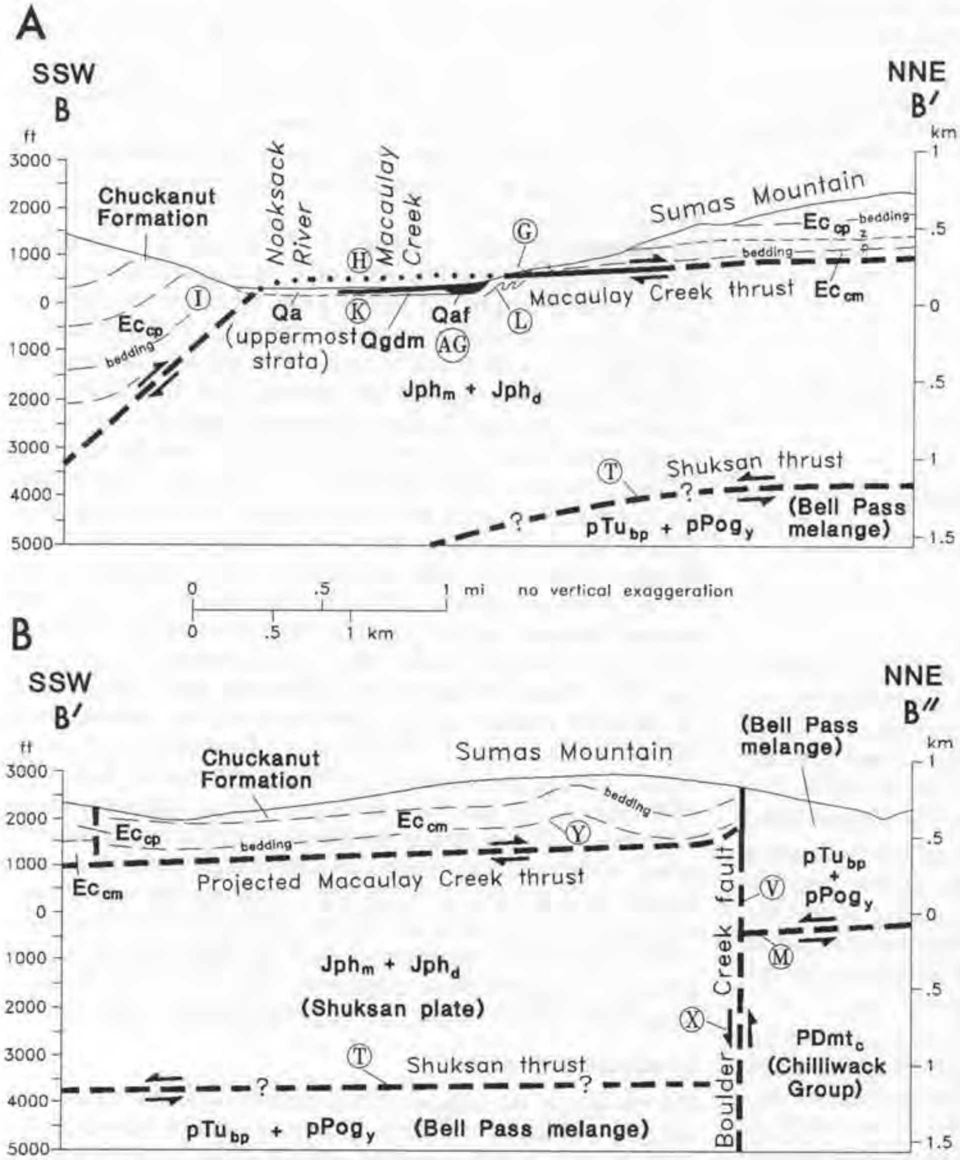


Figure 5. Cross sections B–B′ (**A**) and B′–B″ (**B**). Circled letters are locations cited in the text. See Figures 1 and 4A for locations. Geologic unit symbols defined in Figures 1 and 4A captions; pTu_{bp}, ultramafite of the Bell Pass mélange (pre-Tertiary); $pPog_y$, Yellow Aster complex of the Bell Pass mélange (pre-Permian); $PDmt_c$, Chilliwack Group metavolcanic and metasedimentary rocks, undivided (Permian–Devonian). Miller and Misch (1963), Dragovich and others (1997a), and Johnson (1982) map Shuksan Suite rocks below the Chuckanut on southern Sumas Mountain. Substantial (Eocene) dip-slip displacement on the Smith Creek fault (see Fig. 1) and Boulder Creek fault (Fig. 5B) is required to juxtapose Shuksan plate rocks against the rocks of the Chilliwack Group and Bell Pass mélange. Chilliwack and Bell Pass mélange thrust plates occur structurally lower in the Northwest Cascade System thrust stratigraphy. (See Brown and others, 1987; Tabor and others, 1994). The MCT is inferred to intercept and transferred movement to the Boulder Creek fault (and Smith Creek fault, not shown). Note folds (Y) next to the Boulder Creek fault.

maximum marine limit, and (2) the magnitude of uplift[1] and marine submergence suggests tectonism as the main causative force. Using evidence from geophysical models, Booth (1987) concluded that the magnitude of a crustal ice-marginal bulge was too small to explain the Everson Interstade field relations at Deming.

The strong evidence for fluvial deposition at the Deming Sand foothill type section includes peat and *in-situ* stumps (Fig. 4A, loc. Z) (Easterbrook, 1963; Kovenan and Easterbrook, 1996a). This contrasts with the intertonguing of sand and gravel and glaciomarine drift as well as local probable ice-margin-induced folding and faulting of the glaciomarine drift sand occurrences in the lowlands northeast of Bellingham and to the west of the study area. (See Croll, 1980, and Table 1 for further differences.) Foraminifera and macrofossil data (Balzarini, 1981) support Croll's (1980) interpretation of a marine origin for the "Deming Sand" at Bellingham Bay and a fluvial origin for the Deming Sand at the type locality along the Nooksack River (Balzarini, 1981). Elsewhere in the north half of the Puget Lowland, interlayered thick sand/gravel units in glaciomarine drift are very commonly correlated with ice-marginal marine to deltaic sediments (Carlstad, 1992; Dethier and others, 1995; Domack, 1982, 1983, 1984; Thorson, 1989; Pessl and others, 1989); they are similar to ice marginal glaciomarine deposits worldwide (for example, those observed in Alaska; Powell and Molnia, 1989). Furthermore, probable Everson-age "outwash" mapped by Wunder (1976) in the lowlands portion of the Skagit Valley contains many large marine bivalves dated at 11,330 ±70 yr BP (Robinson, pers. commun. to Siegfried [1978]). Correlation of lowland occurrences of sands in glaciomarine drift (for example, Easterbrook, 1976, 1963) with submarine ice-marginal outwash depositional facies in a marine environment as suggested by Croll (1980) may isolate the fluvial Deming Sand occurrences and explain the "yo yo effect" of Easterbrook (discussed in Kovenan and Easterbrook, 1996a). These differences between Puget Lowland and the Cascade foothill "fluvial" sand/gravel (sand) units of Easterbrook's (1962, 1963, 1976) Deming Sand may be explained by the position of the foothill exposures of the unit on the upper plate of the MCT as shown in Figures 1A and 4A (locs. AB and Z, respectively). In this model, late Pleistocene thrust-displacement-induced uplift along the MCT may have resulted in a transition from marine to fluvial conditions on the MCT upper plate. (Note the uplift effect of the conjugate ramp and backthrust structure in Fig. 2 [locs.S, P, R] below the Deming knob.) Some extensional subsidence following thrusting and/or a continued sea-level rise resulted in a return to marine conditions and deposition of glaciomarine drift on the Deming Sand.

[1]A 30-m tectonic anomaly is similar to the late to post-glacial uplift (7–20 m) along the Seattle fault (Bucknam and others 1992; Thorson, 1989).

Table 1. Summary of evidence used as a basis for distinguishing between marine and fluvial hypotheses for the Deming Sand of Easterbrook, 1962 (from Croll, 1980)

Test	Type section (MCT upper plate)	Other sections (west of MCT upper plate)
Outcrop stratigraphy	3*	1*
Subsurface stratigraphy	not applicable	2
Configuration of top of Deming Sand	not applicable	2
Glaciomarine drift isopachs	not applicable	2
Pebble counts	not applicable	2
Sand mineralogy	3	2
Paleocurrents	4	2
Peat	5	not applicable

*Ranking of evidence is as follows:
1 – Strongly supports marine hypothesis
2 – Tends to support marine hypothesis but not conclusive
3 – Ambiguous or data are conflicting
4 – Tends to support fluvial hypothesis but not conclusive
5 – Strongly supports fluvial hypothesis

We note here a few observations that appear to support a tectonic explanation of the Everson-age anomalies on our MCT upper plate. "The Deming Sand consists almost entirely of phyllite grains" (Easterbrook, 1994). The closest outcroppings of Darrington phyllite (Fig. 4A, loc. AX) are about 8 mi upstream of the Deming Sand type section. We suggest that:

(1) The phyllitic clasts in the Deming Sand are locally derived. Darrington Phyllite is too far upstream, readily degrades upon transport, and would be significantly diluted by newly exposed, easily eroded, and areally extensive glacial deposits and Chuckanut rocks, which dominate the outcroppings around the type section (Fig. 4A); and

(2) The abundant phyllitic clasts in the Deming Sand are due to local uplift and erosion of the semischist of Mount Josephine, which is both phyllitic and a lithologic facies variant of the Darrington Phyllite. (It would be very difficult to distinguish disintegrated Darrington Phyllite from semischist of Mount Josephine using normal visual methods). The abundance of phyllitic debris in the Deming Sand may provide direct evidence of basin instability resulting from MCT-generated uplift. In this scenario, semischist of Mount Josephine emerged and eroded resulting in the semischist-bearing Deming Sand. (Note inferred location of semischist of Mount Josephine directly under the Deming type section [Fig. 4A, loc. Z].)

Western Sumas Mountain (Fig. 4A, loc. WS) is draped by Vashon till and Sumas deposits but lacks elevated glaciomarine drift. This suggests a spatial relationship between anomalously high glaciomarine drift and the MCT upper plate area (Fig. 5B). Finally, the occurrences of "Deming Sand" near present-day sea-level near Bellingham probably require emergence and submergence that is tectonically unfeasible. If these deposits were subareally deposited in mid-Everson Interstade time, then factors other than tectonism appear to be required. (See previous footnote.)

Could the anomalous occurrences of fluvial sands at the Deming Sand type section be the result of thrust-generated uplift in late glacial times? At least two inflections in uplift curves for the southern and central Puget Lowland coincide with probable faults in pre-Quaternary rocks (Thorson, 1980, 1989). The best-determined change in gradient in the northern Puget Lowland, near 48°20′N, corresponds with fault zone A of Gower and others (1985). Thorson (1996) states that deglaciation may have been accompanied by a brief episode of intense seismicity; in his model, ice removal is accompanied by decreasing overburden stress, elevated pore pressures, elastic flexure in the shallow crust, and viscous drag at the base of the crust, providing added impetus for late (Everson age) to postglacial seismic activity.

Anomalous valley bedrock occurrences near Deming and Welcome (shown on Fig. 4B) may be explained by recent thrust-induced uplift of upper-plate Chuckanut along the MCT. These Chuckanut knobs lie curiously in the middle of the Nooksack valley and (1) are veneered by glaciomarine drift and, near Deming, also by Deming Sand, and (2) are sites of anomalously high Everson Interstade deposits east of the Deming type section (for example, Kovenan and Easterbrook, 1996a; Kovenan, 1996). (See Fig. 1A, loc. AA.) The valleys are quite narrow adjacent to the knobs. The Deming knob (Fig. 1, loc. AC) restricts the valley width to only 830 ft, the Welcome knob (Fig. 4A, loc. AD) to about 2,800 ft (typical valley width is 4,000 ft). These knobs may be erosional remnants of bedrock valley "pop-ups" (basement uplifts) resulting from past seismicity on the MCT. Shallow bedrock (Fig. 5A, loc. K) in the valley northwest of Deming and directly south of the MCT appears to be a continuation of the Deming knob (Dragovich and others, 1997b). D. C. Engebretson (Western Wash. Univ., oral commun., 1996, and cited in Kovenan, 1996) noted outcrop-scale conjugate thrust structures at the Welcome knob that mimic the Deming quake conjugate structures. Additionally, a concealed 200-ft-high bedrock escarpment is well defined by water-well data along the western part of Figure 4A (loc. BC) (S. Kahle, USGS, written commun., 1997). Concealed escarpments such as these may be glacial erosional escarpments or Quaternary (MCT bounding?) faults responsible for Quaternary geologic anomalies to the east.

Landslide Anomalies

Correlation of the exposed MCT with the shallow thrust seismically defined by the Deming quakes and our inference that this structure may have been intermittently active could explain the high incidence of landsliding in the area. The 1990 quake was associated with at least three road embankment failures. Dragovich and others (1997a) mapped several landslides above the MCT (Fig. 1, loc. AE, currently active). Engebretson and others (1995, 1996), Kovenan and Easterbrook (1996a), and Kovenan (1996) have correlated the uncommonly high incidence of large, deep-seated, bedrock landslides around Deming with a remarkable clustering of earthquake epicenters in the last 25 years in the same area, including seismicity unrelated to the Deming quake. Additionally, we note a 4.4 to 4.6-magnitude earthquake (our calculation based on the felt area) near Deming on April 17, 1931, as catalogued by Neumann (1932). These epicenters suggest a strong concentration of seismic energy coincident with the inferred map area of the MCT (Fig. 4B, zone 2 approximately). Engebretson and others (1996) suggest climatic factors are not the dominant causative force for these landslides due to lower incidence of deep-seated landslides in areas that contain the Chuckanut and are apparently nonseismic. Additionally they state that

> "radiocarbon ages of about 2,700 and 2,400 ^{14}C years and a limiting age of 1,600 ^{14}C on the Deming landslide [Fig. 1, loc. AF] demonstrate that these huge landslides are not caused by oversteepening of slopes

by the last glaciation, and the position of the landslides high above the valley floor indicate that oversteepening from river undercutting was not a causal factor."

Although further work is required, some geochronology and subsurface geologic mapping suggest slope instability related to past seismic events. Nooksack Valley cross sections based on available water-well and geotechnical boring data (Dragovich and others, 1997b) suggest that alluvial fan deposits from Macaulay Creek prograded basinward (Fig. 5A, loc. AG) after deposition of the Nooksack Valley Middle Fork lahar, dated 5,650 ±110 yr (Kovenan, 1996; Easterbrook and Kovenan, 1996a) and 6,000 yr (Hyde and Crandell, 1978) and prior to deposition of about 5–30 ft of modern Nooksack River alluvium. Mid- to late Holocene alluvial fan progradation may correlate with postulated seismically induced deep-seated landsliding (Engebretson and others, 1995, 1996) after 3 ka. Past seismic events may have caused the liquefaction features observed by Pat Pringle (DGER, unpub. data) in the Nooksack River alluvium near Welcome.

FINAL NOTES

We correlate the MCT with the Deming earthquake and hypothesize that displacement along the broadly defined MCT explains several geologic anomalies around Deming. The idea that the more broadly defined MCT decollement (Fig. 4B) is accommodating north–south compression in the shallow crust parallels the concept that the Puget Sound region lies on a north-directed thrust sheet (for example, Pratt and others, 1994). Similar thrust sheets may underlie the northern Puget Lowland and Cascade foothills (D. C. Engebretson, Western Wash. Univ., and R. A. Haugerud, USGS, oral commun., 1996, unpub. data and work under way). Late Eocene thrusting of the Cowichan fold and thrust system on southwestern Vancouver Island and northern San Juan Islands (England and Calon, 1991), west of the study area, provides a further backdrop for considering that low-angle Cenozoic structures exist and are being locally rejuvenated by contemporary tectonic movements.

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Construction Starts on State Emergency Operations Center

On March 26, the Washington State Emergency Management Division (EMD) broke ground for its new headquarters and emergency operations center at Camp Murray near Tacoma. Camp Murray is the headquarters of the Washington Military Department, which includes the Air and Army National Guards in addition to the EMD.

The EMD alerts state agencies and local governments to impending emergencies and coordinates response from state, local, and federal government, as well as private organizations. Ed Carlson, EMD's chief of staff and project manager, said the new center will replace a building from the early 1950s now ranked as the worst facility in the 50 states.

Washington legislators approved initial planning and design money in the 1993/95 budget. The 1995/97 budget provided $9 million to cover design, construction, equipment, furnishings, and taxes. The center is expected to be fully operational in mid-1998. Pease and Sons, Inc., Tacoma, is the building's prime contractor, the architectural firm is NBBJ, and the architect is Barbara Thomas.

The building will have two floors of 28,000 ft^2 each. With a steel frame and a base-isolation foundation, it is designed to survive and operate in a major earthquake. Base isolators allow the foundation to move, while minimizing the movement of the rest of the building.

The building will accommodate 70 staff persons during day-to-day operations and 225 during a catastrophic emergency. It will have its own emergency power and during protracted emergencies will receive support for lodging, food, water, and sanitation from Camp Murray. The EOC uses primarily telephones for communication. When telephone service is disrupted, personnel use radio and satellite communication.

"Construction of the center at Camp Murray will save about $3 million in land acquisition and other costs," said State Adjutant General, Maj. Gen. Gregory P. Barlow, who leads the Washington Military Department. "This is an emergency center that will serve Washington citizens well."

What Is the Age and Extent of the Cascade Magmatic Arc?

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INTRODUCTION

The age and extent of the Cascade magmatic arc are critical to an understanding of the geology of the Pacific Northwest. The most widely held concept (Armstrong, 1978; Beeson and others, 1989; Hammond, 1989; Swanson and others, 1989; Brandon and Vance, 1992; Christiansen and Yeats, 1992, fig. 20; Bestland and others, 1994; Tabor and others, in press) is that the arc has existed nearly continuously since at least the Oligocene in the vicinity of the Cascade Range. Use of the term "ancestral Cascades" for Oligocene to Miocene volcanic rocks (Dott and Prothero, 1994) implies much the same concept.

Significantly, the Cenozoic sedimentary and volcanic rocks of the Pacific Northwest in and to the east of the Puget and Willamette Lowlands occur in four major unconformity-bounded stratigraphic sequences (UBSs) shown in Figure 1. The Eocene to earliest Oligocene Challis sequence consists primarily of arkosic strata and bimodal volcanic rocks; these are preserved in various areas in Washington and Oregon. The Oligocene to middle Miocene Kittitas sequence is dominated by andesitic and felsic volcaniclastic and volcanic rocks and is well preserved in the Cascade Range of southern Washington and northern Oregon. The most voluminous portion of the middle Miocene to Pliocene Walpapi sequence is the Columbia River Basalt Group (CRBG). Although most of the CRBG occurs east of the Cascade Range, it also is present west of the range in the Willamette Lowland and along the coasts of Washington and Oregon (see Reidel and others, 1989, fig. 2; Tolan and Reidel, 1989). The High Cascade sequence includes the Cascade stratovolcanoes and both alpine and lowland glacial deposits.

The central concept of this paper is that the Kittitas and High Cascade sequences were generated by two temporally distinct magmatic arcs that happen to spatially coincide in the Pacific Northwest (but not elsewhere). That is, because each of these UBSs is separated from older or younger sequences by an interregional unconformity, each is a separate, and genetically unrelated, tectonostratigraphic entity (Wheeler and Mallory, 1970; Cheney, 1994). Unconformities bounding and within the Walpapi sequence also show that the Cascade Range has not been a continuous topographic feature since the Oligocene.

Recognition of two distinct magmatic arcs has not been obvious for four reasons. Firstly, outside of the petroleum industry, sequence stratigraphy has been widely practiced for less than two decades and is infrequently applied to volcanic rocks. Secondly, the interregional extent of the Oligocene to Miocene volcanic rocks (from the Pacific Northwest to Mexico) is not widely appreciated. Thirdly, the name of the Oligocene to Miocene volcanic rocks in the Cascade Range has been a major semantic impediment. Lastly, the topography of the Cascades is generally believed to have persisted since the early Oligocene. I address each of the last three reasons below.

Because a more voluminous description of each UBS is in Cheney (1994), detailed descriptions are not repeated here. Instead, I first review the extent of the Oligocene to Miocene (Kittitas) UBS. Then, to test the concept that the Cascade Range has existed since the Oligocene (and that the CRBG ponded against it), I discuss both the sequence stratigraphy within the Walpapi sequence and the regional deformation of the CRBG.

THE OLIGOCENE TO MIOCENE SEQUENCE

A thick succession of Oligocene to Miocene nonmarine volcanic and proximal volcaniclastic rocks does occur in the Cascade Range of southern Washington and northern Oregon (Wheeler and Mallory, 1970; Hammond, 1989; Swanson and others, 1989). Coeval quartz dioritic intrusions also occur in the range; significantly, the northern part of the range in Washington and adjacent British Columbia has intrusions but few volcanic rocks of this age. The near coincidence of the trend of the intrusions with the present crest of the range in Oregon and Washington (refer to Swanson and others, 1989, fig. 1) probably has contributed to the belief that the range has existed continuously since at least the Oligocene.

The presence of Oligocene to Miocene intrusions and nonmarine volcanic rocks in the present Cascade Range does indicate that a magmatic arc and its topography existed in the Oligocene to Miocene. The questions, however, are whether this arc and its topography persisted until today and whether they are related to present Cascade magmatism.

Armstrong (1978) volcanic episodes	Major sequences	Ma	Examples of litho-stratigraphy	Lithologies
High Cascades	*High Cascades*		Logan Hill Tieton	glacial and andesitic
———	∿∿∿∿	2	∿∿∿∿	∿∿∿∿
Columbia	*Walpapi*		Columbia River	basaltic
———	∿∿∿∿	20	∿∿∿∿	∿∿∿∿
Cascade	*Kittitas*		Fifes Peak Ohanapecosh	felsic and andesitic
———	∿∿∿∿	36	∿∿∿∿	∿∿∿∿
Challis	*Challis*		Lake Wenatchee Naches Roslyn Teanaway Taneum Swauk	arkosic, felsic, and basaltic
———	∿∿∿∿	55	∿∿∿∿	∿∿∿∿

Figure 1. Major unconformity-bounded sequences in the Pacific Northwest. See Cheney (1994) for details. Armstrong's (1978) volcanic episodes are included for comparison. The examples of some constituent lithostratigraphic units from south-central Washington are listed for convenience.

Importantly, the Oligocene to Miocene (Kittitas) rocks are deformed, whereas the High Cascade rocks are not. In the southern Cascade Range of Washington, Kittitas rocks are folded along northwesterly axes (Swanson and others, 1989). Strata commonly dip 25 to 40 degrees, and folds range from 1 to 20 km in width and 1 to 5 km in amplitude (Hammond, 1989). Elsewhere in western Washington, correlative rocks of the marine Blakeley Formation are locally vertical. Some of the volcaniclastic rocks and flows on the High Cascade stratovolcanoes have significant initial dips, but they are not folded; nor do the volcanic edifices dip 25 to 40 degrees. The structural discontinuity between the Oligocene to Miocene (Kittitas) rocks and the High Cascade rocks in the same area implies a significant temporal difference between the two sequences.

The semantic problem with nomenclature arose because when the Oligocene to Miocene rocks of the Pacific Northwest were first systematically dated radiometrically, they were called the Cascade volcanic episode (Armstrong, 1978). As a result, many geologists refer to these informally as the Cascade rocks or more formally as the Western Cascade Group (Hammond, 1989) or the Western Cascade arc (Christiansen and Yeats, 1992). These names reinforce the belief that the Oligocene to Miocene rocks are genetically related to the currently active Cascade arc.

Sequences are given names of areas that contain the sequence and that are named after indigenous peoples; in contrast, lithostratigraphic units have more conventional geographic names. Thus, I (1994) proposed the name Kittitas for the Oligocene to Miocene sequence. This name has the added advantage of not implying any genetic relationship to the Cascade Range.

Oligocene to Miocene volcanic rocks with compositions similar to those in the Cascade Range exist throughout the American Cordillera and south into Mexico (Fig. 2). In the Basin and Range Province, these are the "ignimbrite flare-up". The sources of many of the welded tuffs were calderas in Nevada and adjacent Utah (Christiansen and Yeats, 1992, fig. 21B; John, 1995), most of which have been recognized only during the past two decades. In southwestern Colorado, the San Juan volcanic field is representative of this sequence.

Distal deposits from these eruptive centers are widespread (Fig. 2). Below the western margin of the CRBG in Washington, they are the volcaniclastic rocks of Wildcat Creek (Swanson and others, 1989), which is not shown in Figure 2, and the upper member of the Wenatchee Formation (Cheney, 1994). In eastern Oregon, intermediate to distal rocks are the John Day Formation (compare Hammond, 1989; Christiansen and Yeats, 1992; Bestland and others, 1994). Farther to the east, distal rocks are the Renova Formation of southwestern Montana (Alt and Hyndman, 1995), the White River Formation of Wyoming and the Dakotas (Dott and Prothero, 1994; Alt and Hyndman, 1995; Larson and Evanoff, 1995), and the Wall Mountain Tuff of Colorado (Christiansen and Yeats, 1992). Erosion caused by post-Kittitas uplifts of the Cordillera, tectonic extension of the Basin and Range Province, and unconformably overlying sequences have reduced the continuity of both the proximal and the distal deposits of this sequence.

To name even the proximal parts of this continental arc the Cascade arc seems spatially misleading. Because this Oligocene to Miocene arc from British Columbia to Mexico was caused by subduction of the Farallon plate (Fig. 2), it might well be termed the Farallon arc. A number of authors have noted that in the southwestern United States this arc is significantly wider and more distant from the subduction zone than

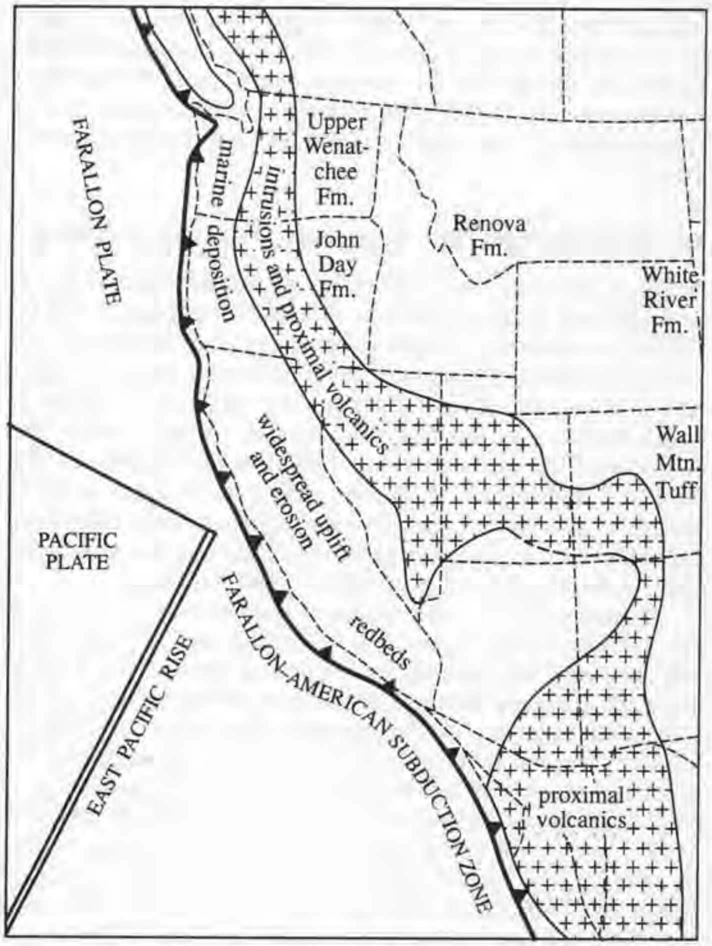

Figure 2. Distribution of Oligocene to Miocene volcanism in the Cordillera. Note that the paleogeography largely predates Basin and Range extension and initiation of the San Andreas Fault. Sources of information are Brandon and Vance (1992, fig. 1) and Dott and Prothero (1994, figs. 15.5 and 15.25). The field of intrusions and proximal volcanic rocks shown by Dott and Prothero (fig. 15.5) has been expanded to include the Patsy Mine volcanic rocks of southernmost Nevada (Frost and Heidrick, 1996) and is dashed across southeastern Utah to include the coeval laccolithic centers of the La Sal, Henry, and Abajo mountains (Christiansen and Yeats, 1992). The location of some of the distal deposits are shown by their formational names.

most subduction-related continental arcs. However, the volcanic rocks probably did form by subduction (compare van der Lee and Nolet, 1997, and included references) and, no matter what their origin, they do constitute an interregional UBS.

Two spatially and temporally distinct magmatic arcs could imply two spatially different subduction zones. Figure 2 shows a Farallon–American subduction zone; the only presently onshore portion is in the core of the Olympic Peninsula of Washington. In the core of the peninsula, predominantly deep marine lithic sandstones are juxtaposed against predominantly Eocene basalts to the north, east, and southeast. If the eleven reportedly unreset fission-track ages from detrital zircons in the marine clastic rocks of the core (48, 47, 39, 38, 37, 34, 33, 32, 27, 19, and 19 Ma) determined by Brandon and Vance (1992) prove to be representative, the depositional age of the clastic rocks may be predominantly Eocene to middle Miocene. Although the marine rocks are generally believed to be a subduction complex (Brandon and Vance, 1992), the nature of the tectonic contact between them and the basalts is still unknown. Obviously, this tectonic contact must be younger than the rocks involved. Figure 2 follows the suggestion of Brandon and Vance (1992) and of Dott and Prothero (1994) by illustrating the tectonic contact as a Kittitas-aged subduction zone. If this interpretation is valid, at 2 Ma subduction resumed by jumping westward (offshore) to the Cascadia zone.

DEFORMATION OF THE WALPAPI SEQUENCE

Another prevalent reason for believing that the Cascade Range and arc have persisted since at least the Oligocene is that the CRBG is commonly thought to have ponded in the Pasco basin of south-central Washington (against the range to the west) and to have flowed down the gorge of the Columbia River to reach the sea. As discussed next, dips of the basalt away from the core of the Cascade Range (Wheeler and Mallory, 1970; Swanson and others, 1989), the structural (not depositional) nature of the Pasco basin, and the structural (not paleotopographic) nature of the gorge of the Columbia River indicate that the basalts did not pond against the Cascades.

Swanson (1997) rather elegantly showed that the basalts on the southeastern margin of the Cascade Range in Washington are uplifted a few kilometers relative to their source areas to the east. Because these basalts dip eastward away from the Cascade Range, at least some uplift of the range postdates the CRBG. Structural relief on Grande Ronde basalt along the southeastern margin of the Cascade Range in Washington is >2,700 m (Swanson and others, 1989). In addition, Swanson (1997) has shown that the gradient of the 80-km valley filled by the 1.0 Ma Tieton andesite in the southeastern Cascade Range of Washington is steeper than the gradient of the present Tieton River valley in the same location. Evidently, at least some uplift of the range could postdate 1.0 Ma (Swanson, 1997).

The presence of numerous unconformities within the CRBG refutes the idea of ponding against the Cascades. Here, I ignore the existence of the paleotopography recorded by valley-filling basalt flows in order to focus on regional unconformities. The existence and/or significance of regional unconformities generally has not been recognized, even by the authors who described them.

Because the >3.4 Ma Ringold Formation "pinches out against structural highs" and "basaltic detritus dominates the alluvial fan facies...around the periphery of the basin" (Lindsey and others, 1994, p. 1C-4), an unconformity must exist at the base of the Ringold. Additionally, the contacts at the top of the Wanapum and Grande Ronde generally appear to be conformable but are marked locally by angular unconformities, absence of the uppermost units in the Grande Ronde, and saprolites on the underlying basalts (Swanson and others, 1979, p. 26-27). Furthermore, Figure 3 shows that regionally the Saddle Mountains and Wanapum overlie not just the next oldest stratigraphic unit (Wanapum and Grande Ronde, respectively) but other units or the pre-CRBG basement as well.

Another unconformity must exist in the Grande Ronde. Figure 4 shows that the Grande Ronde (by far the thickest portion of the CRBG) has four magnetostratigraphic units (MSUs) of reversed and normal polarity. Along the western and northern margin of the CRBG in Washington, the Imnaha and R_1 and N_1 of the Grande Ronde are missing (Cheney, 1994), and R_2 rests directly on pre-CRBG units.

Other unrecognized unconformities occur in the Grande Ronde. MSUs of any kind, like UBSs (and unlike many lithostratigraphic units), represent separate slices of geologic time. Hence, the variable thicknesses of the MSUs in Figure 5 and the variable position of a given marker unit within them indicate that the four MSUs are UBSs. Therefore, their contacts are shown as unconformities in Figure 4.

Because the CRBG is riddled by unconformities, accumulation of the basalts was punctuated either by episodic changes in sea level and consequent erosion or by episodic uplift and erosion, rather than by continuous subsidence of the Pasco basin or continuous uplift of the Cascade Range. Because the extent to thickness ratio of the regional MSUs and other basalts above unconformities is so great, only minor contemporaneous topography existed when a basalt flowed along a given unconformity. In other words, R_1, N_1, and R_2 did not change greatly in thickness by ponding, but primarily by postdepositional erosion along upper bounding unconformities.

The synclinal nature of the CRBG in eastern Washington (Fig. 3) also shows that the basalts did not pond in the Pasco basin. The youngest unit, the Saddle Mountains Basalt, is the most areally restricted and in the center of the Pasco basin (rather than being the most widespread, as would be the case if each formation progressively filled (ponded in) a basin bounded on the west by the Cascade Range). The regional dips of the basalts into the Pasco basin are well known (Wheeler

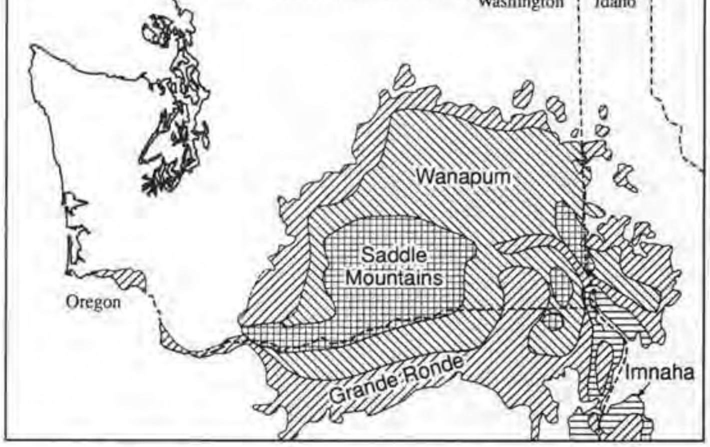

Figure 3. Distribution of formations of the Columbia River Basalt Group east of the Cascade Range. Sources of data are Choiniere and Swanson (1979, fig. 1) and Cheney (1994, fig. 11). See Figure 4 and text for explanation.

Age (Ma)	Name	Lithology	Thickness (m) Maximum	Pasco
3.4	Ringold Formation		285	185
6	Saddle Mtns. Basalt		?	175
	Ellensburg Formation		?	0–15
14.5	Wanapum Basalt		?	120
	Vantage sandstone		?	0–13
15.5	Grande Ronde Basalt N_2		520	520
	R_2		1460	1460
	N_2		863	863
16.5	R_1		>935	≥935
17.5	Imnaha Basalt N_0		500	0

Figure 4. The Walpapi Sequence in eastern Washington. Note that the scales for thickness and time are not linear. Sources of data are Mackin (1961), Swanson and others (1979, 1989) and Lindsey and others (1994).

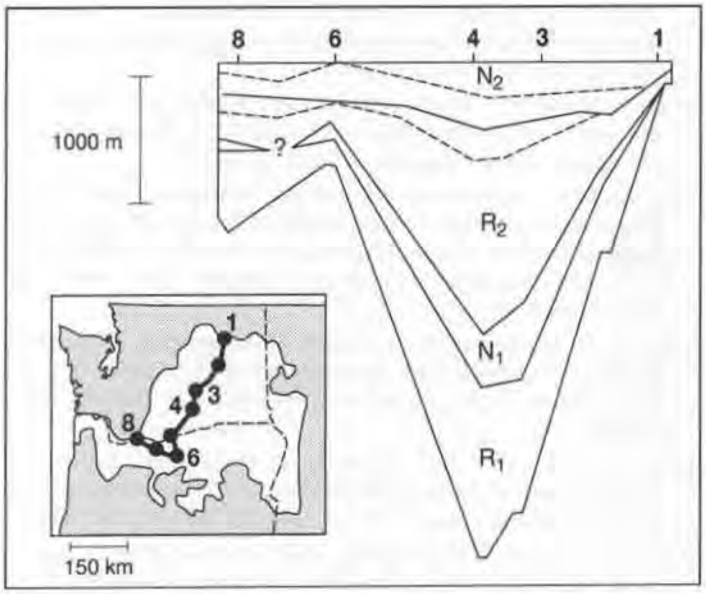

Figure 5. Truncation of magnetostratigraphic units of the Grande Ronde Basalt. Dashed lines are marker horizons. After Reidel and others, 1989, fig. 9.

and Mallory, 1970; Swanson and others, 1989); if these dips are not structural, the basalts flowed uphill.

The presence of CRBG in the Willamette Lowland, along the mouth of the Columbia River, and on the coasts of Oregon and Washington (Fig. 4) is commonly explained by the basalts having flowed down the Columbia River gorge (and other paleogorges) through a long-standing Cascade Range (Beeson and others, 1989). However, in the vicinity of the Columbia Gorge, the basalts are folded and cut by thrust faults and normal faults (Beeson and others, 1989; Tolan and Reidel, 1989). The fact that the CRBG is nearly flat lying along some portions of the gorge is a structural accident (later exploited by the river). Thus, rather than being an undeformed valley fill, the CRBG in the Columbia River Gorge defines a westerly striking syncline between anticlinal uplifts of the CRBG in the Washington Cascades to the north and the Oregon Cascades to the south (Wheeler and Mallory, 1970).

In addition to the above physical evidence, paleontological studies also imply that the Cascade Range was not a significant topographic barrier during the Miocene. Within the Walpapi, the flora of the Vantage, Ellensburg, and Ringold record a mixed conifer-deciduous hardwood forest and swamps rich in woody genera; this flora is typical of a warm-temperate, summer-wet climate, unlike the present steppe and local grassland caused by the rain shadow of the Cascade Range (Leopold and Denton, 1987). Similarly, fossil mammals from the Ringold Formation are predominantly browsing, rather than grazing forms (Gustafson, 1973).

Independent tests of post-Walpapi uplift of the Cascade Range would be welcome. For example, ages and rates of uplift might be determined by argon and fission-track dating, especially in some of the Oligocene to Miocene batholiths that have topographic reliefs approaching 2 km.

CONCLUSIONS

Because the Oligocene to Miocene rocks of the Cascade Range in Washington and Oregon are representatives of a UBS that extends from British Columbia to Mexico, they are portions of a continental "Farallon arc", not a regional "Cascade arc". The topography and Pleistocene volcanic rocks of the present Cascade Range (including the stratovolcanoes) postdate antiformal uplift and erosion of the once more extensive CRBG. Some uplift of the range in Washington could postdate the 1.0 Ma Tieton andesite. The sequence of Pleistocene volcanic rocks of the Cascade Range defines the Cascade arc, which extends only from northern California to southern British Columbia. This geological definition is particularly obvious from central Washington northward, where few Oligocene to Miocene volcanic rocks are preserved (only their intrusive counterparts are); accordingly, the northern Cascade stratovolcanoes almost exclusively overlie pre-Tertiary crystalline rocks.

ACKNOWLEDGMENTS

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Trailhead Parking Fees Instituted for Washington National Forests

Starting in June, hikers, horseback riders, and other recreational trail users will be paying trailhead parking fees in the Olympic, Mt. Baker–Snoqualmie, and Wenatchee National Forests of Washington. The fees, $3 per day or $25 for a calendar year pass, will supplement shrinking maintenance budgets for deteriorating trail systems.

An additional annual pass for a second vehicle belonging to the same family is available for $5 if purchased at the same time as the first family annual pass. Golden Age and Golden Access cardholders can get a 50 percent discount if they show their cards when purchasing these new passes. Volunteers who complete two days of work to improve forest trails will qualify for a free pass. The passes will also be accepted at trailheads in the Okanogan National Forest in place of an overnight camping and parking pass, which will be required in many parts of that forest.

The passes must be purchased in advance and will be sold at the offices and visitors centers of participating national forests. In addition, arrangements are being made for local vendors, businesses, and other parties to sell passes. The Trail Park Pass must be displayed in the windshield of all vehicles parked at or within .25 mile of the trailhead. These passes cannot be used at Sno-Park Trailheads.

The Trail Park Pass is part of an experimental recreation fee approved by Congress. At least 80 percent of the revenues will remain in local areas where the fees are collected, according to Ron Humphrey, Forest Supervisor of the Olympic National Forest. Enforcement of the pass requirement during the first year will emphasize informing the trail users about the pass.

Specific information about Trail Park Pass availability, sales locations, and volunteer opportunities can be obtained at local national forest offices.:

Mt. Baker–Snoqualmie National Forest
21905 64th Ave. W
Mountlake Terrace, WA 98043
(206) 775-9702

District offices are in Darrington, Glacier, Sedro Woolley, Skykomish, Snoqualmie Pass, Granite Falls, and Enumclaw.

Wenatchee National Forest
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District offices are in Hoodsport, Quilcene, Quinault, and Forks. ■

Outstanding Surface Mine Reclamation Honored

David K. Norman
Washington State Department of Natural Resources
Division of Geology and Earth Resources
PO Box 47007, Olympia, WA 98504-7007

In 1996, the Department of Natural Resources established annual awards to recognize outstanding achievement in the reclamation of surface mines. These awards honor permit holders who reclaim mines in an exemplary manner. Awards also recognize reclamation efforts on sites exempt from the Surface Mine Reclamation Act [RCW 78.44] because a site was mined prior to 1971. More than one award can be given for any of the categories.

The mines receiving the first of these awards demonstrate one or more of the following:

- Innovation or creativity in reclamation, such as creating unique wetlands or enhancing wildlife and fish habitat or topographic elements.
- Voluntary reclamation of mined land that is exempt from reclamation under the Act.
- Use of native plant species in revegetation.
- Innovative research and approaches to reclamation that can be applied at other mines.
- Attention to water quality and erosion prevention.
- Orderly segmental mine development resulting in high-quality reclamation.
- A consistent long-term commitment to reclamation.
- Methods that enhance the environment and reduce reclamation liability, such as mining to a final slope.

Small Operation Award

Davis Sand and Gravel of Sequim is the winner of the Commissioner of Public Lands' Recognition for Reclamation for a Small Operation Award. The company has reclaimed approximately 10 acres over the years (Fig. 1). Some of the areas the company reclaimed were exempt from the Surface Mine Act because they were mined prior to 1971. Davis Sand and Gravel has used segmental reclamation and mined to a final slope to minimize earth moving. Reclamation in each segment was done immediately after mining was complete. Storm water is filtered through ponds, which have filled with cattails. The company has used native vegetation such as Douglas fir and blue elderberry in their reclamation.

Davis Sand and Gravel is also the winner of the Good Neighbor Award. This firm has contributed to the community by hosting tours for classes from the community college, by donating gravel to Sequim Boys and Girls Club for fund raising, by providing gravel for local stream and fish habitat restoration, and by helping to fund the newsletter of the Clallam Conservation District.

Commissioner of Public Lands Award

Central Pre-Mix is a winner of the Commissioner of Public Lands' Recognition for Reclamation Award for their Yardley Sand and Gravel Pit in Spokane (Fig. 2). The 65-acre site was mined from World War II to the 1980s, and much of that area was mined prior to the enactment of the Surface Mine Act. The

Figure 1. A reclaimed segment at Davis Sand and Gravel of Sequim, Wash., recipient of the Small Operation and Good Neighbor Awards. Along with Douglas fir and blue elderberry, cottonwood trees have been planted on low-angle reclaimed slopes. The storm-water pond filled with cattails is in the foreground. Operations can be seen in the background.

Figure 2A. Aerial view (before reclamation) of Central Pre-Mix's Yardley sand and gravel pit, recipient of the Commissioner of Public Lands Award. The operation is in a heavy industrial area of Spokane (note train yards), as well as the sole source aquifer. The mine has provided sand and gravel for the Central Pre-Mix cement plant, which is still in operation at the site. Mining began here in the 1940s.

Figure 2B. After reclamation, natural topography has been created in parts of the reclaimed pit. Islands, peninsulas, shallow areas, and gentle contours are used to created a complicated shoreline that benefits wildlife.

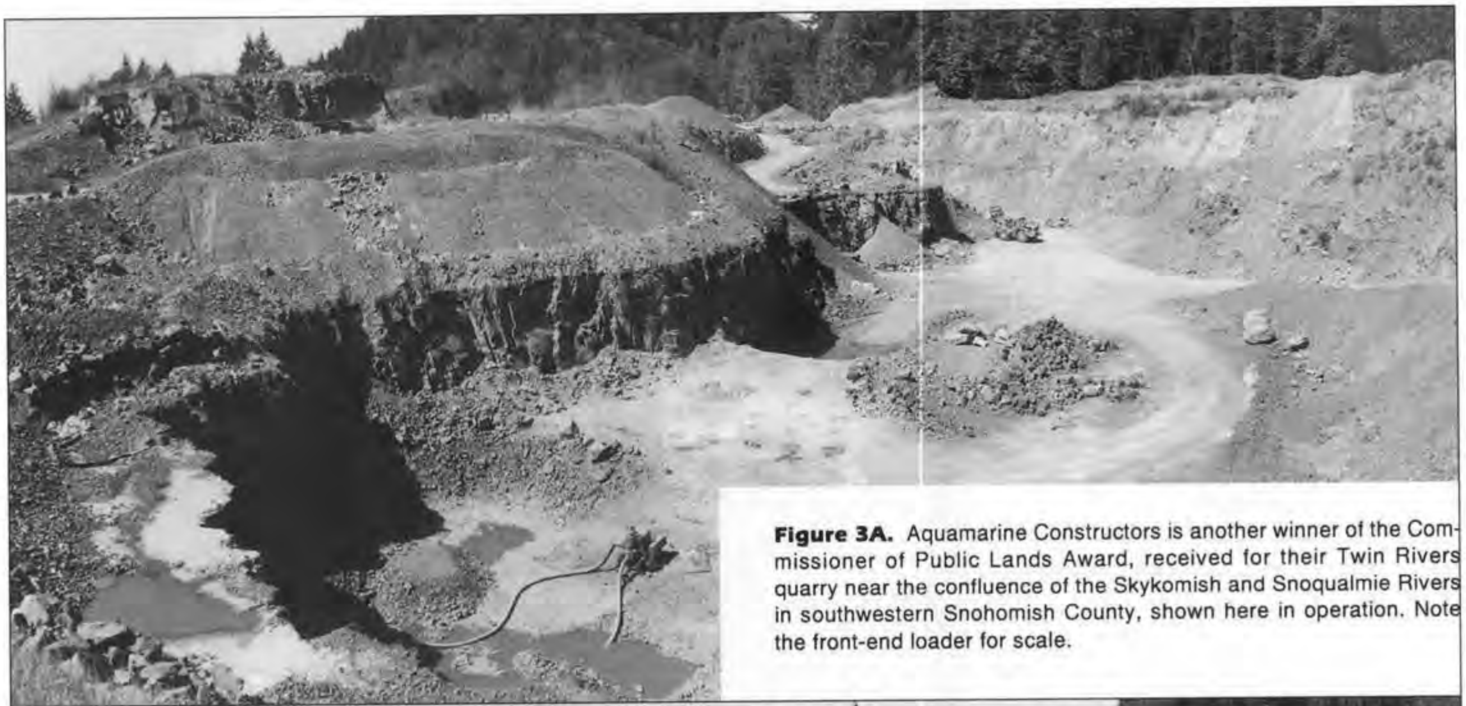


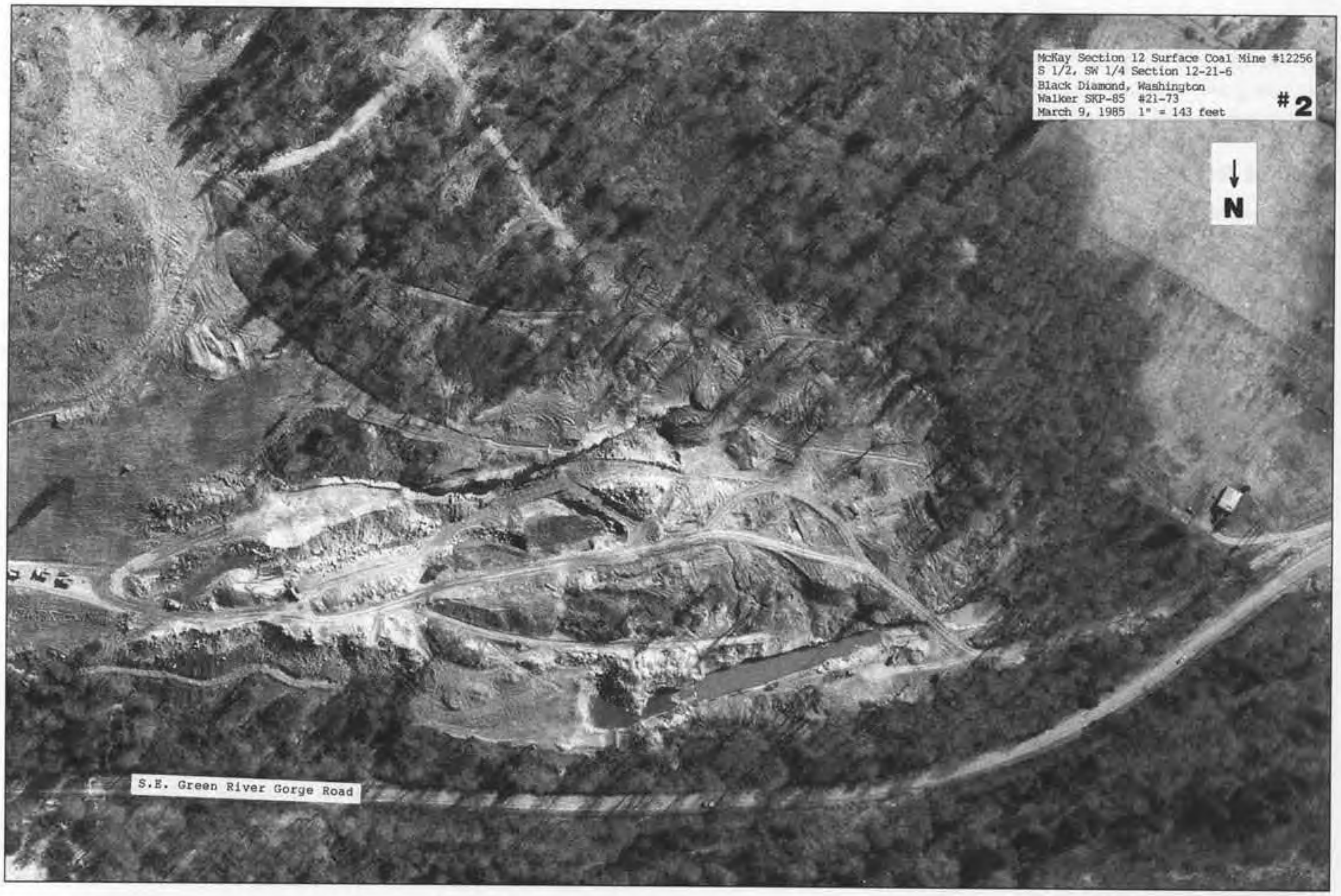
Figure 3A. Aquamarine Constructors is another winner of the Commissioner of Public Lands Award, received for their Twin Rivers quarry near the confluence of the Skykomish and Snoqualmie Rivers in southwestern Snohomish County, shown here in operation. Note the front-end loader for scale.

Figure 3B. Aquamarine Constructors backfilled the Twin Rivers quarry in 1994, eliminating the vertical cliffs and establishing a drainage, which now looks natural and functions appropriately, in the center of the mined area. The rock knob at the left side of the photo is in approximately the same position in both photos. Topsoil was respread across the site, and grasses and trees have been planted to stabilize the area.

company began reclamation of the two-pit site as a lake for wildlife habitat in 1991. It was designed to preserve water quality in the Spokane–Rathdrum Sole Source Aquifer, which provides drinking water for the Spokane area, by eliminating backfilling as means of reclamation. Areas not mined below the water level were reclaimed as peninsulas and islands. Dirt hauled into the site was used to create flatter slopes and rolling topography on the portions of the peninsulas above water, and a channel was opened between the two pits. Grasses were planted across the slopes, and trees line the perimeter of the lake. The new lake is an attractive addition to an industrial area of Spokane.

Aquamarine Constructors is also a winner of the Commissioner of Public Lands Award for their Twin Rivers quarry near the confluence of the Skykomish and Snoqualmie Rivers in southwestern Snohomish County. The mine worked 20 acres from 1981 to 1992. Stockpiled overburden was used for backfilling of the site in 1994. Topsoil was respread over the mined area, mulched, fertilized, and seeded. Successful revegetation and drainage control have stabilized the entire mine

Figures 4A & B. *(facing page, top and bottom, respectively)* Palmer Coking Coal Company is the recipient of a Special Recognition Award for their McKay Section 12 surface coal mine near Black Diamond. ***A***, The mine, shown in this aerial view taken in March 1985, operated from 1982 until 1986. The disturbed area here is approximately 30 acres. The flooded area at the bottom of photo is where coal was removed. Reclamation began in 1984 under Department of Natural Resources permit 12256. **B.** In this photo taken in September 1995, reclamation has approximated original contours. The road at the bottom of photographs is SE Green River Gorge Road. Grasses, clover, Douglas fir, noble fir, and Sitka spruce seedlings were planted on the reclaimed mine site. Red alder and a variety of wetland species have also colonized the site. Good topsoil management practices allowed the company to perform high-quality reclamation. (Photos by Walker & Associates, Inc., Photogrammetric Engineers, copyright 1996. Used by permission.)


McKay Section 12 Surface Coal Mine #12256
S 1/2, SW 1/4 Section 12-21-6
Black Diamond, Washington
Walker SKP-85 #21-73
March 9, 1985 1" = 143 feet
#2
N
S.E. Green River Gorge Road


McKay Section 12 Surface Coal Mine #12256
S 1/2, SW 1/4 Section 12-21-6
Black Diamond, Washington
Walker KC-95 #13-25
September 22, 1995 1" = 143 feet
#4
N
S.E. Green River Gorge Road

site (Fig. 3). The re-established natural drainage and topography blend well with the surrounding area. The reclamation at this site goes well beyond minimum reclamation standards for rock quarries and the approved reclamation plan.

Special Recognition Award

Palmer Coking Coal Company is the recipient of a Special Recognition Award for their McKay Section 12 surface coal mine near Black Diamond (Fig. 4). The mine operated from 1982 until 1986, and reclamation began in 1984. Reclamation approximated the original contours of the land, and the company replanted with grasses, clover, Douglas fir, noble fir, and Sitka spruce seedlings. Red alder and a variety of wetland species have also colonized the site. The company preserved topsoil and returned it to the mined areas. Five retention facilities used during operation were incorporated into the final reclamation design and now serve as water recharge areas and wetlands at the site.

These Surface Mine Reclamation Awards are an annual event, and companies are encouraged to submit nominations and photographs for the awards to be given in 1998. Plan to take photos in the warm weather months and to show the progress over a period of years. A new category for 1997 is being created to honor individual employees whose skills and efforts have made contributions to successful reclamation. Nomination forms for the 1997 awards will be available from the Division later this year. ■

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Map Collection, (206) 543-9392
e-mail: maplib@u.washington.edu

Natural Sciences Library, (206) 543-1244; *fax:* (206) 685-1665
e-mail: natsci@u.washington.edu

Geoscience collections are included in other collections: Geology, geophysics in Natural Sciences Library; Maps, aerial photos in Map Collection; Oceanography, marine geology in Fisheries–Oceanography; Engineering geology, technical reports in Engineering. Broad geologic coverage with comprehensive emphasis on Pacific Northwest. Collection sizes: Natural Sciences, 206,000 volumes, 2,200 other serials currently received; 255,000 geoscience maps in the Map Collection; 60,566 aerial photos in the Map Collection; 68,632 microfilm/microfiche units in Natural Sciences, 5,449 in the Map Collection; 110 CD-ROMs; copies of most University of Washington M.S./Ph.D. theses housed in the respective branches. More than 1,000,000 science/engineering technical reports are housed in the Engineering Library. Digital maps on CD are accessed on a personal computer.

Collections are open to the public. Photocopying available. CD-ROMs available: GeoRef, Water Resources Abstracts, WorldCat via FirstSearch. Online public access catalog accessible; WWW access: http://www.lib.washington.edu

The branch library's accesses are:
http://www.lib.washington.edu/libinfo/libunits/sciences/nsl
http://www.lib.washington.edu/libinfo/libunits/sciences/fish
http://www.lib.washington.edu/libinfo/libunits/sciences/engineering

Interlibrary loan available.

Washington Department of Natural Resources Library, Division of Geology and Earth Resources
PO Box 47007, Olympia, WA 98504-7007
phone: (360) 902-1472; *fax:* (360) 902-1785
e-mail: cmgg490@wadnr.gov; rcgg490@wadnr.gov
cjmanson@u.washington.edu

Separate geoscience collection with comprehensive coverage of Washington geology and mineral resources. 60,000 volumes, including some rare materials; 100 current journal subscriptions (many on loan from the Washington State Library); western U.S. state survey exchange program; partial USGS and USBM depository; full set of USGS open-file reports on Washington geology; many technical reports; 3,000 geoscience maps with emphasis on state; 1,000 aerial photos, with emphasis on state; 100 microfiche; 1,700 theses on Washington geology and mineral resources, 1901 to date.

Collection is open to the public; onsite use only. Photocopying available. CD-ROMs available: GeoRef, Earth Sciences Database, Geophysics of North America, Water Resources Abstracts. Free in-house database on Washington geology, 1801 to date.

Interlibrary loan available; photocopies only, volumes are not loaned, but contact the librarian if we are the library of last resort.

Washington State Library
Documents, PO Box 42460, Olympia, WA 98504-2460
phone: (360) 753-4027; *fax:* (360) 586-7575

Geoscience materials are integrated with the collection. Broad geologic coverage of U.S. and Canada. 1,600 geoscience volumes; 35 current geoscience journal subscriptions; 100 atlases; 500 aerial photos; more than 5,000 microfiche. Regional USGS depository, with full runs of the Bulletins, Professional Papers, and Water-Supply Papers and open-file reports on microfiche, 1979 to current. 2,500 topographic maps for Washington, Oregon, Idaho, and Alaska. Other maps are housed at the University of Washington Map Library.

Collection is open to the public; documents and periodicals are in closed stacks. Photocopying available. CD-ROMs available: Aerial Photography Summary Record System, Geographic Names Information System, Stratigraphic Nomenclature databases for the U.S.

Interlibrary loan available.

Washington State University
Owen Science and Engineering Library,
Pullman, WA 99164-3200
phone: (509) 335-4181; *fax:* (509) 355-2534

Geoscience materials are integrated with science and engineering collection. Broad geologic coverage with regional emphasis. 25,000 volumes; 160 current journal subscriptions; 240 other serials; 5,000 geoscience maps; 5,000 microfilm/fiche units; 430 theses (including Washington State University theses, 1923 to current). Significant strengths in: geophysics; hydrogeology and hydrology; mineralogy of the Pacific Northwest; paleontology; sedimentology; stratigraphy and historical geology; surficial geology, soils, and geomorphology; technical reports. Geoscience maps are in a separate collection that includes 5,000 topographic maps.

Collection is open to the public. Online catalog is available (WWW access at http://www.wsulibs.wsu.edu). Photocopying available. CD-ROMs available: GeoRef, Agricola, Water Resources Abstracts; WorldCat via FirstSearch; Biosis; SCI. Interlibrary loan available.

Western Washington University
Huxley Map Library, MS 9079, Bellingham, WA 98225
phone: (360) 650-3272; *fax:* (360) 650-7702

Wilson Library, 516 High St., Bellingham, WA 98225
fax: (360) 650-3044; *e-mail:* jcollins@nessie.cc.wwu.edu

The Map Library is a separate collection; most geoscience materials are housed in the Wilson Library. 951 atlases; map library organization journals; 9 other serials; 221,607 maps, with emphasis on U.S. and Canada; 145,00 topographic maps; 77,000 thematic maps; 28,000 air photos, with emphasis on historical photos of Whatcom County; 52 microforms; 74 theses, including Western Washington University Geography M.S. theses, 1968 to current. Full depository for USGS topographic and geologic maps, Canada Map Office topographic maps; partial depository for DMA, National Ocean Service, Washington Division of Geology and Earth Resources open-file reports. Significant collection of historical materials, with emphasis on U.S. and Canada.

Collection open to the public; onsite use only. Paper card catalog only; no offsite access. CD-ROMs available: USGS GNIS, Cart. Catalog. Photocopying available. Interlibrary loan available.

Whitman College
Penrose Memorial Library, 345 Boyer Ave.
Walla Walla, WA 99362
phone: (509) 527-5919; *fax:* (509) 527-5900

Geoscience materials are integrated with the college library. Depository collection of USGS books and maps. 5,000 topographic maps.

Collection is open to the general public. Online catalog. CD-ROMs available: WLN Lasercat, SCI. Photocopying available. Interlibrary loan available.

SPECIAL MATERIALS

A. Aerial Photographs

Indexes:

(1) Aerial Photography Summary Record System, a CD-ROM index compiled by the USGS, is available at:
- Pacific Lutheran University library
- Seattle Public Library
- U.S. Geological Survey (Spokane)
- University of Washington, Map Library
- Washington DNR Division of Geology and Earth Resources
- Washington State Library
- Washington State University library
- Western Washington University Map Library

(2) The Washington DNR, Division of Photo and Map Sales maintains the index of DNR aerial photography.

Sales:
- Washington DNR, Division of Photo and Map Sales
- Walker & Associates (12652 Interurban Ave. S., Seattle, WA 98168; *phone:* (206) 244-2300; *fax:* (206) 244-2333)

Library collections:
- University of Washington, Map Library (60,000 photos)
- Washington State Library (500 photos)
- U.S. Army Corps of Engineers has extensive files of historic aerial photography

B. Coal mine maps

Index of coal mine maps is maintained by the Washington DNR, Division of Geology and Earth Resources library.

Sales: The microfilm of the underground coal mines is available from Washington State Archives. Contact the Washington DNR, Division of Geology and Earth Resources for ordering instructions.

Library collections: The coal mine maps are held at the Washington DNR, Division of Geology and Earth Resources.

C. Geologic maps

Indexes are maintained by the Washington DNR, Division of Geology and Earth Resources library.

Sales: Geologic maps are generally only available for sale from the respective publishers, e.g.:
- U.S. Geological Survey Earth Science Information Center (Spokane)
- U.S. Geological Survey Water Resources Division (Tacoma)
- U.S. Geological Survey Information Services (Denver)
- Washington DNR, Division of Geology and Earth Resources
- Washington Department of Ecology, Publications Distribution

Library collections: Reports that include geologic maps of Washington are held at various libraries, including:
- Pacific Lutheran University library
- Seattle Public Library
- U.S. Geological Survey (Spokane)
- University of Washington, Map Library
- Washington DNR, Division of Geology and Earth Resources
- Washington State University library
- Western Washington University Map Library

D. Indexes

The index of Washington geology, which includes all known articles and abstracts, is maintained by the Washington DNR Division of Geology and Earth Resources library. It includes materials issued from 1798 to 1996. Printed bibliographies are available for purchase and are held at many libraries.

GeoRef, the international index to geology, 1785 to 1996, is maintained by the American Geological Institute and updated quarterly. It is available for lease from SilverPlatter Information (100 River Ridge Drive, Norwood, MA 02062-5026). Lease costs vary.

GeoRef is available online (via Dialog and other vendors) at these libraries (search fees vary):
- Eastern Washington University
- Pacific Lutheran University
- Seattle Public Library
- University of Washington (for campus community only)
- Washington State Library (for state employees only)
- Washington State University

GeoRef is available on CD-ROM at these libraries:
- Battelle Pacific Northwest Laboratory
- Eastern Washington University
- Pacific Lutheran University
- University of Washington, Natural Sciences Library
- Washington DNR Division of Geology and Earth Resources
- Washington State University

E. Soil surveys

Soil surveys are produced by the U.S. Natural Resources Conservation Service (NRCS, formerly U.S. Soil Conservation Service).

Sales: These reports are usually prepared county by county and are free. The NRCS Washington field offices are in Olympia (with local offices in Aberdeen, Chehalis, Kelso, Lake Stevens, Lynden, Montesano, Mount Vernon, Port Angeles, Puyallup, Port Orchard, Renton, and Vancouver) and Ephrata (with local offices in Davenport, Nespelem, Okanogan, Ritzville, Waterville, and Wenatchee).

Library collections: Soil surveys are depository items, and so are held in standard library collections at:
- Eastern Washington University
- Seattle Public Library
- University of Washington, Government Documents
- Washington DNR, Division of Geology and Earth Resources
- Washington State Library
- Washington State University
- Whitman College

Soil surveys are available from the Washington DNR.

Sales: Available by quadrangle, as opaque overlays on orthophoto quads. They sell for $14.00 per quadrangle from Washington DNR, Division of Photo and Map Sales.

The explanations, organized by DNR region, sell for $5 to $10 each from Washington DNR, Division of Geology and Earth Resources.

Library collection: The full set of the Washington DNR soil survey maps and explanations are held at:
- Washington DNR, Division of Geology and Earth Resources

F. State agency reports

Sales: Generally available for sale only from the issuing agency, e.g.,
- Washington DNR, Division of Geology and Earth Resources
- Washington Department of Ecology, Publications Distribution

Library collections: Reports of Washington State agencies are held at:
- Eastern Washington University
- Pacific Lutheran University
- Seattle Public Library
- University of Washington, Government Documents
- Washington DNR, Division of Geology and Earth Resources
- Washington State Library
- Washington State University

G. Theses

Library collections: Copies of the theses are held at the generating university. Full set of all known theses on Washington geology is held at Washington DNR, Division of Geology and Earth Resources

H. USGS topographic maps

Sales:
- U.S. Geological Survey (Spokane)
- Washington DNR, Division of Photo and Map Sales
- map dealers (check the yellow pages of your local phone book under MAPS – RETAIL)

Library collections: USGS topo maps of Washington are held at:
- Eastern Washington University
- Pacific Lutheran University
- Seattle Public Library
- University of Washington, Map Library
- Washington DNR Division of Geology and Earth Resources
- Washington State Library
- Washington State University
- Western Washington University
- Whitman College

I. USGS published reports (Bulletins, Circulars, Professional Papers, Water Supply Papers)

Sales:
- U.S. Geological Survey Earth Science Information Center (Spokane)
- U.S. Geological Survey Information Services (Denver)

Library collections: Published reports on Washington are held at:
- Eastern Washington University
- Seattle Public Library
- University of Washington, Government Documents
- University of Washington, Natural Sciences
- Washington DNR Division of Geology and Earth Resources
- Washington State Library
- Washington State University
- Whitman College

J. USGS open-file and water-resources investigations reports

These reports have had very limited distribution. They may be available from the generating office, e.g.,
- U.S. Geological Survey Water Resources Division (Tacoma)
- U.S. Geological Survey Water Resources Division (Portland)

Sales:
- U.S. Geological Survey Information Services (Denver)

Since 1981, microfiche copies have been depository items and are available at:
- University of Washington, Natural Sciences Library
- Washington State Library

Paper copies of all USGS open-file reports and water-resources investigations reports are held at:
- Washington DNR, Division of Geology and Earth Resources
- U.S. Geological Survey Earth Science Information Center (Spokane)

K. Well logs

In Washington, water-well drillers are required to file the water-well logs with the Washington Department of Ecology. Copies of those logs are held at the various Ecology region offices. ■

Northwest Paleontological Society

An August field trip is planned to Olequah and Coal Creeks to view the Cowlitz Formation. For more information, contact Bill Smith, 13332 Ridgeland Dr., Silverdale, WA 98383. Membership in the society is $15/yr, $25 for families, $10 student or senior, and $5 junior; send checks to Betty Jarosz, 17807 NE 102nd Ct., Redmond, WA 98073.

Selected Additions to the Library of the Division of Geology and Earth Resources

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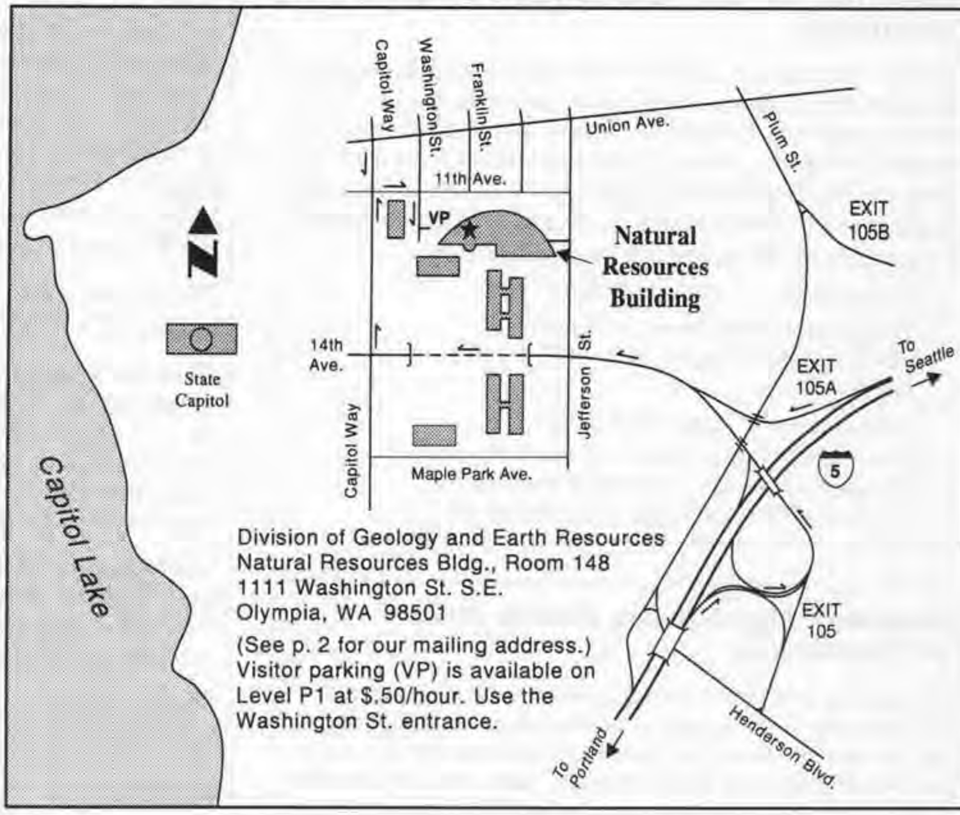

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Reprints of the Landslide Article Available

Thanks to financial support from the Federal Emergency Management Agency, reprints are available for the recent article about the December/January landslides around the Puget Lowland by Wendy Gerstel and others from the Division and the Department of Ecology. The article appeared in the previous issue (March, v. 25, no. 1) of this magazine. Free copies of the reprint can be obtained from:

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Another Significant Fossil Find at Stonerose

Although it was found several years ago by a visitor, a middle Miocene fossil cycad in northeastern Washington was only recently identified by paleobotanists. This kind of palm-like plant had not previously been seen in material collected at Republic and may be helpful in paleoclimate reconstruction for the area. It adds to the already enormous plant community diversity recorded in the fossil flora.

This fall a team of paleontologists from the Smithsonian Institution (Natural History Museum), the Denver Natural History Museum, and the Burke Museum will assemble in Republic to make a detailed stratigraphic study of the lakebed deposits in the town in hopes of clarifying when and how plants and communities changed.

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Division Releases

Preliminary Bibliography and Index of the Geology and Mineral Resources of Washington, 1996, compiled by C. J. Manson, Open File Report 97-1. The 135-page report lists 363 items published in 1996 and more than 900 items from previous years that were not included in earlier compilations. Some of the older material presents information about mines and mining in the early 1900s. $4.63 + .37 (tax for WA residents only) = $5.00.

The following two reports, supported by the U.S. Geological Survey's STATEMAP Program, are now in press:

Geologic map of the Kendall and Deming 7.5-minute quadrangles, western Whatcom County, Washington, by J. D. Dragovich, D. K. Norman, and P. T. Pringle of the Division and R. A. Haugerud of the USGS. The report, Open File Report 97-2, includes a geologic map of each quadrangle and a sheet of cross sections.

Geologic map of the Mead 7.5-minute quadrangle, Spokane County, Washington, by R. E. Derkey, W. J . Gerstel, and R. L. Logan. The report, Open File Report 97-3, includes a geologic map and a sheet of cross sections.

Please contact the Division (see p. 2) for prices.

Errata

In the last issue (March 1997, v. 25, no. 1) of *Washington Geology*:

- The photos for Figures 2 and 3 in the article on Washington's coal industry (p. 15–16) were inadvertently switched.
- The last sentence in the caption for Figure 6 (p. 5) should read "If sufficient resources can be identified, the company would reopen the Pend Oreille mine when their giant lead-zinc *Sullivan* deposit in British Columbia is mined out in about 4 years."
- On page 17, the address for Hugh Shipman is actually 3190 160th Ave. SE, Bellevue, WA 98008-5452.
- On page 22, in Figure 13, the location of the landslide in Figure 17 is approximately where Figure 19 is shown, and the photo in Figure 19 was taken somewhat farther west than is shown in Figure 13.

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